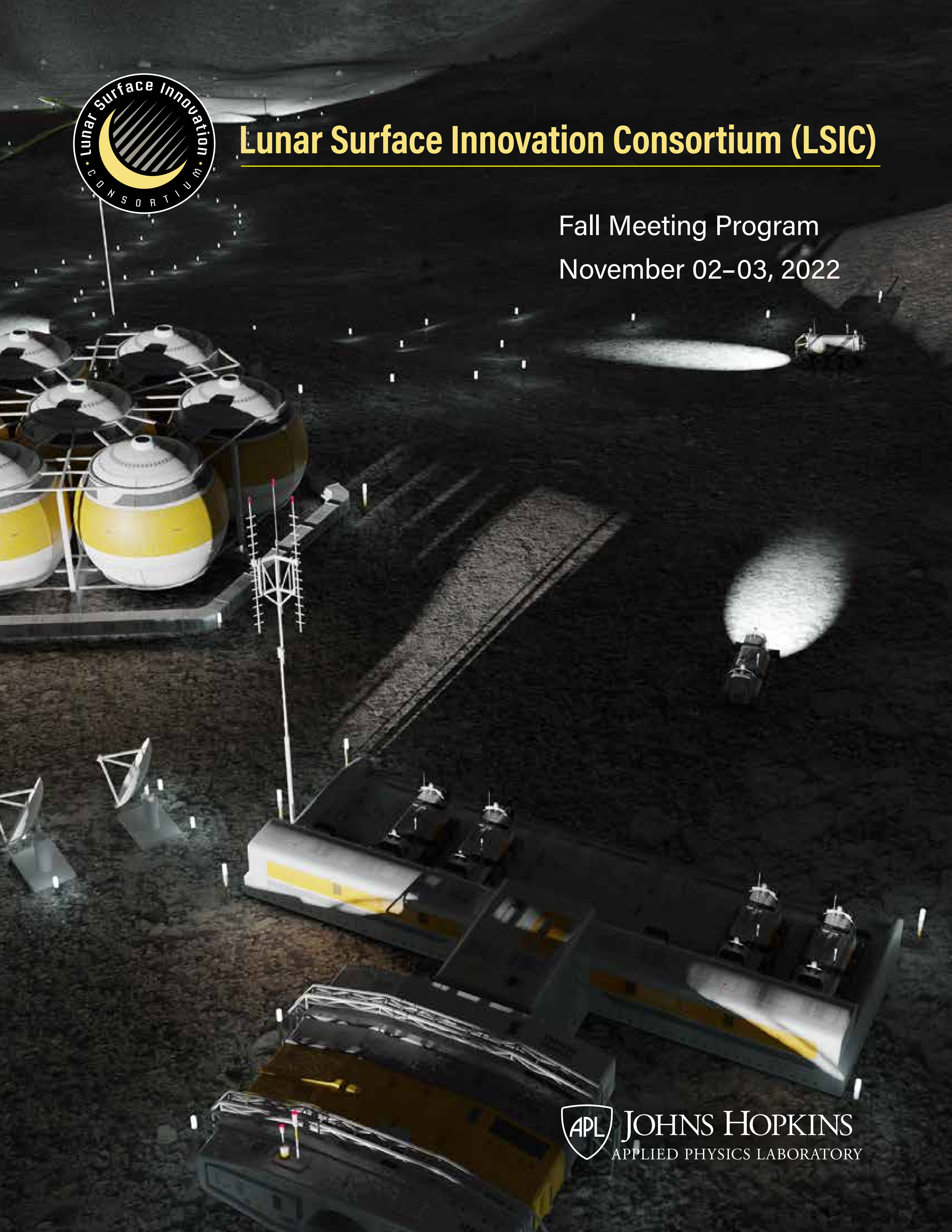


Lunar Surface Innovation Consortium (LSIC)

Fall Meeting Program

November 02–03, 2022

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Technical Organizing Committee

Shirin Afroza, University of Texas at El Paso
Reza Ashtiani, University of Texas at El Paso
Jodi Berdis, JHU Applied Physics Laboratory
Athonu Chatterjee, JHU Applied Physics Laboratory
Ahsan Choudhuri, University of Texas at El Paso
Alice Cocoros, JHU Applied Physics Laboratory
Karl Hibbitts, JHU Applied Physics Laboratory
Jose Hurtado, University of Texas at El Paso
Kristin Jaburek, JHU Applied Physics Laboratory
Michael Nord, JHU Applied Physics Laboratory
Mark Perry, JHU Applied Physics Laboratory
Md. Mahamudur Rahman, University of Texas at El Paso
Samalis Santini De Leon, JHU Applied Physics Laboratory
Lindsey Tolis, JHU Applied Physics Laboratory
Sarah Withee, JHU Applied Physics Laboratory
Sean Young, JHU Applied Physics Laboratory

LSIC Summary

The purpose of the Lunar Surface Innovation Consortium (LSIC) is to harness the creativity, energy, and resources of the nation to help NASA keep the United States at the forefront of lunar exploration.

LSIC operates in collaboration with the NASA Space Technology Mission Directorate under the Lunar Surface Innovation Initiative. LSIC fosters communications and collaborations among academia, industry, and Government. Members have expertise in LSII key capability areas.

Please visit the LSIC website for further information: http://lsic.jhuapl.edu

PROGRAM

Lunar Surface Innovation
CONSORTIUM

FALL MEETING 2022 NOVEMBER 2–3

Day 1

All times are Mountain. Full speaker bios are listed in the online program book accessible on the event page on LSIC's website.

TIME	EVENT	SPEAKER(S) OR DETAILS
8:00 AM	Coffee and Networking in Person and in GatherTown	
8:30 AM	Welcome to the University of Texas at El Paso	Kenith E. Meissner II and Ahsan Choudhuri
9:00 AM	Day 1 Keynote Address	Stephen Robinson, UC Davis
9:20 AM	NASA Space Tech Envisioned Futures	Niki Werkheiser, NASA Space Technology Mission Directorate
9:40 AM	Lunar Surface Innovation Initiative	Rachel Klima, Johns Hopkins Applied Physics Laboratory (APL) Karen Stockstill-Cahill, APL James Mastandrea, APL Wes Fuhrman, APL
9:55 AM	BREAK	
10:05 AM	Panel: Terrestrial and Lunar Construction	**PANELISTS:** Eric Reiners, Caterpillar Keith Churchill, Bechtel Global Inc. Leslie Gertsch, NASA Glenn Research Center
11:15 AM	Lunch and Aerospace Center Tours	
12:45 PM	Panel: Lunar Proving Grounds	**PANELISTS:** Paul van Susante, Michigan Technological University Sam Ximenes, Astroport Space Technologies Inc. Nick Downs, Nevada National Security Site Vlada Stamenković, Blue Origin Timothée Pourpoint, Purdue University
2:10 PM	BREAK	
2:20 PM	Lightning Talks	Members of the Community
3:10 PM	BREAK	
3:15 PM	Breakout Session 1	
4:15 PM	Poster Session and Networking	
5:15 PM	Sessions Adjourn for the Day	
5:30 PM	Shuttles Depart for Evening Tours and Dinner	
5:45 PM	Tours of Spacecraft Design and Engineering Facility	
6:30 PM	Tour of Tech1 Campus with Food Trucks and Cash Bar	
8:30 PM	Shuttles Return to Downtown El Paso	

PROGRAM CONTINUED

Day 2

All times are Mountain. Full speaker bios are listed in the online program book accessible on the event page on LSIC's website.

TIME	EVENT	SPEAKER(S) OR DETAILS
8:00 AM	Aerospace Center Tours, Coffee and Networking in Person and in GatherTown	
9:00 AM	Day 2 Keynote Address	James Reuter, NASA Space Technology Mission Directorate
9:25 AM	Excavation, Construction and Outfitting	Mark Hilburger, NASA Space Technology Mission Directorate
9:45 AM	Emerging Technology and Space Law	Justine Kasznica, Babst Calland LLP
10:05 AM	Session Q&A	
10:20 AM	BREAK	
10:35 AM	Panel: Early Lunar Infrastructure	**PANELISTS:** Matt Mahlin, NASA Langley Research Center Christopher Dreyer, Colorado School of Mines Elizabeth Taylor, NASA Ames Research Center
11:55 AM	Lunch, Networking and Tours	
1:25 PM	Panel: Space Tech Opportunities/Awardees	**PANELISTS:** Md Mahamudur Rahman, University of Texas at El Paso (Lunar Surface Technology Research) Bill Anderson, Advanced Cooling Technologies (Small Business Innovation Research) Theresa Nosel, University of Connecticut (Big Ideas Challenge)
2:45 PM	BREAK	
3:00 PM	Panel: Lunar Resources — Prospecting, Processing and Usage	**PANELISTS:** Clive Neal, University of Notre Dame (Resource Prospecting) Ryan Vaughan, NASA (VIPER) Melodie Yashar, ICON (3D Printing)
4:00 PM	BREAK	
4:10 PM	Breakout Session 2	
5:00 PM	Return to the Tomás Rivera Conference Center	
5:10 PM	Breakout Findings and Closing	
5:30 PM	Sessions Adjourn for the Day	
5:45 PM	Shuttles Depart for Fort Bliss	
6:00 PM	View ICON 3D-Printed Barracks	
7:00 PM	Shuttles Return to Downtown El Paso	

Speakers

Bill Anderson

Chief Engineer, Advanced Cooling Technologies, Inc.

Bill received his Ph.D. in Mechanical Engineering from MIT in the early 80's and has a track record of designing and developing unique heat transfer devices to solve difficult thermal problems for both ground-based and space applications. Devices range in temperature from cryogenic (20 K Hydrogen LHPs) to temperatures in excess of 2000°C (Lithium Magnetoplasmadynamic Thrusters), with heat fluxes of up to 6,800 W/cm2.led the technical innovation at ACT since its inception in 2003. For the past decade, he has been working on developing thermal devices to solve the Lunar night. Bill currently serves as the Chief Engineer for Advanced Cooling Technologies, Inc.'s (ACT's) R&D program.

Dr. Jodi Berdis

In-Situ Resource Utilization Focus Group Lead, LSIC
Senior Staff Scientist, JHU Applied Physics Laboratory

Dr. Jodi Berdis is the LSIC ISRU Focus Group Lead and a Senior Staff Scientist in the Applied Space Research Group at the Johns Hopkins Applied Physics Laboratory. Dr. Berdis' background is in near-infrared spectroscopic analysis and composition of icy satellites, primarily Jupiter's moon, Europa. Her dissertation focused on determining where, and in what quantities, water ice was present on Europa's surface, and her passion for finding and understanding water ice has extended to our own Moon, including how we might go about locating, extracting, and processing resources at the South Pole. She was heavily involved in a project at APL to create mortar for regolith bricks on the Moon using a thermite welding technique. Dr. Berdis also organizes the Ice Giant Systems Seminar Series, and led a project on flyby asteroid imagery for planetary defense. She is especially interested in Equity, Diversity, and Inclusion initiatives, and serves on the Professional Culture & Climate Subcommittee (PCCS) of the AAS Division for Planetary Sciences (DPS).

Dr. Josh Cahill

Deputy Director, LSIC
Senior Staff Scientist, JHU Applied Physics Laboratory

Dr. Joshua Cahill is the Deputy Director of the Lunar Surface Innovation Consortium (LSIC) and a Senior Staff Scientist in the Planetary Exploration Group at the Johns Hopkins Applied Physics Laboratory. He is a multi-disciplinary planetary geologist with experience in the fields of lunar and terrestrial spectroscopy and radar remote sensing, geochemistry, and petrology. He is a Co-Investigator on NASA's Lunar Reconnaissance Orbiter (LRO) mission supporting both the Mini-RF synthetic aperture radar and the Lyman Alpha Mapping Project (LAMP) instrument payloads. He has supported various aspects of these instrument's investigations of the lunar surface over the last 10 years. This includes utilizing Mini-RF observations to create some of the first global mapping perspectives of the Moon in S-band radar. His LRO research has focused upon characterization of the lunar surface and subsurface physical and thermophysical properties, composition, volatiles, how space weathering influences those interpretations, and polar and non-polar permanently shadowed regions. Dr. Cahill is also a Co-Investigator on the recently selected Lunar Vertex (LVx) mission which will investigate the legendary magnetic anomaly and lunar swirl, Reiner Gamma.

Speakers

Dr. Athonu Chatterjee

Excavation & Construction Focus Area Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Athonu Chatterjee is a researcher in the space exploration sector of APL. His background is in mechanical engineering, materials processing, and modeling and simulation. His present activities at APL include laser-material interaction, spacecraft design,and lunar exploration. Prior to joining APL, he worked at the research centers of General Electric (GE) and Corning. There he worked on new product and process development for diverse applications such as high-temperature ceramics matric composites (CMC) for aircraft engines, turbine blade manufacturing processes, solid-oxide fuel cells (SOFC), micro-reactors, etc. He obtained his Ph.D. in mechanical engineering from Stony Brook University, NY.

Dr. Ahsan Choudhuri

Associate Vice President, Aerospace Center, Professor of Mechanical Engineering, University of Texas at El Paso

Dr. Ahsan Choudhuri is Associate Vice President for Aerospace Center and Professor of Mechanical Engineering at the University of Texas at El Paso (UTEP). He is the founding Director of UTEP NASA MIRO Center for Space Exploration and Technology Research (cSETR) and holds the endowed Mr. and Mrs. MacIntosh Murchison Chair II in Engineering. Dr. Ahsan Choudhuri's academic career has evolved within the paradigm of UTEP's access and excellence mission. He is a part of UTEP's strategic vision to create abundant educational opportunities to ensure social mobility for the residents of the Paso Del Norte region.

Dr. Ahsan Choudhuri is an internationally renowned expert in aerospace and defense systems. He is the founding director of UTEP NASA supported Center for Space Exploration and Technology Research (cSETR). Dr. Choudhuri led the growth of UTEP's aerospace and defense and energy education and research program from infancy to a nationally recognized program. He has formed strategic collaborations and partnerships with NASA, DOE, DOD, and aerospace and defense industries. Dr. Choudhuri is a key institutional leader for developing and managing the partnership with Lockheed Martin and NASA. Dr. Choudhuri is a member of the Executive Committee of the Lunar Surface Innovation Consortium (LSIC), which supports NASA's Space Technology Mission Directorate.

Dr. Choudhuri is a proud alumnus of Khulna University of Engineering and Technology, where he received his B.S. in Mechanical Engineering. He received his M.S. and Ph.D. from the University of Oklahoma School of Aerospace and Mechanical Engineering.

Speakers

Keith Churchill

Chief Innovation Officer, Bechtel Global, Inc.

With over 20 years of construction experience in both heavy infrastructure and industrial construction, Keith currently serves as Bechtel's Chief Innovation Officer focusing on the identification, testing and implementation of new technology aimed at improving both cost and schedule performance while enhancing safety and quality. His goal is to improve construction delivery methods and installation activities by leveraging the latest in technology, both digital and physical, geared toward improving the certainty of outcome of the projects that Bechtel delivers. With the belief that improving the jobsite experience for the craft workforce will ultimately be the catalyst to refresh the image of the industry and attract the next generation of talent, he is driven to combat the labor shortage head-on by rebranding the industry as a technology leader. He has worked for Bechtel for 14 years and is a graduate of Purdue University with a Bachelor of Science in Civil Engineering.

Dr. Angela Dapremont

Policy, Strategy, and Recruitment Lead, LSIC
Associate Staff, JHU Applied Physics Laboratory

Dr. Angela Dapremont is a Post Doctoral Fellow at the Johns Hopkins University Applied Physics Laboratory. As a member of the Lab's Planetary Exploration Group, Dr. Dapremont provides policy, strategy, and recruitment support to the Lunar Surface Innovation Consortium. Dr. Dapremont's scientific research is focused on understanding the composition of terrestrial bodies in the solar system. Her research publications have incorporated datasets from numerous orbital remote sensing missions including the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), the Context Camera (CTX), and the High Resolution Imaging Science Experiment (HiRISE) camera currently orbiting Mars. Dr. Dapremont also uses Moon Mineralogy Mapper (M3) data to investigate lunar surface composition and is an Affiliate of the Lunar Trailblazer mission.

Nick Downs

Senior Scientist, Geoscience Operations,
Nevada National Security Site

Nick Downs is a Senior Scientist within the Geoscience Operations group at the Nevada National Security Site (NNSS). The NNSS is the premier outdoor, indoor, and underground national laboratory supporting the National Nuclear Security Administration (NNSA)'s nuclear weapons Stockpile Stewardship Programs, national defense programs, and national security research, development and training programs. The NNSS was one of the primary training grounds for Apollo astronauts and Nick is actively working to establish multiple Lunar/Martian testbeds at the globally unique setting of the NNSS.

Speakers

Dr. Christopher Dreyer

Professor of Practice,
Space Resources Program, Colorado School of Mines

Dr. Christopher Dreyer is a Professor of Practice and co-founder of the Space Resources Program and Director of Engineering in the Center for Space Resources at the Colorado School of Mines. Dr. Dreyer's research focuses on the development of technologies that enable the development of space resources. Research topics include instrument development for resource discovery, site preparation for construction, resource extraction from the Moon and asteroids, water processing, and in situ produced part verification instruments. Dr. Dreyer's teaching in Space Resources includes the introductory graduate course that reviews the scope, challenges, and potential of the use of resources in space, and graduate project classes. He has been involved with early and mid-phase technology development for two decades. Most recently as PI of ASPECT, Autonomous Site Preparation: Excavation, Compaction and Testing, a NASA LuSTR award for a lunar surface autonomous site preparation system.

Dr. Wesley Fuhrman

LSII Lead
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Wesley Fuhrman is a condensed matter physicist passionate about the interface between public and private science, with active research in remote sensing and advanced materials. Wesley earned his PhD from The Johns Hopkins University in spectroscopy of correlated topological materials, involving techniques such as elastic and inelastic neutron scattering, neutron spin echo, prompt-gamma activation analysis, X-ray absorption spectroscopy, X-ray magnetic circular dichroism, etc. Following this, he was an inaugural Schmidt Science Fellow, a program in partnership with the Rhodes Trust which builds interdisciplinary skills that cross boundaries between academia, industry, and government. Materials expertise spans solid-state synthesis (including uranium compounds), characterization, spectroscopy, and theory of strongly correlated and topological materials.

Dr. Leslie Gertsch

NASA GRC ISRU Engineering Lead

Leslie Gertsch holds geological and mining engineering degrees from Colorado School of Mines. She has worked for the U.S.Bureau of Mines, the Colorado School of Mines, Michigan Technological University, and the Missouri University of Science andTechnology (S&T). She is also a Member of the Missouri Mining Commission, and is currently seconded from S&T to NASA Glenn Research Center.

Speakers

Dr. Karl Hibbitts

In Situ Resource Utilization (ISRU) Focus Area Lead, LSIC
Principal Staff Scientist, JHU Applied Physics Laboratory

As a planetary scientist, Dr. Karl Hibbitts conducts research to understand the compositions of the surfaces of airless bodies in our Solar System, including how otherwise volatile materials like water can exist on the illuminated Moon. He is deputy-PI of the Europa Clipper MISE infrared mapping spectrometer and was deputy-PI and mid-IR camera lead on the NASA BRRISON and BOPPS stratospheric balloon missions that demonstrated the scientific and cost effectiveness of spectral imaging of solar system objects from NASA balloon platforms in the upper stratosphere. Dr. Hibbitts also leads an active planetary laboratory spectroscopy effort in a facility he developed at APL that couples VUV –LWIR spectral capabilities with a UHV system capable of mimicking the vacuum, temperature, and radiation environments of the Moon and other airless bodies in our solar system.

Dr. Mark Hilburger

Principal Technologist for Structures and Materials, NASA STMD

Dr. Mark W. Hilburger was appointed Space Technology Mission Directorate (STMD) Principal Technologist (PT) for Structures, Materials, and Nanotechnology at NASA HQ in 2019. His roles and responsibilities include identifying technology needs and developing technology investment plans across his assigned discipline areas in coordination with NASA Exploration Programs and Mission Directorates. He conceives and leads focused technology studies and coordinates with Agency Capability Managers in technology development activities to maintain and advance capabilities. He is currently focused on developing capabilities for the autonomous excavation, construction, and outfitting of lunar infrastructure, and includes investments across the entire TRL pipeline, and in collaboration with US industry, academia, and OGA. Specific emphasis on early lunar infrastructure and technology demonstrations that will lead to a permanent lunar presence and robust industry-led economy.

Dr. Hilburger has over 25 years of experience in the field of structural mechanics and materials and specializes in the development and implementation of High-Fidelity Structural Analysis and Design Technology, Advanced Experimental Methods, and Design Criteria for Aerospace Structures. He has been presented with numerous awards and including the 2018 Middle Career Stellar Award presented by The Rotary National Award for Space Achievement; the NASA Exceptional Engineering Achievement Medal, 2010; selected as one of the nation's top 100 young engineers and scientist by the National Academy of Engineering, 2009; and the NASA Silver Snoopy Award, (Astronauts' Personal Achievement Award), 2006. He received his M.S.E. and Ph.D. in Aerospace Engineering from the University of Michigan in Ann Arbor, MI in 1995 and 1998, respectively, and his B.S. in Mechanical Engineering from Rutgers University in New Brunswick, NJ in 1993.

Speakers

Justine Kasznica

Shareholder at and Chair of Emerging Technology Practice Group, Babst Calland LLP

Justine Kasznica is a shareholder at and the Chair of the Emerging Technology Practice Group at Babst Calland LLP. Kasznica is a technology and corporate attorney who represents the legal and regulatory needs of clients who are customers and vendors of software, SaaS, IoT, AI, robotics and other technology products and services across diverse industries from banking to transportation. She specializes in supporting the regulatory and business services needs of clients in the autonomous mobility (UAS and AVs), and commercial space industries. She serves as outside general counsel to a number of aerospace clients across the U.S., including KSC members Astrobotic Technology, Inc. and Acoustic Research Systems, Inc. In 2021, Kasznica founded and currently serves as the Board Chair of the Keystone Space Collaborative, a non-profit committed to growing the space industry in Pennsylvania, Ohio and West Virginia.

She serves on numerous other boards and is involved in many community economic developments initiatives, including the Moonshot Museum (founding Board-member), Ascender PGH, and the Yale Club of Pittsburgh (former President). She serves on the Council of the Pennsylvania Bar Association's Aeronautical and Space Law Section, is a member of the Dubai Courts of Space Initiative, and is a member of the Registration Project Working Group, a group of experts working with the Moon Village Association and Global Space Law Center to propose domestic and international laws and policy related to space commercialization, including the registration of space artifacts beyond Lower Earth Orbit.

Dr. Rachel Klima

Director, LSIC

Principal Staff Scientist, JHU Applied Physics Laboratory

Dr. Rachel Klima is the Director of the Lunar Surface Innovation Consortium and a principal staff scientist in the Planetary Exploration Group at the Johns Hopkins Applied Physics Laboratory. Dr. Klima's research focuses on integrating laboratory analysis of lunar, meteoritic, synthetic, and terrestrial rocks and minerals with near through mid-infrared spectral measurements of solid bodies in the solar system to understand such topics as the thermal/magmatic evolution of the Moon, distribution of minerals, water, and hydroxyl on the lunar surface, and the composition of Mercury's crust. Dr. Klima has been involved with numerous missions to bodies throughout the solar system, including the Dawn Mission, the Moon Mineralogy Mapper, a hyperspectral imaging spectrometer flown on Chandrayaan-1, MESSENGER, and Europa Clipper. She previously served as the Deputy PI of the Volatiles, Regolith and Thermal Investigations

Consortium for Exploration and Science (VORTICES) team for the NASA Solar System Exploration Research Virtual Institute (SSERVI). She currently serves as the Deputy PI of the Lunar Trailblazer Mission and is a participating scientist on the Korea Pathfinder Lunar Orbiter.

Speakers

Matthew Mahlin

Principal Investigator. Tall Lunar Tower,
NASA Langley Research Center

Mr. Matthew Mahlin is the Principal Investigator for the Tall Lunar Tower project and an Aerospace Research Engineer in the Structural Mechanics and Concepts Branch at the NASA Langley Research Center (LaRC). Mr. Mahlin's research currently focuses on development of in-space and surface assembly of truss structures by robotic agents. Mr. Mahlin has contributed to multiple in-space and surface assembly projects, including roles as the lead test engineer for the Tendon Actuated Lightweight in-Space MANipulator (TALISMAN) as well as the mechanical and electrical system design lead for the Assemblers scalable modular robotic manipulator. Previously he has served as a research engineer studying refractory composites for the Hypersonic Technology Project at LaRC and a trainee design engineer for the Prototype Development Lab (PDL) at the Kennedy Space Center (KSC).

Dr. James Mastandrea

Acting Surface Power Lead and MOSA Working Group Lead, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. James P. Mastandrea is a Senior Professional Staff member at the Johns Hopkins University Applied Physics Laboratory's Space Exploration Sector. He has aBS in Mechanical Engineering and Materials Science & Engineering, and a MS and PhD in Materials Science & Engineering all from the University of California,Berkeley. He has experience in computational materials science, material nucleation and growth, microstructural evolution of materials, and understanding material performance with an emphasis on semiconductors and metals. He serves as the LSIC Modular Open Systems Approach (MOSA) working group lead and is the Acting Lead for the Surface Power focus group. He also serves on the project management team of a NASA Heliophysics' study on an Interstellar Probe, a mission concept that would explore our habitable astrosphere and our local interstellar medium.

Speakers

Dr. Clive Neal

Professor of Planetary Geology, University of Notre Dame

Clive R. Neal is currently a Professor of Planetary Geology at the University of Notre Dame in Indiana. E has published over 130 peer-reviewed scientific journal articles. He has served on numerous mission and research review panels, including being chair of the Lunar Sample Allocation subcommittee 2005-2009, a member of the 2012 Senior Review panel for NASA's Planetary Science and Chair of that panel in 2014. Neal was the chair of NASA's Lunar Exploration Analysis Group from 2006-2010, where he led a community effort to develop the Lunar Exploration Roadmap, and again from 2015-2018, where he formed the LEAG Commercial Advisory Board. In 2019, Neal was invited to give testimony at the sixth meeting of the National Space Council at the Smithsonian's Udvar-Hazy Center in Chantilly, Virginia. regarding the importance of in situ resource utilization. He is currently a member of the National Academies Committee on Astrobiology and Planetary Science. In 2021, Neal received the LEAG Service Award, which is given to an individual who has demonstrated extensive service to LEAG and/or the lunar community through excellence in leadership, continuous dedication to mentoring and enriching he early-career community, an extensive track record in the field of science and/or exploration of the Moon. Neal is passionate about NASA and in returning humans to the Moon and beyond in a sustainable, economically beneficial, and permanent way. In 2015, he received the NASA Wargo Award for contributions to the integration of exploration and planetary science throughout his career.

Neal grew up and was educated in the United Kingdom and became a United States citizen in 2013. He obtained his PhD in geochemistry and petrology in 1986 from the University of Leeds, UK. He moved to the United States later in that year where he spent 4 years as a post-doctoral research fellow at the University of Tennessee – Knoxville. While there, he studied mantle petrology and was introduced to the study of Apollo lunar samples, and has been involved in the study of the Moon since then using samples, as well as remotely sensed data from missions including and since Apollo.

Theresa Nosel

Undergraduate Student from the University of Connecticut

Theresa Nosel is a senior undergraduate student from the University of Connecticut double majoring in Materials Science and Engineering and Chemical Engineering. She is the organizer and team lead for the 2022 NASA BIG Idea Challenge Finalist team from the University of Connecticut. This team is focused on exploring and developing a robotic modality that morphs from tank motions to quadruped motions with the ultimate purpose of navigating the difficult terrain found at the lunar south pole. Theresa has also been involved in numerous polymer science and synthetic chemistry research projects, particularly ones centered around different 3D printing techniques such as fused deposition modeling and stereolithography.

Speakers

Dr. Timothee Pourpoint

Professor, School of Aeronautics and Astronautics,
Purdue University

Dr. Timothee Pourpoint is a professor in the School of Aeronautics and Astronautics at Purdue University. His research focuses on the engineering and detailed characterization of storable propellants and on the tailoring of their performance or behavior to specific propulsion systems. He specializes in kerosene-based fuels, hypergolic propellants (both as liquids and solids) and monopropellants for high altitude and space applications. He designed and implemented a unique laboratory in the United States to study hazardous propellants, including monomethyl hydrazine and nitrogen tetroxide at representative system conditions. Integral to the evaluation of chemical propellants at representative conditions is an altitude chamber facility developed at the Zucrow Laboratories specifically for the evaluation of chemical thrusters at up to 100,000 ft equivalent. He is the author of 161 technical publications. He is also the co-author of a Rocket Propulsion textbook published in 2019 with Drs. Heister and Anderson at Purdue and Mr. Joe Cassady from Aerojet Rocketdyne. Professor Pourpoint is an AIAA Associate Fellow and has been Chair of the AIAA Liquid Propulsion Technical Committee since December 2019. Along with Dr. Kathleen Howell, he is the co-chair of the Purdue Engineering Cislunar Initiative.

Eric Reiners

Program Manager, Integrated Components and Services Division,
Caterpillar Inc.

Eric Reiners is a Program Manager within the Integrated Components and Services Division of Caterpillar Inc, with responsibility for Automation & Autonomy. He also serves as the Caterpillar liaison for external engagements in this area with universities and government agencies.

Eric's past collaborations with NASA include telerobotic and automation technologies that were showcased in NASA's Exploration Highlights, NASA's 3D Habitat Challenge and Break the Ice Lunar Challenge. Eric has also served as the autonomy judge for the NASA Lunabotics Competition since its inaugural year in 2010. He is also a member of the Commercial Advisory Board for the Lunar Exploration and Analysis Group (LEAG).

During his 30+ year career, he has held a variety of roles in machine design, analysis, validation, new technology introduction, new product introduction, product quality and reliability, as well as development of collaborative government research. In these roles, Eric has gained significant experience in Caterpillar's surface mining, underground mining, construction and earthmoving product lines.

Eric holds 19 patents in the areas of machine design and machine automation algorithms. He has Bachelor of Science in Engineering from the University of Illinois at Urbana-Champaign.

Speakers

James Reuter

Associate Administrator, NASA STMD

James L. Reuter is the associate administrator for the Space Technology Mission Directorate (STMD) at NASA Headquarters in Washington. He provides executive leadership and management of the technology programs within STMD, with an annual investment value of more than $1 billion.

During his almost four-decade career at NASA, Mr. Reuter has held several leadership positions, including: STMD deputy associate administrator, senior executive for technical integration at NASA's Marshall Space Flight Center in Huntsville, Alabama, chair of the standing review board of the Exploration Systems Division at NASA Headquarters, deputy manager of the Space Shuttle Propulsion Office, and environmental control and life support manager for the International Space Station.

Mr. Reuter has received numerous NASA awards and honors, including a Presidential Rank Award, Distinguished Service Medal, Outstanding Leadership Medal, NASA Exceptional Achievement Medal, and NASA Exceptional Service Medal.

Dr. Stephen Robinson

Professor and Director of the Center for Spaceflight Research, University of California, Davis

Before joining the faculty at the University of California, Davis in 2012, Stephen Robinson spent 37 years at NASA, where he worked as a machinist, lab technician, engineer, research scientist, branch chief, safety representative, and astronaut. Robinson is now a tenured professor in the UC Davis Mechanical and Aerospace Engineering Department. He has recently been appointed Director of the UC Davis Center for Spaceflight Research.

Dr. Robinson also directs the UC Davis Human/Robotic/Vehicle Integration and Performance Lab, where graduate and undergraduate students pursue research in human spaceflight, spacecraft design for human health and safety, aviation safety, human/automation/robotic integration, human performance, automation and control, and CubeSat and UAV design.

During his 17 years as a NASA Astronaut, Dr. Robinson flew on four space shuttle missions, including three spacewalks, visited the ISS twice, trained in Star City, Russia, and has extensive expertise in spacecraft systems, human/systems integration, operational safety, space robotics, aerodynamics, and fluid physics.

Dr. Robinson has received numerous awards, including NASA's highest honor - the NASA Distinguished Service Medal, and UC Davis' highest honor – the UC Davis Medal. Robinson is a UC Davis alumnus in Mechanical and Aeronautical Engineering (double B.S., 1978) and received his M.S. and Ph.D. in turbulence physics from Stanford University in Mechanical and Aero/Astro Engineering (1986, 1990).

Dr. Robinson is an active pilot, an artist, and a multi-instrument musician – he currently plays with the mostly-astronaut folk-music band Bandella, and the all-astronaut rock band Max Q.

Speakers

Dr. Afroza Shirin

Lunar Simulants Lead, LSII

Assistant Professor, Aerospace Center,
The University of Texas at El Paso

Dr. Afroza Shirin is an Assistant Professor in the Department of Aerospace and Mechanical Engineering and Aerospace Center. Before joining UTEP, she worked as a Postdoctoral Research Fellow in the Department of Electrical and Computer Engineering at the University of New Mexico. She received her Ph.D. in Mechanical Engineering from the University of New Mexico in 2019. She finished her Bachelor and Master's degrees in Mathematics from the University of Dhaka, Bangladesh. Her research experience and expertise are in dynamical systems modeling, design, navigation, and control, using techniques and algorithms from nonlinear dynamics, nonlinear optimal control, optimization, and machine learning. Her one of the current research interests is modeling the dynamics of space vehicles such as hypersonic vehicles, robotic landers, space satellites, and designing the control schemes to guide and navigate these space vehicles under space considerations. Having versatile and multidisciplinary research experience and interests, Dr. Shirin is also involved with the Aerospace Center ISRU research group in developing advanced thermal mining technology to extract and collect water from icy lunar regolith. She is a member of the Institute of Electrical and Electronics Engineers (IEEE) and American Institute of Aeronautics and Astronautics (AIAA).

Dr. Karen Stockstill-Cahill

Lunar Simulants Lead, LSII

Senior Professional Staff, JHU Applied Physics Laboratory

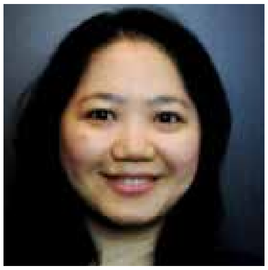
Dr. Karen Stockstill-Cahill is the Lead of the Lunar Surface Innovation Initiative Lunar Simulants team and a senior professional staff scientist in the Planetary Exploration Group at the Johns Hopkins Applied Physics Laboratory. Dr. Stockstill-Cahill's research focuses on using remote sensing data of planetary bodies to understand the geochemistry and petrologic history of solar system bodies. She also conducts a range of laboratory analysis (e.g., UV-MIR spectroscopy, SEM) of planetary samples and terrestrial analog materials to better understand data collected by missions. She also manages the APL Meteorite Lab and Laboratory for Spectroscopy under Planetary Environmental Conditions (LabSPEC). Dr. Stockstill-Cahill has been involved with numerous NASA missions, including 2001 Mars Odyssey, Mars Reconnaissance Orbiter, Mars Exploration Rover, and MESSENGER. She is also a co-investigator on the Planetary Science Institute's TREX SSERVI team and supported research for APL's SSERVI VORTICES team. She is currently a co-investigator for the LRO-LAMP mission and participates in internal instrument development projects focused on Moon-to-Mars missions.

Speakers

Elizabeth Taylor

Associate Chief of Mission Systems,
NASA ARC Intelligent Systems Division

Elizabeth Taylor is the Associate Chief of Mission Systems for NASA Ames Research Center's (ARC) Intelligent Systems Division, as well as the Project Manager for the Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project. The ARMADAS project is developing an autonomous construction and assembly system that utilizes a digital materials approach to form, maintain, and reconfigure structures. This technology enables large-scale infrastructure in space and on planetary surfaces through the development of a robust structural design and an autonomous assembly capability. Ms. Taylor previously worked on numerous missions to assemble and operate the International Space Station. Her career evolved quickly as she led teams through dynamic, complex technical and cultural challenges. In 2014, she moved from Johnson Space Center to Ames Research Center where she began helping researchers and commercial companies make use of space station laboratory facilities. Since then, she has also helped with the design for autonomous operations of the Gateway vehicle, and in addition to her project management role, she provides consultation and oversight of projects within NASA ARC's Intelligent Systems Division. Her passion for and dedication to collaboration, teamwork, innovation, and problem solving have earned her numerous awards.



Dr. Stacy Teng

Analyst, Extreme Access Focus Group, LSIC
Senior Professional Staff, JHU Applied Physics Laboratory

Dr. Stacy Teng is an astrophysicist at the Johns Hopkins Applied Physics Laboratory in the Applied Space Research group. She earned her Ph.D. from the University of Maryland, developing expertise in multiwavelength (radio, optical/IR, X-ray, and gamma-ray) observations to study black holes in merging galaxies. Following her studies, she was a NASA postdoctoral program (NPP) fellow at Goddard Space Flight Center and a member of the NuSTAR science team. Most recently, she was a research staff member in the Science and Technology Division of the Institute for Defense Analyses. In that capacity, she led and participated in studies for the Department of Defense in areas of directed energy, modeling and simulations of weapon system effectiveness, roadmap assessments, technical program reviews, and database development. At APL, Dr. Teng is a member of the Applied Space Research group, working on modeling and simulation projects for a broad set of sponsors. She also brings her diverse science, program analysis, and technology assessment experience to support the interdisciplinary LSIC focus area of Extreme Access.

Speakers

Dr. Paul van Susante

Assistant Professor Mechanical Engineering - Engineering Mechanics, Michigan Technological University

Dr. van Susante is an assistant professor at Michigan Technological University in the Mechanical Engineering – Engineering Mechanics Department and the founder and PI of the Planetary Surface Technology Development Lab (PSTDL), also known as HuskyWorks. Dr. van Susante's research focuses on robotic systems for In-Situ Resource Utilization (ISRU) and construction and in particular robotic mechanical systems under lunar and mars conditions interacting with the lunar and Mars surface. He is actively researching, developing and testing technologies under lunar and mars environmental conditions for detecting volatiles in lunar regolith, determining geotechnical properties of lunar regolith, conveying and compacting lunar regolith, excavating (cemented) lunar regolith, excavating gypsum and extracting water from excavated gypsum and buried glaciers for Mars applications as well as developing power transfer via (superconducting) tether into the lunar Permanently Shade Regions. Dr. van Susante is PI on multiple NASA and industry funded ISRU projects with a combined value of over $4M. More information can be found at: https://www.huskyworks.space

Ryan Vaughan

Mission Systems Engineer, VIPER

Ryan Vaughan is a Spacecraft Systems Engineer at NASA Ames Research Center with expertise in planetary robotic spacecraft mission formulation, implementation and operations. He is currently the lead Mission Systems Engineer for the Volatiles Investigating Polar Exploration Rover (VIPER) mission, following having the same role during the development of the Resource Prospector mission, the predecessor of VIPER. Previously, he was the Spacecraft Systems Engineer on the LADEE lunar orbiter mission during integration and operations and a systems engineer for the LADEE Ultra-Violet and Visible Spectrometer instrument, which flew aboard LADEE. Mr. Vaughan also previously held the division chief position for the Spaceflight Division at NASA Ames. In addition to his work at NASA, he is also a pilot and is currently homebuilding his own two-seat aircraft in his garage. He can be spotted backpacking in the Sierra Nevada from time to time.

Niki Werkheiser

Director, Technology Maturation, NASA

Niki Werkheiser serves as the Director for Technology Maturation in the Space Technology Mission Directorate (STMD) at NASA Headquarters. The Technology Maturation portfolio includes over 120 projects within the Game Changing Development (GCD) Program and the Lunar Surface Innovation Initiative (LSII). In this role, she leads the advancement of key technologies for future space missions, including establishing policy, formulating budgets, and providing technical leadership. Prior to her current role, Ms. Werkheiser led the Agency's In-Space Manufacturing (ISM) efforts, including the development of novel, on-demand manufacturing, repair, and recycling capabilities.

She brings a wealth of expertise and a proven approach to managing complex projects and has over 25 years of experience developing and flying new technologies in space. Ms. Werkheiser is particularly passionate about creating competitive programs and partnerships across government, industry, academia, and non-profit organizations. Ms. Werkheiser holds a Master of Science Degree from the University of Alabama at Huntsville with an emphasis in Gravitational and Space Biology, as well as a Bachelor of Science in Biology and a Bachelor of Arts in Russian Language and Studies.

Sam Ximenes

CEO, Astroport Space Technologies Inc.

Sam Ximenes is a Space Architect with over 30 years' experience in the aerospace industry with NASA, DoD, and international space programs.

He is currently CEO of Exploration Architecture Corporation (XArc), a space architecture consulting firm he founded in 2007. The firm specializes in commercial spaceport development and design, and space systems development for space exploration initiatives for planetary surface systems for habitation and human settlement

He is also Founder and Board Chair of WEX Foundation, a non-profit organization for advancing careers in space exploration through Space-STEM education. His latest venture is CEO of Astroport Space Technologies, Inc., founded in 2020 as a wholly owned subsidiary of XArc to develop lunar construction technologies for emplacement of critical elements of lunar surface infrastructure.

Melodie Yashar

Director of Building Design & Building Performance, ICON

Melodie Yashar is the Director of Building Design & Performance at ICON, a construction technologies company focused on large scale additive manufacturing for Earth and in space. Melodie oversees the architectural direction of ICON's built work as well as the performance of ICON's building systems to deliver optimally-performing structures that shift the paradigm of homebuilding on Earth and beyond. Collaborating across technology and construction teams, her department supports design and construction of dignified and resilient terrestrial housing solutions in addition to supporting the development of ICON's off-world construction systems.

Melodie teaches undergraduate and graduate design studios at Art Center College of Design. In previous roles Melodie was a Senior Research Associate with the Human Systems Integration Division at NASA Ames via San Jose State University Research Foundation (SJSURF), as well as a co-founder of Space Exploration Architecture (SEArch+), a research group developing human supporting designs for space exploration.

Melodie obtained a Master of Architecture from Columbia University and a Master of Human-Computer Interaction with an emphasis in Robotics from the School of Computer Science at Carnegie Mellon. She is of Iranian heritage and geeks out on new material & fabrication technologies. She likes tiny robots. She would like to visit the Moon (though not yet Mars) in her lifetime.

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Utilization of Optical Profilometer and Image Analysis to Characterize Angularity and Form Factor of JSC-1 Mars and LHT1 Highlands Lunar Regolith Simulants

Caleb Carnes[1], Reza Ashtiani[2], Col Joel Sloan[2], and Kimberly D. De la Harpe[2]

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[2] Department of Civil and Environmental Engineering (DFCE), United States Air Force Academy (USAFA), Colorado, USA

Subject Area: Excavation and Construction

Abstract. In the next decade, NASA is prioritizing moon missions such as safe human transportation, deployment of instrumentations, establishment of habitats, and exploration of native resources to set the stage for future Mars missions. One of the main challenges to achieve these goals, however, is our lack of understanding of the synergistic interactions between the native soil, lunar vehicles, habitats, and EVA suits. In addition to the particle size distributions, surface properties, and compaction characteristics of the surface regolith, the geometry of the particles is of paramount importance for proper understanding of the settlement properties, distortion characteristics, and orthogonal strength of the particulate medium. Additionally, the angularity of the particles has implications on durability of the EVA suits and low cycle fatigue characteristics of mechanical elements deployed to low gravitational environments. Therefore, our multi-disciplinary team in this research envisioned using a state of the art optical profilometer equipment supplemented by image analysis techniques to characterize the geometrical features of a lunar regolith simulant, specifically the LHT-1 highlands type. The distributions of the particle form, angularity and surface macro-texture of lunar regolith were in turn contrasted with JSC-1 Mars simulants and a calcareous construction aggregate at multiple size fractions, for comparative purposes in this study. The results will be instrumental to better understand the anisotropic nature of the angular particles, particle interlocking effect, and its relevance to the strength and deformation characteristics of native soils on extra-terrestrial planetary surfaces.

Keywords: LHT1 Highlands Simulants, Martian Regolith Simulants, Particle Angulaty, Particle Form

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Disclaimer

Native Soil Considerations for Path Planning and Landing Site Selection

Arash Karimi Pour[1], Reza Ashtiani[2], Jesus Baca[1]

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[2] Department of Civil and Environmental Engineering (DFCE), United States Air Force Academy (USAFA), Colorado, USA

<u>Subject Area: Excavation and Construction</u>

Abstract. Proper understanding of the terramechanics and native soil-rover interactions are paramount for the analysis of the deformation potential and settlement characteristics during rover manoeuvres on planetary surfaces. The dynamic nature of the stresses imparted on regolith surface, loading rate dependency and dilatancy behavior of the particulate assembly have significant implications in assessing the responses of native soils on Moon and Mars. The primary objective of this study was to provide insight into the significance of the geotechnical characteristics of the planetary soils on the rover-regolith dynamics through a full factorial numerical simulations. To achieve this objective, our research team used the Finite Element (FE) approach using ABAQUS software with coded materials models for realistic simulation of rovers' operations in low gravitational environments in this study. Orthogonal axial stresses and plastic strains, shear stresses, isobars of vertical stresses relevant to the gravitational accelerations, sinkage characteristics of rovers, maximum height of suspended soil particles and particle setting time for dust lift-off and plume formation analyses were of main interest in this effort. The results underscored the significance of incorporating the gravitational acceleration and loading rate in both the laboratory characterization of the regolith and numerical simulations of soil-rover interactions. Additionally, the numerical imulations showed the significance of the rebounding effect of the rover wheels and the level of compaction of the surface regolith as the primary factors influencing the maneuverability of the rover on planetary surfaces. The results have implications on the sinkage potential, settlement characteristcs, and manoeuvrability capabilities of the rovers considering the inherent variability of regolith density in low gravitational environments.

Keywords: regolith dynamics, lunar regolith, Martian regolith**,** finite element method; survey rovers.

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Investigation of Convective Heat Transfer of Supercritical Fluids for Circular-Pipes in Horizontal Flow for Power Cycle Applications in Lunar Environments. Alaba Bamido[1] , V. Prasad[3], and Debjyoti Banerjee[1,2], [1]J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843-3123. [2]Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, TX 77843-3116. [3]Department of Mechanical Engineering, University of North Texas, Denton, TX 77843. (Contact: dbanerjee@tamu.edu)

Abstract: The convective heat transfer characteristics of a supercritical fluid in a circular pipe for horizontal flow configuration was explored using analytical and numerical studies. The motivation of this study was to explore the efficacy supercritical fluids in heat exchangers involving forced convective heat transfer of supercritical fluids (tube side) integrated with air cooling (i.e., in free convection), for power-cycles in lunar applications. A critical challenge in lunar environments is the severe fluctuations in the diurnal temperature as well as the duration of the diurnal cycles. Super-critical power cycles are considered to be attractive option for these harsh environments. Hence, the goal of this study was to determine the forced convective heat transfer characteristics of supercritical carbon dioxide (sCO_2) in air-cooled tube heat-exchangers. The scope of this study was limited to the values of Reynolds number (*Re*) varying from 10 ~ 10^4 (i.e., involving both laminar and turbulent flow correlations for analytical formulations and computational models). The predictions for the forced convection heat transfer characteristics (e.g., heat transfer coefficient, pressure drop, volume flow rate, mass flow rate, pump penalty/ pumping power/ required compressor ratings, Nusselt number (*Nu*), *Re*, thermal and hydrodynamic entrance lengths, etc.) were obtained using analytical formulations and compared with that of computational models. The flow configurations involved a horizontal circular pipe of 1 m length and with different diameters (ranging from 1 mm – 10 mm). The supercritical properties of the working fluid were investigated at a fixed value of reduced pressure (P_r = 1.1) and a fixed range of temperatures, i.e., T, varying from 550 to 750 [K]. The fluid properties were gleaned from the NIST property database (available online at the NIST website). For the second part of this study, the forced convective heat transfer characteristics of sCO_2 flowing in a horizontal tube with circular cross-section were studied using analytical correlations (e.g., Dittus-Boelter correlation) and validated using commercial tools for Computational Fluid Dynamics (CFD)/ Computational Heat Transfer (CHT), i.e., using Fluent® (Ansys®). Validation of the analytical predictions using CFD/ CHT tools was performed to ascertain the level of uncertainty in the predicted results due to acute variation of the thermo-physical properties as a function of temperature and pressure (since the thermo-physical properties are expected to oscillate widely in the vicinity of the critical point). In the simulations, the inlet temperature for the supercritical fluid (sCO_2) was fixed (at T_{in} = 700 [K]), and the ambient temperature was also fixed (at T_{amb} = 300 [K]), for the purpose of determining the values of the natural convection coefficients (external to the tube). Constant values of the thermo-physical properties of sCO_2 at the mean film temperature (and corresponding to the inlet pressure values) were assumed for obtaining the analytical predictions. The results from the CFD / CHT simulations helped to quantify the level of uncertainties in the assumption of constant properties (in the analytical model) at different values of Reynolds number (i.e., for both laminar and turbulent flow regimes).

LUNAR DUST ADHESION TO SPACEFLIGHT MATERIALS.

D. C. Barker[1], [1]Jacobs Technology, 2224 Bay Area Blvd, Houston, TX, 77058, USA; donald.c.barker@nasa.gov.

Introduction: All future human activities on the lunar surface will be directly impacted by the fine grained lunar dust that blankets the surface. Ensuring hardware functionality and lifetime operations requires a thorough understanding of this dust's physical and material interactions, movement, and electrostatic and adhesive properties, and processes.

A dust adhesion experiment was designed to semi-quantitively measure the adhesion of JSC-1/1A lunar simulant to various materials [1]. This approach proved valid, and an updated and highly automated version of this experimental test stand is currently in work.

Experimental Approach: The process of measuring dust adhesion to material samples used a vertical rotating cylinder and a centripetal force mass shedding experimental design, which parallels work done by Dove [2] and others.

The experimental test stand holds the vertical rotatable sample cylinder and was tested under vacuum (~10^{-6} Torr) and vacuum UV conditions on bare aluminum, anodized aluminum, Ortho fabric and Z93P painted aluminum. The simulant was sieved to <45 µm in diameter and was uniformly deposited on sample surfaces. The cylinder's maximum rotation speed generated a centripetal force greater than 400 g's at the dust shedding surface. Figure 1 shows an image of the test stand being prepared for testing following dust application.

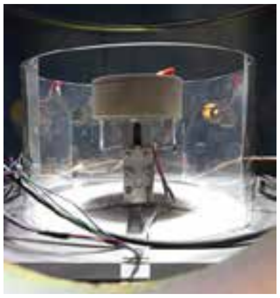


Figure 1. Lunar dust adhesion test stand.

Results: The experimental results demonstrated that all material coverage amounts exhibited a similar shedding profile with individual plateaus occurring below 30 µm depending on material. Bare and anodized aluminum had higher adhesion values in vacuum than did the samples exposed to UV at high centripetal acceleration levels. The Z93P painted aluminum and Ortho fabric indicated the opposite, whereby UV exposed samples retained more dust at higher acceleration levels and thereby larger dust particles likely adhered to the surfaces. Metals are shown to have a measurably different adhesive responses in the presence of UV in comparison to just vacuum conditions, and that coatings are shown to also impart significant effects, either enhancing or diminishing the properties of adhesion. Figures 2 and 3 show dust coverage changes across acceleration intervals. Figure 4 shows adhesion force vs particle sizes remaining on final rotation.

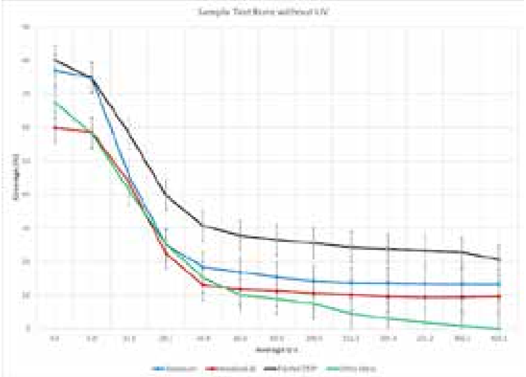


Figure 2. Dust coverage on materials without UV.

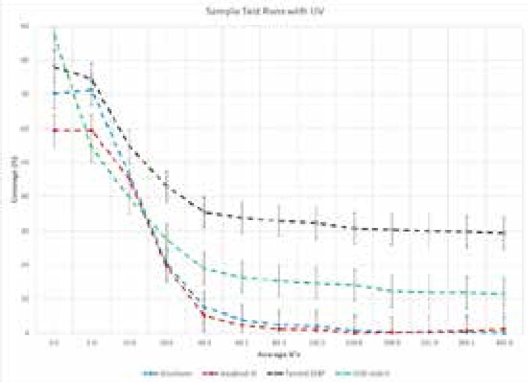


Figure 3. Dust coverage on materials with UV.

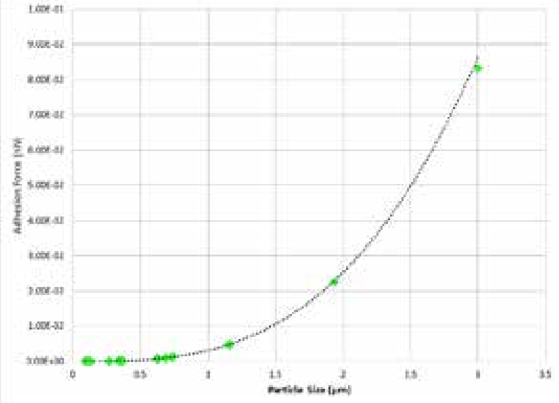


Figure 4. Quadratic dependence of adhesion force with particle sizes.

Ultimately, it was shown that the finest of the fine dust will likely remain attached to all materials in the lunar environment. This has great implications that need to be considered regarding mitigation methods and hardware design tolerances and longevities.

References: [1] Barker, D.C. et al. (2022). Acta Astronautica, 199, 25–36, [2] Dove, A. et al. (2011) Planet. Space Sci. 59, 1784-1790.

In Situ Resource Utilization of Lunar Minerals Through Biomining Extraction Processes. K. Bywaters[1], E. Seto[1], N. Bouey[1] and K. Zacny[1], [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, C 91001. (Contact: kfbywaters@honeybeerobotics.com)

Introduction: Moon offers minerals resources including silicon and aluminum (Table. 1). Biomining, the process of using microorganisms to extract metals of economic interest from rocks and regolith, offers an attractive method for making in situ resource utilization (ISRU) of Lunar minerals possible. As a part of microbial metabolism, microorganisms produce organic acids, and these can be used to leach metals in the biomining process. Biomining is currently being used, on Earth, in the mining industry to extract Cu, Al, Fe, and Au and obviate the requirement for toxic chemicals.

Table 1. Composition of a lunar mare sample 10017 [1].

Element	Lunar Sample 10017, weight %
Oxygen	40.7
Silicon	19.6
Aluminum	4.4
Iron	14.6
Calcium	8.2
Magnesium	4.8
Sodium	0.347
Potassium	0.206
Titanium	7
Manganese	0.148

European Space Agency (ESA)'s European Programme for LIfe and Physical Sciences in Space (ELIPS) project BioRock, investigated the behavior of microbes in contact with particles in altered gravity regimens on the International Space Station (ISS) to evaluate if microbial-supported bioproduction and life support systems can be effectively performed in space. In BioRock, microorganisms were dried on rock samples and then rehydrated once on the ISS. The microorganisms were then allowed to grow and extract elements from the rocks. BioRock found no significant differences in the microorganism growth between different gravity regimes [2].

Considering the BioRock experimental results and the mineral resources available on the Lunar surface, we propose using biomining as a method for Lunar ISRU.

Lunar Operational Scenario: Biomining the Lunar surface would be a straightforward process, very similar to the procedures used on Earth. Regolith would be mixed with microorganisms and nutrients, then allowed incubated for 1-5 days (depending on the organism and culturing conditions) to provide time for the microorganisms to extract metals into solution. During this period, culturing conditions, such as pH, temperature, mixing, would need to be maintained. Metals would then be extracted from the solution using conventional methods (e.g., electrowinning or precipitate).

Lunar Regolith Simulant Experiments: To investigate the bioleaching efficiencies of different strains and evaluate the production potential of aluminum extracted from Lunar regolith simulants, using microorganisms, the following experimentation is conducted.

Aspergillus foetidus, species of fungus, and *Acidithiobacillus ferrooxidans*, an acidophilic and chemolithoautotrophic bacterium, were selected. Both organisms are known for effective metal solubilization. Cultures will be grown in media containing Lunar Highland Simulant (LHS-1). Over the culturing duration, glucose consumption and organic acids (citric acid in *Aspergillus foetidus* cultures and sulfuric acid in *Acidithiobacillus ferrooxidans* cultures) production will be quantified using high performance liquid chromatography (HPLC) to investigate the corresponding bioleaching efficiencies. Inductively coupled plasma mass spectrometry (ICP-MS) will be used for Al analysis of culturing media over the duration of the experiments to determine production rates. Scanning electron microscope (SEM) images will also be taken to evaluate any changes in the morphology of the simulant.

Conclusion: From these experiments we will quantify the production rates of Al from Lunar simulate using microorganisms. These data will feed into an analysis of the feasibility of employing biomining as a strategy for ISRU of Lunar materials.

References: [1] Wänke, H., et al. (1970) *Lunar and Planetary Science Conference Proceedings.* Vol. 1. [2] Santomartino, R., et al. (2020) *Frontiers in Microbiology* 11: 579156.

Lunar Array, Mast, and Power System (LAMPS) for Deployable Lunar Power Production

Author(s): Hunter Williams(1); Robert Van Ness(1); Evan Cloninger(1); Brian Vogel(1); Ray Crum(1); Vishnu Sanigepalli(1); Murat Okandan(2); Jason Wilson(2); Kevin Hell(2); Kaveh Rouhani(2)
Author Affiliation(s): 1. Honeybee Robotics Spacecraft Mechanisms Corp, New York, NY, United States. 2. mPower Technology, Albuquerque, NM, United States. (Contact: ejcloninger@honeybeerobotics.com)

Introduction: As of 2022, it has been 50 years since the last astronauts stepped foot onto the lunar surface. Relatively recent developments, such as the proliferation of private space companies with goals of sending humans on missions beyond low-Earth orbit and discovery of permanently shaded water ice in deep, polar lunar craters have re-ignited the interest of the space exploration community in sending astronauts back to the lunar surface, establishing permanent bases to further study the Moon, and utilizing the resources and environment of the Moon as a jumping-off point from which astronauts can reach deeper into the solar system than ever before.

In order to achieve the goals of lunar permanence, a solar power grid will be necessary; a grid that can be used to power life-support systems for lunar base infrastructure, charge battery-powered exploration and mining equipment, whether human-operated or autonomous, and enable energy-intensive processing of in-situ resources like re-purposing lunar soil into building materials or fueling hydrolysis equipment to create hydrogen-based fuel for the inevitable space-ports which will permit human travel to and from the moon and beyond. Honeybee has developed the Lunar Array, Mast, and Power System (LAMPS) vertical solar array to rapidly meet these needs **(Figure 1)**.

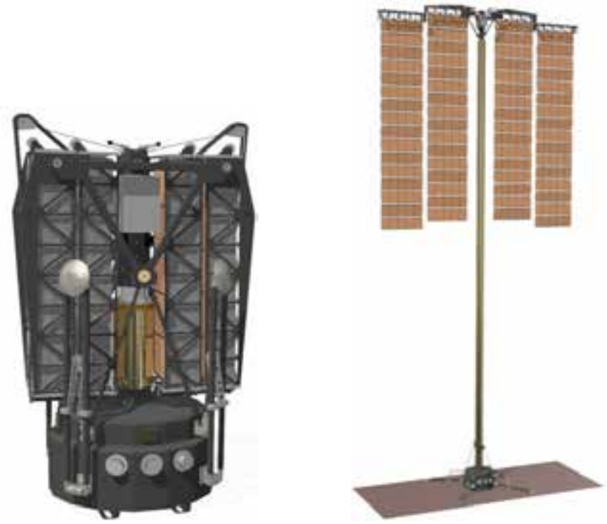


Figure 1: LAMPS Stowed, left, and fully deployed, right.

The versatility of LAMPS allows it to function not only as a standalone power system for lunar bases, but, with minimal reconfiguration, as a one-time deployable atop a lunar lander or transport vehicle.

Design and Testing: The lunar poles present particular challenges for solar power production, with the Sun's incident rays at an average of 1.5 degrees from the horizon. While this means the solar array can hang like a drape, it also means long shadows necessitate raising the array relatively high above the Lunar surface. In order to achieve this goal Honeybee robotics has designed and tested a collapsible mast system (DIABLO) capable of raising the lowest portion of the 40 square meter solar array up to 10 meters off of the ground to avoid shading. Given the criticality of this technology to overall success of LAMPS, raising the maturity of DIABLO to TRL 5 via full-scale testing was prioritized. A successful TRL 5 demonstration was completed in May 2022 with DIABLO deploying to 14.3 m and then retracting.

Additionally, a solar array will be subjected to nearly the full power of the Sun's radiation and related degradation and thermal management concerns. Lunar dust mitigation may prove to be a formidable challenge when activity around the array increases. Prioritizing operational flexibility necessitates the ability to relocate portions of the power grid, demanding a retractable and re-deployable system. Maintenance conops and parts caches have yet to be established, requiring all systems to survive for multiple years in order to effectively serve as starter nodes for the Lunar grid.

Through design, fabrication, and test of the LAMPS subsystems, Honeybee has addressed all of these problems. By leveraging high technology readiness level and commercial off-the-shelf components, Honeybee has drastically reduced the time to market for a technology demonstration fidelity level LAMPS. In this presentation we will describe work done to date to prepare LAMPS for flight mission integration.

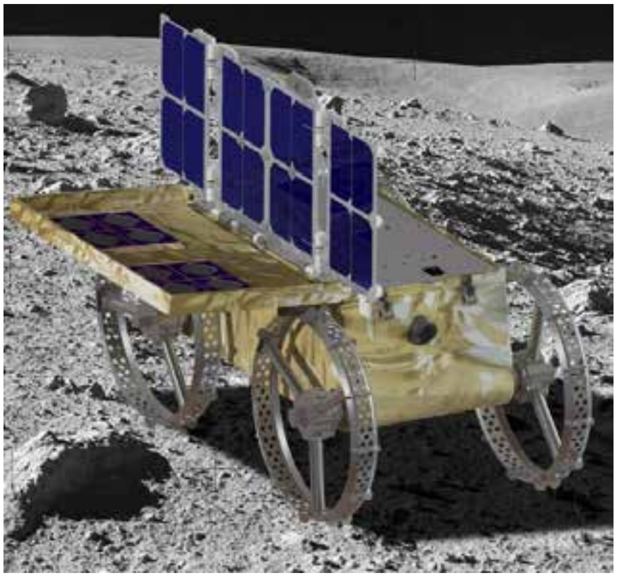
A CubeRover Designed for Extreme Access and Night Survival. C. Corpa De La Fuente[1] and J. Landreneau[1], [1]Astrobotic Technology, Inc. 1016 N. Lincoln Avenue, Pittsburgh, PA 15233, mike.provenzano@astrobotic.com

Introduction: Surviving the lunar night is the most significant environmental challenge to such robotic platforms given the harsh cold temperatures. Lunar surface temperatures can drop to 40K during the night, and permanently shadowed regions at the north and south poles can reach as low as 25K. Some systems have addressed this challenge by supplying radioisotope power supplies, but these systems are often heavy, expensive, add technical complexity to development programs, and require significant regulatory approval to fly.

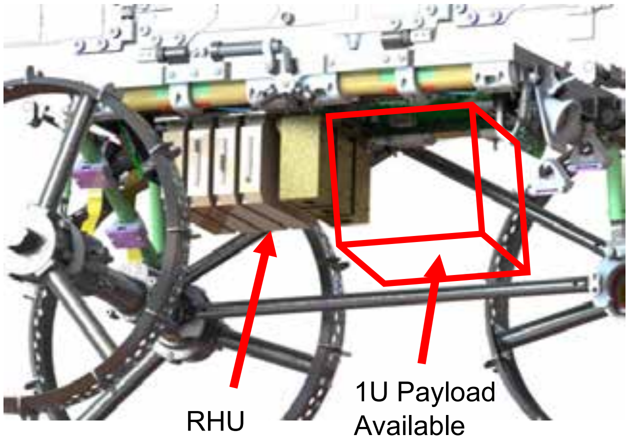
Astrobotic is developing the technologies that allow small exploration rovers, like CubeRover, to survive the lunar night. That technology can be applied to virtually any size rovers for excavation and exploration and enable payload developers to access the regions of the Moon exposed to extreme cold temperature and extend mission to multiple lunar days. The technology consists of a light-weight radioisotope heater unit (RHU) capable of delivering heat throughout a multi-week mission, and an extra-small thermal management system regulating the temperature of the rover. The RHU will be capable of delivering a continuous power output and is compliant with the CubeRover standard payload envelope to simplify its integration in the payload bay.

All thermally regulated components of the CubeRover are grounded to the bottom of a space-facing radiator on the rover. The outside of the rover chassis is lined with a multi-layer insulation (MLI) blanket to reduce radiative heat transfer to deep space and to the lunar regolith. The MLI is a critical component of the thermal design for both transit and lunar surface operations. Payloads are mounted inside the MLI enclosure to control the thermal environment and mitigate dust ingress, but they can be mounted outside the enclosed thermal environment as well. The stowage and deployment interface with the lander deck is comprised of a series of hold down release mechanisms and latches that hold the rover rigidly fixed to the lander and electrically connected during flight.

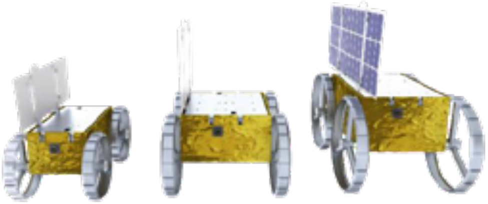
The demonstration of the technology with a CubeRover has been funded for a lunar mission under NASA's SBIR program and will be demonstrated in 2025.



CubeRover in its deployed configuration. The rover will have a lid allowing the rover to preserve heat throughout the lunar night or while driving in permanently shadowed region.



The 2U CubeRover has a payload volume of 20x10x10 cm and supports 2 kg of payload. Under the funded flight, some payload volume reserved for the RHU and remaining volume is available for payload customers.



The RHU, thermal control system, avionics, and comms system can be re-used across multiple applications beyond CubeRovers.

Lunar Regolith Simulant Porosity as a Function of P-Wave Velocity and Thermal Conductivity.

M. Pourakbar[1], J. A. Castelo[1], C. Valenzuela[1] and D. D. Cortes[1], [1]New Mexico State University, 3035 S. Espina street, Las Cruces, NM 88003, p. 575.646.6012 (Contact: dcortes@nmsu.edu)

Introduction: Meeting the sustained objectives of NASA's Artemis program will require the landing of multiple assets with larger lander vehicles than ever before. Successive landings on unprepared surfaces would expose existing surface hardware to unacceptable risks due to landing plume ejecta and blast effects. Hence, the development of engineered landing and launching surfaces is critical to the program success. Regolith compaction and in-situ verification of geotechnical properties have been identified by NASA's STMD as necessary components of landing and launching pad (LLP) construction. This work explores the porosity (or density) evolution of Lunar regolith simulants undergoing compaction. Thermal conductivity (λ_T) and p-wave velocity (v_p) are also monitored during the tests to explore their potential use in in-situ assessment of geotechnical properties.

Laboratory Methods and Materials: Two Lunar regolith simulants are used in the study. Lunar Mare Simulant (LMS-1) and Lunar Highland Simulant (LHS-1), both from the Exolith Lab. Simulant is air pluviated into a zero-lateral-strain cylindrical cell (15.24 cm in diameter and 17.1 cm in height). This specimen preparation method results in very low initial density (high porosity). Two piezoelectric disk elements (source and receiver) are embedded in the regolith at approximately mid-depth. When the cell is full a thermal needle probe is installed at the top and a 530 g aluminum cap placed on top to seal it. The bench scale experiment setup is presented in figure 1 along with the peripheral electronics used for data collection.

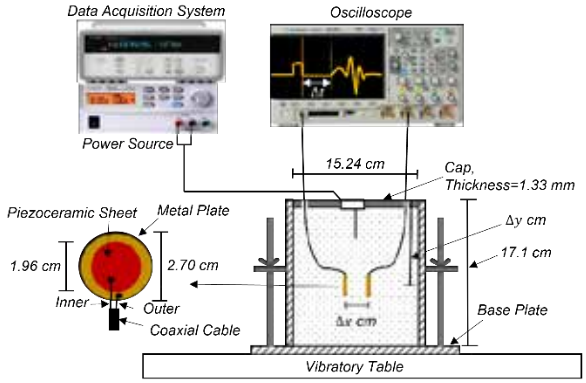


Figure 1. Test setup and peripheral electronics.

The instrumented cell is placed on top of a vibrating table and specimen height, λ_T and v_p measurements are conducted. λ_T is determined from the transient thermal response of the simulant to a preset input power that causes a temperature spike of about 1°C in 60 s. The v_p measurements are conducted using an impulse input signal (10 μs wide, 5 v amplitude) at a frequency of 21 Hz. The waveform recorded by the receiver is analyzed to determine the time of first arrival at constant distance between the source and receiver. After the measurements are completed, the specimen is densified by the vibrating table (10 Hz amplitude for 3 to 5 s) to achieve gradual reductions in porosity.

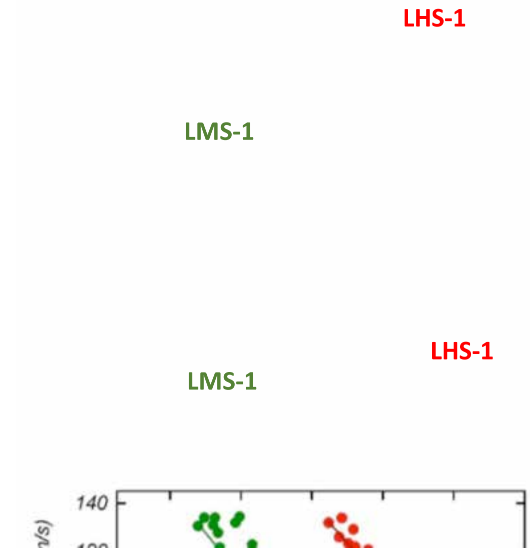


Figure 2. P-wave velocity (top) and thermal conductivity (bottom) as a function of porosity.

Results: Distinct linear relationships can be observed between v_p and porosity and λ_T and porosity. Figure 2 combines the results of 16 independent tests (8 for each simulant). The data highlight the high sensitivity of both thermal and seismic methods to relatively small changes in the density of the regolith simulant. While changes in the magnitude of both v_p and λ_T are expected under relevant pressure and temperature conditions, the results of this study suggest that relatively simple thermal and/or seismic methods could be used to assess in-situ changes in density during compaction at Lunar LLP construction sites.

Acknowledgment: Support for this work was provided by NASA (award no. 80NSSC21M0313). Expressed opinions, findings and conclusions, or recommendations are those of the authors, and do not necessarily reflect those of NASA.

Hybrid Bio-Inspired Lunar Regolith Penetrator Performance.

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Introduction: Earthworms and plant roots have been the source of inspiration for devices that attempt to penetrate the subsurface using alternative processes to the conventional surface-initiated drilling, hammering, and pushing. Earthworm-inspired penetration in Lunar regolith simulant has been shown to significantly reduce penetration resistance when compared to a conventional push-in system [1]. This can translate into a reduction in the rover mass necessary to reach a certain depth, or an increase in depth range for a certain rover mass. This work explores a hybrid device that combines the previously developed earthworm-inspired cone and a root inspired penetration tip.

Laboratory Methods and Materials: Our original earthworm-inspired soil penetration device combines a miniature steel cone penetrometer with a soft membrane (figure 1). The penetrator uses a removable conventional conical steel tip and has been deployed it in a bed of Lunar regolith simulant (LMS-1 Exolith Lab).

Figure 1. Earthworm-inspired subsurface penetration probe.

The role of tip morphology has been an active area of research in bio-inspired subsurface penetration. Root-inspired tips have been shown to decrease the penetration resistance of cone penetrometers in dry sandy loam when compared to cylindrical, conical, parabolic, and elliptical tips [2]. A stainless-steel root inspired tip (figure 2 insert) was fabricated and fitted to our earthworm-inspired penetrator and deployed in a bed of LMS-1.

Testing and results: The complete test procedure is reported in [1]. In essence, under earthworm-inspired penetration, the device is pushed into a certain depth, stops and a flexible membrane is 'inflated' to mimic the interaction between the worm anterior end and the particulate medium. Test results obtained using the conical tip are used as control to assess the effects of the root-inspired tip (see figure 2). The data shows a definite reduction in penetration resistance associated to the root-inspired tip when the penetrometer is pushed into the simulant. However, we observe no significant advantage during earthworm-inspired penetration.

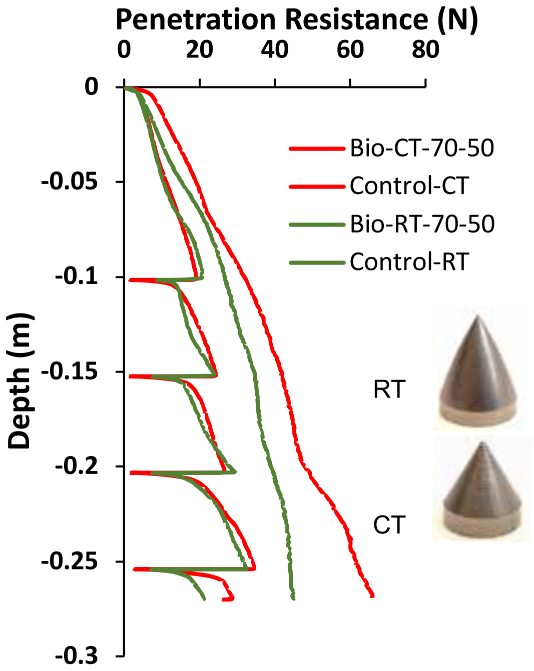

Figure 2. Penetration resistance of bioinspired probe with cone and root-inspired tips and control tests.

Conclusion: For the selected depth interval (5 cm) earthworm-inspired penetration diminishes the potential advantages of a root-inspired tip.

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Acknowledgements: Support for this work was provided by NSF (award no. EEC-1449501). Expressed opinions, findings and conclusions, or recommendations are those of the authors, and do not necessarily reflect those of NSF.

J. Davis, Illumination Pairs Near the Lunar South Pole

Vertical deployable solar arrays are one of the most effective near-term ways to produce power on the moon, but there may be long periods of darkness depending on site location. The overall goal of this project is to create a program using MATLAB that will autonomously identify illumination pairs near the lunar South Pole. Illumination pairs are locations where at least 10 kW of power is always produced from the paired arrays. This investigation uses NASA code developed by Mazarico (2011) that uses the horizon method to calculate illumination over long periods of time and previously identified high illumination sites near the South Pole. At these sites, this investigation characterizes the intervals of illumination and darkness as a function of array height over an extended period of at least one lunar year. To successfully identify illumination pairs, the important characteristics that influence favorable illumination such as terrain topography and sun angle were identified. To support future exploration, MATLAB code was developed to identify candidate site pairs. Data will be presented specifically for 10 kW vertical solar arrays, the impact of illumination and darkness periods on battery charging, how illumination will impact solar power availability for the VIPER rover, and the best site pairs near the lunar South Pole.

Risks Associated with the Construction of Lunar Surface and Underground Structures. Roberto deMoraes, AECOM, roberto.demoraes@aecom.com

Abstract: The last decade has seen a resurgence of interest in lunar exploration and the emergence of countries like China and India as spacefaring nations. In 2004, the US announced a new Vision for Space Exploration, whose objectives focused on human missions to the Moon and then Mars. The near future is likely to see the emergence of a worldwide drive to revisit the Moon as the first step in investigating the Solar System. To date, the Apollo missions provide our only experience of human operations on the Moon or anywhere else beyond Low Earth Orbit. Much was learned from these missions. However, their short duration means that many of the environmental effects that will be important for longer-duration missions could not be quantified. In addition, long-duration missions and infrastructure on the Moon require new technologies and capabilities, which must operate successfully and reliably in this lunar environment. Developing these technologies poses significant challenges for the exploration program. The paper discusses the risks associated with the construction of lunar surface and underground structures and the challenges to adopting the standards and rock mass classification systems developed on Earth and their applicability to the Moon. Moreover, an exchange of views to explore near-surface geologic and geotechnical profiles of the Moon is emphasized and implications of the lack of knowledge on rock mass characterization of the Moonrock mass, the lack of theoretical/empirical experience on the use of rock mass systems outside Earth, and uncertainties.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

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Electron Yield Measurements For Space Environmental Charging of Lunar Dust. H. Allen, T. Keaton, M. Robertson and J.R. Dennison. Materials Physics Group, Department of Physics, Utah State University, 4415 Old Main Hill, Logan, UT, 84322, USA, (Contact: JR.Dennison@USU.edu)

Introduction: Electron yield (EY) measurements of high-insulating granular materials directly addresses one of the most immediate and critical issues NASA faces as we expand our presence into deep space—mitigation of charged dust. Although such issues have been recognized since the Apollo era, previous experimental studies [1-3] have failed to acquire accurate EY data that defines these fundamental charging properties. This has led to a critical knowledge gap for both engineering strategies and basic science issues essential for myriad important lunar applications and simulations related to Lunar dust and regolith electrostatic charging properties. These include applications in lunar dust and asteroid technologies and lofting, electrostatic dust agglomeration in space, granular and aerosol coatings for spacecraft charge mitigation, biological issues, and many coating, contamination and roughening issues applied to a wide variety of fields subject to charging.

Electron Yield Measurements: This work presents a systematic study of total, secondary, and backscattered EY measurements of highly-insulating, granular materials which unequivically demonstrate our ability to make these critical measurements for lunar dust. EY measurements of highly-insulating materials, especially those with high EY, are challenging as sample charging effects can be large even for very low fluence electron probe beams. EY measurements of particulates are further complicated by: (i) roughness effects from particulate size, shape, coverage, porosity, and compactness; (ii) particle adhesion; (iii) substrate contributions; and (iv) electrostatic repulsion and potential barriers from charged particles and substrates.

EY measurements are presented here of very low-conductivity samples of granular Al_2O_3 and SiO_2, the two primary constituents of lunar regolith. These include robust results for particle sizes typical of regolith from ~1 μm to ~100 μm; both highly angular and spherical particle shapes; and fom low coverages to multilayers. Preliminary studies of high-purity angular Al_2O_3 polishing compound particles adhered to graphitic carbon conductive tape from 0% to ~100% coverage demonstrate the effectiveness of the sample preperation methods used for dust samples [4]. The effects of surface roughness [5] were demonstrated through comparison of EY for highly polished single crystal sapphire, rougher microcrystalline Al_2O_3, and very rough and porous layers of granular alumina; these were found to have the same shape of the yield curves and energy at maximum yield, while maximum yield decreased from >15 to ~2.5 as roughness increased. Acquisition of these accurate high-yield curves, which showed minimal charging effects, demonstrated our ability to make EY measurements for high-yield highly-insulating samples, unlike previous results for lunar dust which showed highly suppressed yields due to severe charging effects [1-3]. Low fluence, pulsed electron probes (3-5 μs at 1-30 nA-mm^{-2}) used 10^0 to 10^2 electrons per pulse per particle to measure EY with minimal charging effects, with 1-2 s bursts of flood UV photons and low energy electrons to dissipate accumulated charge between pulses [6]. Additional EY measurements studied the effects of particulate composition. shape, porosity, and compactness.

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Lunar Dust Filtration and Collection System. Vijay V. Devarakonda[1] and Michael D. Hogue[1], [1]Analytical Scientific Products LLC, 4616 Willow Ln., Dallas, TX 75244. (Contact: analyticalscientificproducts@gmail.com)

Introduction: Past space exploration missions to planetary bodies have noted the potential for fine particulates to foul mechanisms, alter thermal properties, and obscure optical systems. Therefore, there is an urgent need for the development of technologies to remove, manage, and monitor aerosolized particulates and dust intrusion into the pressurized habitable volumes and compartments in crewed spacecraft systems.

Through a Phase I SBIR project funded by the NASA GRC, Analytical Scientific Products LLC (ASP) is developing a unique dust filtration and collection system for spacecraft cabin air and airlock compartments in future lunar missions. The ASP device uses a combination of fluid dynamics and electrodynamics to filter the dust particles from air and collect them in a regenerable canister. Also included in this device is a real time monitoring system that measures the concentration of dust in the streams that enter and exit the filter to track its performance. This device is compact, lightweight, and energy efficient. Electrodynamic methods typically have low power requirements. Since the dust particles do not collect inside the filter, it requires minimal maintenance. This filter is unique because it has no moving parts. This device is equally effective in filtering both the dust particles generated by the crew inside the spacecraft and those that enter the spacecraft from outside due to extra vehicular activities. The ASP device is all-inclusive and fully autonomous, and it does not rely on external sensors and monitoring systems to track its performance. It is scalable and can be sized to handle various gas flow rates and dust loadings and can clean both the cabin and the airlock compartments.

The effectiveness of this dust filtration and separation device depends on the filter geometry, operating conditions (gas pressure, gas flow rate, particle size distribution, composition, and bulk density of dust particles), design parameters (geometry, dimensions, voltage, and frequency applied to the electrodes). The objective of this project is to fine-tune these parameters to maximize the filtration efficiency while minimizing the filter size, mass, and power consumption. This paper presents a detailed overview of the progress made in this project to date in the following areas: (a) design and construction of dust filtration, collection, and characterization system, (b) selection of challenge dust to simulate the properties of spacecraft cabin aerosol, and (c) the design and construction of a laboratory test apparatus to evaluate the performance of dust filter.

The Effect of Sample Mass on the Angle of Repose of Lunar Regolith Simulants.

P. Easter[1], J. Long-Fox[1], C. Ortez[1], D.Britt[1] [1] CLASS-Exolith Lab, 532 S Econ Cir STE 100 Oviedo, FL, 32765 (Contact: parks.easter@ucf.edu)

Introduction: Lunar regolith simulants are designed to be high fidelity analogs of actual lunar regolith. The fidelity of a lunar regolith simulant is partially determined by its ability to match geotechnical characteristics of lunar regolith, much of which were determined during or shortly after the Apollo missions. Angle of repose is a geotechnical characteristic that is commonly measured and provides fundamental insight into the cohesion, internal friction, and flowability of a regolith. This test is typically nondestructive and requires very little technology to run.

While the angle of repose of lunar regolith is reported in the Lunar sourcebook [**1**], there is very little data on how that value is derived. In addition, any testing of lunar regolith from the Apollo samples was done with very small amounts of regolith, estimated to be less than 20 grams [**2**]. This study examines the effect of “mass used” on the results of an angle of repose test, and measures the minimum mass required to achieve consistent results.

Methods: The lunar regolith simulant used in this study is Exolith Lab’s Lunar Highlands Simulant, LHS-1 [**3**]. Five different samples of LHS-1 were gathered from the same production batch: 10g, 25g, 100g, 250g, and 500g. For each sample we used the Angle of Repose method by Geldart et al [**4**] where the simulant was allowed to flow out of a funnel, down a chute and against a wall, then free fall to form a half cone at the base of the wall. Both the funnel and chute have vibration motors attached to ensure a consistent flow of material. As the simulant gathers at the bottom of the wall, it forms a half slope that builds up to the final angle of repose. A GoPro records the build up and ImageJ processing software [**5**] is used to record the angle of the slope. Five trials were conducted for each of the mass values.

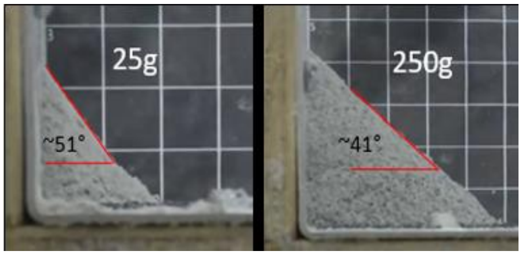

***Figure 1**. Angle of Repose Measurements*

Results: The average angle of repose measurements are given in Table 1. As the mass of regolith increases, the average angle of repose decreases. Additionally, there is a large amount of variability in the average angle of repose at low mass values. For samples with a mass of 100g and more, the values for angle of repose remain consistent, with all of the values falling between 39-41 degrees.

***Table 1**. Average Angle of Repose*

Mass (g)	Angle of Repose ± 1σ (degrees)
10	46.98 ± 3.21
25	47.20 ± 2.82
100	41.53 ± 1.08
250	39.54 ± 0.77
500	39.58 ± 1.28

Discussion: There is a significant difference in the angle of repose of LHS-1 at low vs. high masses; using a very small mass can achieve a very high angle of repose, which is misleading as the angle of repose decreases as mass is added. This is problematic for a variety of reasons: one being the fact that any slope or *In Situ Resource Utilization* mechanism on the lunar surface will require more than 100 grams of regolith. Utilizing the high angle of repose values found with a low sample mass may be unrealistic, and any application of this value could result in the collapse of a regolith slope or disruption of material processing on the lunar surface. In addition, this variation in values makes it difficult to compare a lunar regolith simulant to the small samples of actual lunar regolith. The findings of this experiment highlight the need for consistent, well-described testing methodologies for characterizing lunar regolith simulants, as well as continued research into the physical properties of *in situ* and returned lunar regolith.

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Gaseous By-Product of Thermal Vacuum Processing of Lunar Highland Simulant. D. Essumang[1], K.W. Engeling[1*] and A. Meier[1], [1]NASA John F. Kennedy Space Center, KSC-UBE00, Kennedy Space Center, FL. (Contact: deborah.essumang@nasa.gov)

Introduction: Scientists at Kennedy Space Center are advancing technologies to achieve oxygen extraction on the Lunar surface. One such technology is Molten Regolith Electrolysis (MRE) in which regolith simulant is melted under high temperatures to perform oxygen extraction through electrolysis of the melt pool. A study was conducted to understand the molten formation and properties of Lunar Highlands Simulants (LHS-1) under high vacuum environments ranging between 10^{-6} Torr. These studies include investigating the regolith melt behavior and by-product gas analysis systems to prepare for pilot plant development and operations. The off-gassing rates and pressure build-up, gaseous compounds, and material compatibility may be a risk to MRE systems. The KSC findings are reported here for inclusion into future mission architecture and operational planning. The four stages of the experiment were vacuum, resistive heating, regolith melt and gas detection. The regolith mass of 70 g was melted in a 40 cm tall x 50 cm diameter vacuum chamber at temperature increase rate 47 ℃ /min and ramp rate of 1 ampere/3 min up to an 18-amp maximum. The test is conducted for about 60 minutes and the constituent gases produced during heating of regolith is monitored with a residual gas analyzer. During the molten formation, primary off-gassing volatiles included water vapor (18 amu), a peak at 44 amu (FeO_2 – expected), and atomic oxygen (16 amu), among a series of other compounds that could create compatibility issues such as magnesium, chlorine, and silicon oxide. These results add to the knowledge required for successful oxygen extraction on the moon.

Characterization of H_2O Transport Through a Packed Bed of Lunar Mare and Lunar Highland Simulant at Conditions Relevant to *in-situ* Lunar Resource Utilization Technology.

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Introduction: The development of *in-situ* resource utilization technologies for H_2O extraction is integral for supporting further space exploration. Utilizing lunar resources (*e.g.*, H_2O extracted from permanently shadowed regions) affords the opportunity for the deployment of permanent settlements. This also allows for the on-site synthesis of propellants further space exploration using the Moon as a base. Recent work has focused on identifying and predicting favorable volatile extraction locations with H_2O(s) content approaching >5 wt.% [1]. Gas transport of the volatiles in the transition and Knudsen flow regimes relevant to *in-situ* applications was previously examined to inform extraction technologies. This work expands upon previous efforts with JSC-1A [2] to characterize H_2O(v) lunar simulants, including lunar mare (LMS) and lunar highland simulants (LHS).

Results: Experimentation was performed in a flow apparatus [2] with beds of LHS and LMS with the pressure drops measured as functions of mass flow rate of H_2O(v). A model fitting approach was developed utilizing a piecewise function for fitting throughout the transition space of the flow. The piecewise model fits a Knudsen number that predicts the transition between advective and Knudsen flows, the particles tortuosity shape factor, and the permeability shape factor.

The normalized diffusivity measurements approach the predicted Knudsen diffusivity for both simulants as shown in Figure 1. Non-linear regression was used to determine a tortuosity shape factor of 2.6752 ± 0.0527 and 0.1004 ± 0.0003, a transition Knudsen number of 1.567 and 4.100, and a viscous flow permeability of $0.534 \pm 0.181 \times 10^{-12}$ m^2 and $8.372 \pm 1.231 \times 10^{-12}$ m^2 for the LMS and LHS, respectively. The resulting Knudsen diffusivities are 6.436 ± 0.588 cm$^2 \cdot$s^{-1} and 19.316 ± 0.106 cm$^2 \cdot$s^{-1}, respectively.

These results are consistent with previous work studying the transport characteristics though JSC-1A and highlight the relevance of Knudsen flows for in-situ lunar resource utilization. Further work is being conducted to study the variation of sublimation rates and coupling that to heat transfer models.

Acknowledgments: This work was carried out as part of REVEALS which was directly supported by the NASA Solar System Exploration Research Virtual In-stitute cooperative, agreement number NNA17BF68A.

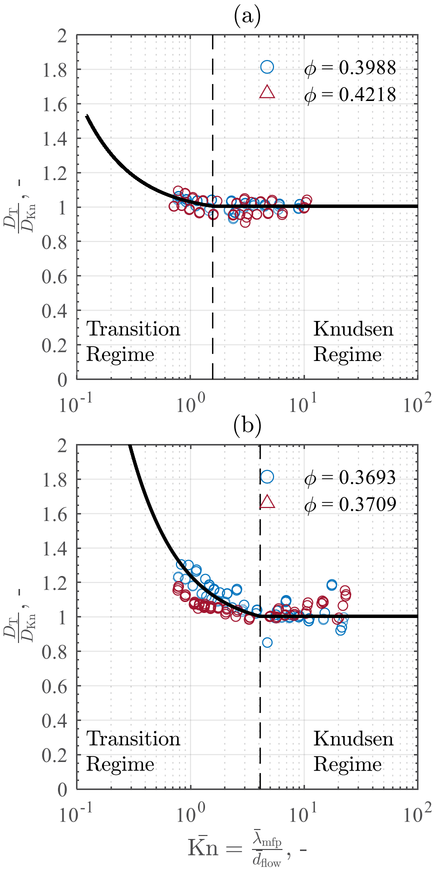

Figure 1: Measured total diffusivity normalized to the resultant Knudsen diffusivity as a function of average Knudsen number for (a) lunar mare and (b) lunar highland simulant. The solid line represents the fitted piecewise model for each simulant, and the vertical dashed line represents the KnT for each packed bed.

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Commercially Available Radioisotopes to Enable Extreme Access. B. Fisher[1] and C. Morrison[1], [1]Ultra Safe Nuclear, 2320 W Commodore Way,Seattle, WA 98199. (Contact: b.fisher@usnc-tech.com)

Introduction: With greater access to the lunar surace, an increasing importance is being placed on exploring permanently shadowed regions (PSRs) and surviving the lunar night. Currently, many tens of kilograms of batteries are necessary to not just electricaly power the instrumentation of lunar landers and rovers but also provide the thermal power required to protect electronics from extreme colds. Radioisotope systems offer a uniquely high specific power which answers many of the needs for landers and rovers to explore extreme lunar environments. However, the traditional radioisotope thermoelectric generators which rely upon Plutonium 238 or Strontium 90 have several practical limitations and cost drivers that keep them from addressing commercial efforts.

Ultra Safe Nuclear is productizing a family of radioisotope offerings around it’s core technology, Ember. Ember’s novel manufacturing process leverages the established supply and quality systems of the medical radioisotope industry. This approach enables customization of modular radioisotope products to meet missions objectives while minimizing volume and mass. By prioritizing a commercially feasible radioisotope with a clear path toward launch, Ember-based products are ideal for integration into commercial landers and rovers.

Applications: EmberCore is a radioisotope heater unit (RHU) built from multiple Embers. Ultra Safe Nuclear is progressing towards a 2024 flight demonstration of a 40W_{th} solution as the first offering in the EmberCore product line of 1 to 40+ W_{th} commercial RHUs. The 40 W_{th} EmberCore will provide passive, reliable heat for multiple lunar nights or extended investigation of PSRs.

Figure 1: EmberCore RHU assembly

EmberPower is a radioisotope electrical power system powered by EmberCore. New capabilities enabled by sun-independent power are expected to allow for scientific discovery as previously inaccessible terrains can be explored. Many of these regions concentrate volatile organic compounds which are anticipated to be central to in situ resource utilization. While static power conversion using thermoelectric is a flexible near-term option, higher efficiency dynamic power conversion is an attractive alternative. Regardless of the means of conversion, radioisotope power mitigates the risk of exploring locations where dust poses a challenge to solar based systems.

EmberSource is an additive product which utilizes the high energy photons from radioisotopes sources as a science instrument for gamma and x-ray fluorescence and backscatter. This scientific use case leads to shorter acquisition times with an expanded range. These advances can be used to identify substances such as water in regolith over greater distasnces than currently accessible, allowing for more efficient evaluation of regional in situ resource utilization potential. EmberSource can be added as a functionality with either the EmberCore or EmberPower products.

Conclusions: The Ember-based product line is developing a suite of solutions to greatly expand the scope of lunar lander and rover operations. By selecting an appropriate radioisotope source in alignment with the mission scope commercial customers can optimize their system and payload design. Ultra Safe Nuclear has a development roadmap revitalizing this technology for the commercial space age, including licensing, ground and flight demonstrations. Interested parties are encouraged to reach out to the author and attend the meeting session to learn more or contact the author.

Development and Testing of Printable Sulfur Concrete for Planetary Construction 3D Printing. I. Giwa[1], D. Mary[1], H. Marc[1], M. Fiske[2], and A. Kazemian[1]. [1]Louisiana State University, 3319 Patrick F. Taylor Hall, Baton Rouge, LA 70803, [2]Jacobs Space Exploration Group, Huntsville, AL, 35806. (Contact: Kazemian1@lsu.edu)

Abstract: To establish a sustained presence of humans on the Moon and Mars, NASA aims to test numerous technologies on the Moon through the Artemis program. Artemis missions will serve as a preparation and learning experience before undertaking more complex missions to Mars. The extreme environment prevalent on these celestial bodies demands the need to protect humans and technological assets. Supporting structures such as lunar bases, launching and landing pads, hangers, research labs, and protective shields are some critical infrastructures needed to safeguard lives against dusty terrain, cosmic/galactic ionizing radiations, and extreme temperatures. Construction 3D printing (C3DP) is an innovative construction technology that can be used to build the supporting infrastructures needed to support human space exploration. Although initially conceived for terrestrial applications, this automated construction technology can help to eliminate safety risks associated with laborious manned construction operations in deep space. In-Situ Resource Utilization (ISRU) allows local materials to be extracted and harnessed for planetary construction purposes. A sustained exploration in deep space becomes viable by utilizing indigenous resources. Hence, the prohibitive cost of transporting construction materials from Earth and the increased up-mass on the Space Launch Systems (SLS) can be avoided.

Although a variety of construction materials have been identified as viable options for planetary surface construction, these materials are still subject to early research activities needed to understand their behavior before deployment on the Moon and Mars. One potential construction material for planetary construction is sulfur concrete. As a high-temperature water-less material, sulfur concrete provides an attractive alternative compared to other materials due to the scarcity of free water on the Moon and Mars. Also, the ubiquitous presence of regolith and the abundance of Sulfur on the Martian surface (although limited availability on the Lunar surface) makes sulfur concrete a viable option. As a basis to gain more insights into the performance of sulfur concrete printed using extrusion-based C3DP, this study evaluates the printability and properties of 3D printed sulfur concrete. Early experimental results show that sulfur concrete can be successfully 3D printed by carefully tailoring the mixture proportions and extrusion process parameters (Figure 1). Experimental data on the effect of various factors including temperature, cooling rate, interlayer printing time gap, and fiber addition, on the printability and properties of 3D printed sulfur concrete will be presented and discussed.

Figure 1. 3D printed sulfur concrete specimen at LSU

Platforms for Lunar Testing as a Service. A. M. Goode[1], [1]Aegis Aerospace, 17146 Feather Craft Lane, Suite 350, Webster, TX 77598. (Contact: allison.goode@aegisaero.com)

Introduction: Rapid development of lunar technologies for dust mitigation, excavation and construction, extreme access, in situ resource utilization, extreme enviornments, and surface power will require commoditized access to lunar testing opportunities. Aegis Aerospace has developed two lunar surface testbeds, Regolith Adherence Characterization (RAC) and Space Science Technology and Evaluation Facility (SSTEF), to enable a streamlined commercial testing service for technologies of all types and technology readiness levels (TRLs). Both platforms are available commercially to NASA, industry, and academia for ongoing and future efforts toward lunar surface testing.

Regolith Adherence Characterization (RAC): The RAC platform offers an unparalleled materials testing opportunity for classic and novel space materials considered for lunar applications. RAC has customizable sample trays and thus can accommodate samples of varying sizes, thickness, and shapes. An optional retractable cover protects the second sample tray, which can act as a control for landing events. During its mission, the four enclosed cameras take high resolution photos of the samples to evaluate regolith adherence, material durability, and other properties of interest. Photos and environmental data are provided to experimenters to qualify their materials for flight.

Current Status: The first RAC has completed its system integration and is manifested on Firefly Aerospace's Blue Ghost Mission 1, launching in 2024. It carries two identical sets of 15 unique samples provided by NASA and industry. Future RAC missions are available for partial or full manifests.

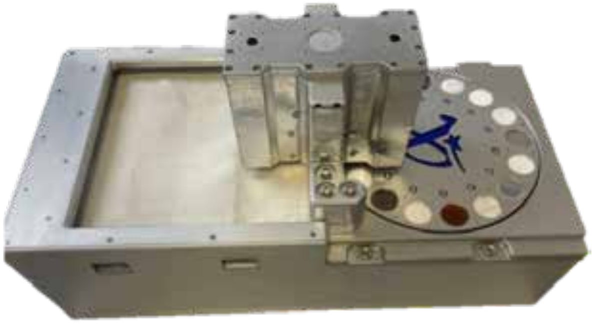

Figure 1. RAC.

Space Science Technology and Evaluation Facility (SSTEF): Aegis Aerospace's second lunar platform, SSTEF, expands upon RAC's capabilities and provides power and data for customer-provided experiments in addition to imaging for materials testing. SSTEF offers various physical orientations, communications, up to 20W of power per experiment, and up to several kilograms of capacity to technologies wishing to raise TRL to 7 or 8 through in situ lunar testing. In addition to standard experiments, SSTEF can provide a solar cell test bed, analog-to-digital ports for sensors, and numerous environmental sensors. For maximum flexibility, SSTEF is designed with modular experiment and lander interfaces.

Current Status: SSTEF-1 is fully-funded and is currently in prototype testing in preparation for its Critical Design Review. Aegis purchased the 2025 SSTEF-1 lunar landing on an Intuitive Machines Nova-C lander. SSTEF-1 has seven technology experiment partners from industry, government agencies, and academia. Future SSTEF missions are in development, with space available as early as SSTEF-2 for payloads of all sizes.

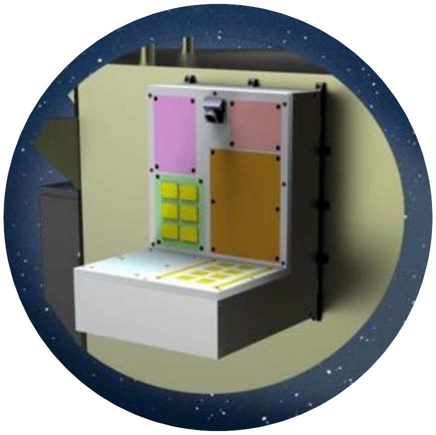

Figure 2. SSTEF-1.

Conclusion: Establishing a sustained presence on the lunar surface requires proven materials and technologies. RAC and SSTEF provide that requisite lunar testing as a service by simplifying the process for experimenters, allowing them to focus on critical development instead of lander integration requirements. With opportunities for experiments from small materials samples to solar cells and cutting-edge technology, RAC or SSTEF can accommodate the needs of almost any experiment looking for a simple, rapid, commercial path to the lunar surface.

Lunar Radiation Shielding for Astronauts Using 3D Printed Lunar Regolith.

A.J. Grant[1,3], A.J. DeSears[2,3], and R.L. Klima[3], [1]North Carolina Agricultural and Technical State University, Greensboro, NC, [2]Spelman College, Atlanta, GA, [3]Johns Hopkins Applied Physics Laboratory, Laurel, MD.(Contact: Rachel.Klima@jhuapl.edu)

Introduction: With recent developments in lunar technology and machinery, a point in space exploration has been reached where there is an increased importance placed on developing a sustained human and robotic presence on the lunar surface. Adjacent to this comes the need for shelters that can provide protection from unpredictable stints of the lunar environment like meteorite impacts and solar flares. We present initial results of a project to design a habitat that can provide astronauts with this protection, as well as any additional resources they may need to make their work on the lunar surface as efficient and productive as possible.

Research and Criteria: Our initial design effort included several considerations. First, the average human can only withstand up to about 500 rem of radiation, and anything after that may lead to death without medical treatment. This limit applies to conditions here on Earth, where access to medical help is readily available. On the lunar surface, exposure limits need to be updated to take into consideration the available medical treatment and the time and distance required to evacuate back to Earth. Based on standards set by NASA, there is currently a 30-day 25 rem dose limit for blood forming organs (BFO) and 50 rem for the central nervous system [2]. Another condition that impacted the design process is the state of the lunar regolith and its tendency to adhere to the surfaces of machinery used to collect and analyze data. The last condition that needs to be addressed is the possibility for micrometeoroid impact and penetration. The goal of a shelter is to afford a 0.993 "probability of no penetration" over each 5-year period that the shelter is in use [1].

Many of the preexisting designs for lunar habitats are cylindrical or hemispheric in shape, leading us to also experiment with these forms as well as the cone shape. The materials proposed to build these forms include Kevlar, water, polyethylene, and lunar regolith. Though we initially thought that lunar regolith would be the best option for this, there is research that suggest that this would not be the best material due to factors such as:

- needing substantial equipment for collection and placement;
- operational deployment modules (which can cause dust problems);
- long pressurized tunnels will be required for connection between them;
- external equipment may end up buried
- regolith blocking direct outside views [1].

Methodology/Initial Results: Using the software Creo Parametrics, the design process began. Initially, the dome and cone shape were chosen, but through additional study it was decided that the flattened cone shape and dome would be the shapes of focus. AutoDesk Revit 2022 was also a software used to design and model the shapes decided upon.

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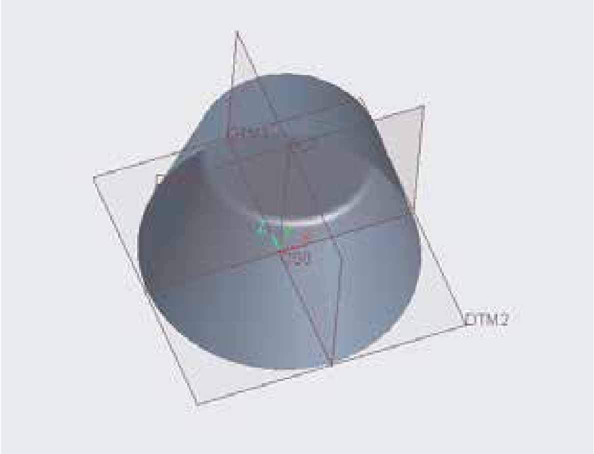
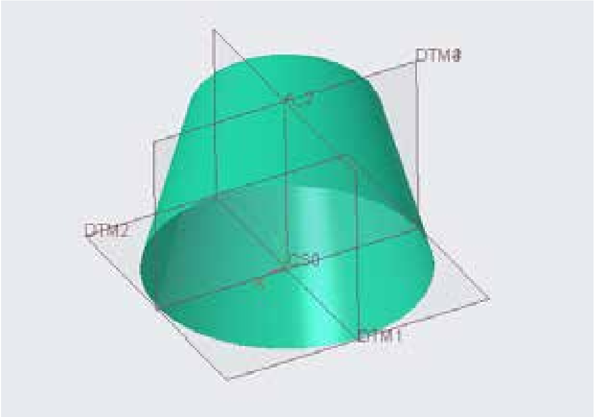
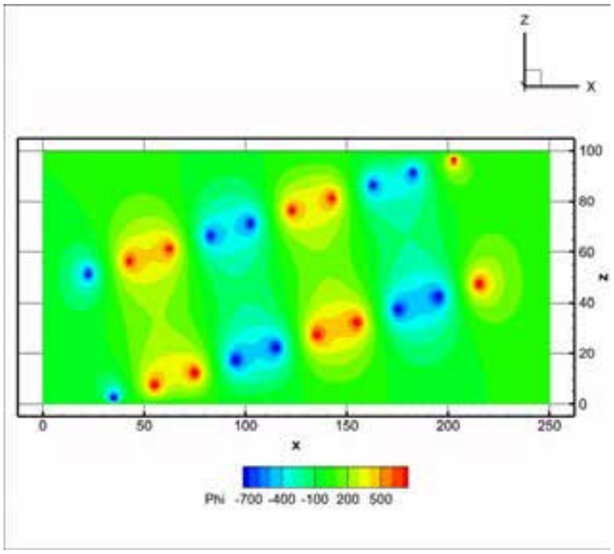




References: [1] Bell, L., and Bannova, O., (2011) "Lunar Habitat Micrometeoroid and Radiation Shielding: Options, Applications, and Assessments".Journal of Aerospace Engineering ASCE, Vol.24, Issue 1. [2] Townsend, L.W. (2007). Overview of solar energetic particle event hazards to human crews, Univ. of Tennessee, Knoxville, <https://hesperia.gsfc.nasa.gov/spvse/oral/Lawrence_Townsend/Invited.ppt>

Kinetic Modeling of Electrostatic Transport of Lunar Regolith Particles with Applications to Electrostatic Sieving. Aaron Berkhoff[1], Easton Ingram[1], and Daoru Han[1], [1]Missouri University of Science and Technology, 400 W. 13th St., Rolla, MO 65409, (Contact: handao@mst.edu)

Introduction: Mineral benefication practice enhances and adapts the segregation tendencies of natural geologic processes to enhance the efficiency of subsequent processing and manufacturing tasks, which need appropriately sized and prepared mineral feedstock. Our LuSTR project directly addresses this need for lunar *in-situ* resource utilization (ISRU) through designing, building, and testing an integrated system comprised of a selection of separation subsytems for particle size classification and enrichment. Here, we report our progress on developing a modeling capability to simulate electrostatic transport of lunar regolith particles with applications to electrostatic sieving. Particularly, concept designs proposed by Kawamoto and Adachi [1] using traveling-wave configuration of electrodes are to be modeled and simulated. The electric field is solved by an immersed-finite-element (IFE) Poisson solver [2] while the motion of charged particle grains are tracked by a kinetic approach [3]. Results on particle size classification and yield will be compared with measurements reported.



References: [1] Kawamoto and Adachi. (2014) *AIAA 2014-0341*. [2] Kafafy. et al. (2005) *Int. J. Num. Methods. Eng., 64, 940-972*. [3] Zhao. et al. (2022) *J. Aerospace Eng.*, 35(6): 04022095.

Kinetic Modeling of Electrostatic Transport of Lunar Regolith Particles with Applications to Electrostatic Sieving.

Aaron Berkhoff[1], Easton Ingram[1], and Daoru Han[1], [1]Missouri University of Science and Technology, 400 W. 13th St., Rolla, MO 65409, (Contact: handao@mst.edu)

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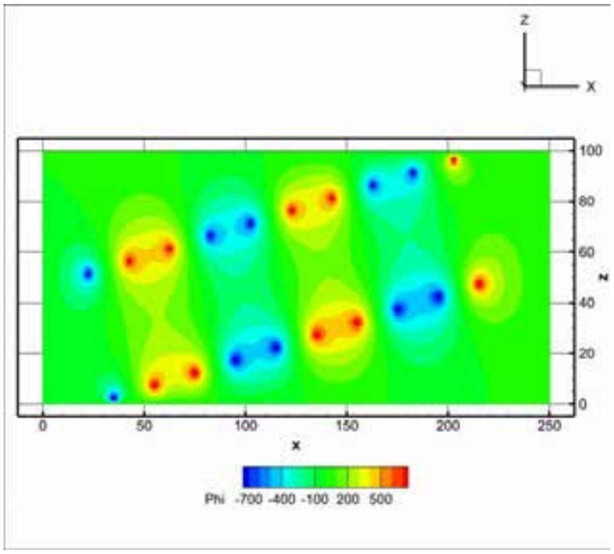

References: [1] Kawamoto and Adachi. (2014) *AIAA 2014-0341*. [2] Kafafy. et al. (2005) *Int. J. Num. Methods. Eng., 64, 940-972*. [3] Zhao. et al. (2022) *J. Aerospace Eng.*, 35(6): 04022095.

Power Generation to Support a Robust Lunar Economy.

M. Blood[1], L. Carrio[1], T. Cichan[1], A. Elhawary[1], S. Hilliard[1], L. May[1], J. Reichert[1], C. Edwards[1] and R. Wiseman[1], [1]Lockheed Martin Space. 12257 S Wadsworth Blvd, Littleton, CO 80127 (Contact: sommer.hilliard@lmco.com)

Introduction: This paper describes Lockheed Martin's unique lunar power architecture vision, with a focus on core technology element deployment. Lockheed Martin is investing in the future of power on the lunar surface, continuing a long history of furthering cutting-edge deep space science, new technology development, and complex system integration alongside industry partners. As the only company with both nuclear and solar power awards for lunar surface applications, Lockheed Martin is well positioned to offer a variety of power services supporting our customers' near and long-term missions, on the lunar surface and beyond.

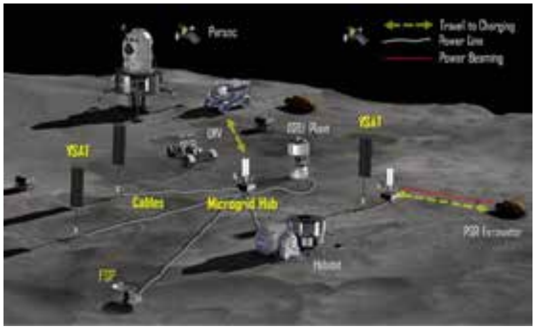

Fig. 1: Lunar surface power architecture.

Lunar Power Technologies: Lockheed Martin power solutions combine 386 years of cumulative, on-orbit experience with proven technologies. Both solar and nuclear will play strategic roles in near and long-term architectures to meet the dynamic and evolving demands of lunar operations.

Solar. The Lockheed Martin Lunar Vertical Solar Array Technology (LVSAT) flex array will produce 11 kW of continuous power at beginning of life. It offers transportable solar power production by means of a rover and z-fold flight-qualified array deployment mechanism. LVSAT provides flexible and reliable power solutions for early implementation in the south pole lunar architecture.

Nuclear. Fission Surface Power (FSP) will produce 48 kWe continuously by means of a monolithic core designed by our partners, BWX Technologies, with direct Brayton power conversion system. FSP also features an innovative lightweight radiator array solution that utilizes the proven LVSAT z-fold solar-array deployer. High commonality with proven deep space vehicle and reactor technologies minimizes cost and schedule uncertainty while accelerating independent technology maturation to keep pace with increasing extraterrestrial power demands.

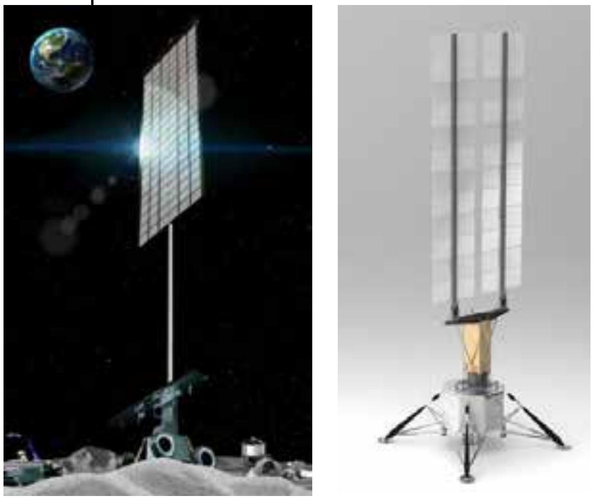

Fig. 2: LVSAT (left) and FSP (right) with deployed solar and radiator arrays respectively.

Extensibility: In addition to providing near-term solutions for early lunar operations power needs, Lockheed Martin has also invested in scalable power infrastructure technologies such as power storage, distribution, and management, in anticipation of meeting power demands for lunar infrastructure and Mars operations.

Lockheed Martin's LVSAT architecture requires minor rework to be viable at the lunar equator, as the moon traces a much steeper angle across the lunar field of view. As fission power is identified as the critical technology for robust continuous power for a permanent human presence in space, the FSP core is inherently scalable to higher powers forecasted to support a sustaining lunar presence. Furthermore, Lockheed Martin is actively advancing Brayton systems for power production levels into the 100s of kilowatts, lending the design to be highly scalable for lunar applications and readily extensible to Mars operations.

Conclusion: Lockheed Martin envisions full lunar surface scale applications of power in support of a robust cislunar/lunar economy with extensibility to Mars. Our extensive work with government, industry, and international partners drives a lower barrier of entry for exploration, science, and commerce. Lockheed Martin envisions a phased-base lunar power architecture approach that will scale with the lunar economy and leverage modular technologies throughout.

Excavation, Construction and Beyond via Constructor Engineering. W.E. Hollier, Director, EnGen Institute, 8 The Green, Ste A, Dover DE 19901. (Contact: william.hollier@engen.institute)

Introduction: The author has developed the design of a prototype mobile robotic machine system (1 - 3-ton single payload) that combines teleoperation & assigned AI control, lunar exploration (sensing, drilling and sampling), 'earth' works, excavation, tunnelling, hard-stand production, basic materials processing and surface and sub-surface excavation and construction in one package.

The author and EnGen Institute are interested to partner with space industry to develop, deploy and operate space-qualified versions of this technology, which could be achieved this decade.

The author is now developing robotic machine systems for part-production and construction extending these capabilities to enable construction of sealed, pressurized, self-assembling and self-repairing structures, buildings, habitats and infrastructure using ISRU derived feedstock materials.

NASA Study: This unprecedented extent of functional integration completes a significant portion of the lunar mining, materials processing, part-production, machine assembly, construction and deployment to establish lunar industry, envisaged in NASA's 1980 study 'Advanced Automation for Space Missions' [1]. It has been achieved by further development and refinement of the scientific foundations and advances in computer science that inspired the study. In particular, further development of the foundations and implementation of self-replicating systems (SRS) as physical engineering systems, beyond John von Neumann's kinematic and cellular-automata based models of his Theory of Universal Construction [2].

NASA's landmark study already achieved such advances in part by introducing the concept of a developmental sequence of machines to extend the range of self-replicating system concepts beyond computational models and assembly of duplicates in an environment of components as described by JvN, to SRS in an environment of materials and SRS in an environment of resources. However, as noted in NASA study reports the concept was incomplete and connection to theoretical foundations established by JvN was not made.

Research: Over decades of research, largely unpublished, the author has first established this connection to the formal foundations and practice of computer science, recognized by NASA's Georg von Tiesenhausen and Synthesis Group [3] as a scientific breakthrough, subsequently extending SRS foundations beyond JvN's theory and models to include a formal basis for SRS that was not only evolutionary but developmental, analogous to biological development (ontogeny). This developmental systems approach can be applied to provide a formal foundation for synthetic and natural biological development (ontogeny), including for in-space biomanufacturing and recycling [4].

SRS Engineering: Applied to engineering it provides the missing detail in NASA's study of SRS as a means of establishing lunar industry and extends the scope of SRS to include logistics, deployment, construction, life-support systems and space habitat as both spacebases and spaceships for extended resupply-independent space voyaging.

Other Applications: While space exploration has the greatest immediate need for SRS, its development will have many other beneficial uses, such as greatly improved productivity and adaptability of industry, improved biosecurity, disaster resilience and pandemic preparedness.

Other Research: While there have been many investigations into SRS, too many to list here, they have largely been conceptual, non-physical (cellular automata) or engineering based (NASA's NIAC SRS investigations). Major research approaches are modular robotics [5,6] (duplicating configurations is not interior, that is 'self', replication/duplication) and 3D printers producing some of their components [7] (to only self-replicate is useless; rather developmental universal construction is required). Both approaches are subsumed and extended in our Developmental Universal Constructor SRS.

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Toward digital twins of lunar regolith and simulants for advanced selenotechnical investigations.

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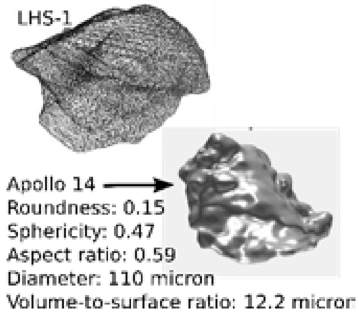
Introduction: Geotechnical engineers have long used numerical simulation and advanced modeling to understand the behavior of terrestrial soils in on-shore and off-shore environments. To design and build safe infrastructure, to exploit geomaterials for construction or to understand excavation processes, a complete and accurate understanding of the near-surface soil behavior is vital. In recent years, the geotechnical field has begun using digital twins ("virtual soil samples composed of digital grains") to aid terrestrial engineering design practices. In a general sense, a digital twin is a virtual representation of an object or system that can be updated with real-time data and used in simulation to infer the response of the system to an input. A digital twin in the geotechnical context enables one to account for specific characteristics of the soil (e.g., shape and size of grains) and the environment (e.g., overburden pressure, gravity, and temperature).

We use the three-dimensional level-set discrete element method (3DLS-DEM) for our digital twins of lunar regolith. A key reason to use 3DLS-DEM digital twins for lunar regolith particles is to capture important grain-shape-related properties such as internal friction and to better model grain-shape-related phenomena such as grain rotation during (cyclic) loading. Most importantly, we want to be able to replicate the extreme lunar environmental conditions with numerical (i.e., 3DLS-DEM) simulation to overcome obstacles encountered in the terrestrial laboratory (e.g., mimicking low gravity). 3DLS-DEM is increasingly applied in the study of granular material behavior [1,2] and it has a place in the study of extraterrestrial regoliths and their simulants.

Thus, over the last year we have begun to investigate lunar regolith simulants and Apollo 11 and 14 samples from the selenotechnical point of view. We use the term selenotechnics here to refer to geotechnics in the lunar environment, in line with terms like selenophysics. In this presentation, we will share an overview of our digital twin capabilities and our analysis of initial results related to the two Apollo samples and the *Exolith Lab* LHS-1 (lunar highlands) and LMS-1 (lunar mare) simulants [3].



We derive digital twins from nano- and micro-three-dimensional X-ray computed tomography (3DXRCT). After processing and segmenting reconstructed 3DXRCT volumes, we build 3D grain representations using level sets [4]. The figure above (not to scale) shows an example of one LHS-1 level-set grain-surface triangulation (upper) and one Apollo 14 grain (lower). With these digital grains we can do two important things: 1) we can precisely extract surface- and volume-based grain morphology characteristics (e.g., sphericity and roundness) to calculate distributions of these parameters from multi-grain samples, and 2) we can use these digital grains in numerical mechanics simulations to better understand the emergent macroscopic behavior derived from nanoscopic and microscopic properties and processes [4].

As 3DLS-DEM models require calibration to physical experiments, we will present results of our laboratory experiments on LHS-1 and LMS-1 used to tune their digital twin models. Additionally, we will present initial grain morphology characterization of all samples to which we have access. We will conclude by discussing the steps we are taking to improve the physics within the LS-DEM method (e.g., adding grain-boundary electrostatics [1] and grain breakage [2]) to more accurately represent lunar conditions.

References: [1] Bustamante D. et al. (2020). *Granular Matter*. 22, 90. [2] Pazmiño S. et al. (2022). *Computer Methods in Applied Mechanics and Engineering.* 399, 1. [3] Britt D. T. and Cannon K. M. (2020) *Lunar Surface Science Workshop, 2241*. [4] Jerves A. et al. (2015). *Acta Geotech.* 11(3).

Dusty Environment Classification and Testing: Dust Mitigation Slide Cleaning Material Study. N. Jimenez[1], [1] NASA Glenn Research Center, 21000 Brookpark road. Cleveland OH, 44135. (Contact: Nathan.Jimenez@NASA.gov)

Introduction: During the Apollo missions many mechanisms, equipment, and surfaces were contaminated by lunar dust and often negatively affected [1,2]. The methods used to clear these devices of dust proved ineffective, which led to premature failure in some cases [2,3]. Systems being designed for upcoming missions to the Moon will need to address the performance degradation risk of dust contamination. Surfaces at risk include thermal control surfaces, solar cells, camera and sensor optics, seals, metal joints and tools, and space suit assemblies [1].

To improve state of the art dust mitigation approaches, the dust mitigation team at NASA Glenn Research Center (GRC) explored the effects imposed on substrates during cleaning activities in the presence of lunar dust. The Uniform Dust Deposition System (UDDS) was used to conduct a study of various cleaning techniques on different substrates [4]. Test substrates and cleaning media were selected to represent a wide range of structural and functional materials. Substrates included orthofabric, thermal radiator coating, aluminum, quartz glass, silicone rubber, aluminized Mylar, and FEP. Cleaning materials included cloth wipes, tapes, a brush, and a pliable cleaner concept. Cleaning material / substrate pairs were rated on cleaning efficiency, substrate damage, cleaning material longevity, and ease of use. The best performing cleaning method varied based on application. The results of this study are summarized here.

References:

[1] International Agency Working Group (2016) *Dust Mitigation Gap Assessment Report*. [2] Goodwin R. (2002) *Apollo 17 NASA Mission Report*. [3] Bean, A.L. et al. (1970) NASA SP-235. [4] Gerdts S., Jimenez N. et al. (2021) *Lunar Simulant Deposition Technique for Dust Tolerance Studies*.

Development of Thermal Control Devices for Extreme Lunar Environments at Marshall Space Flight Center.

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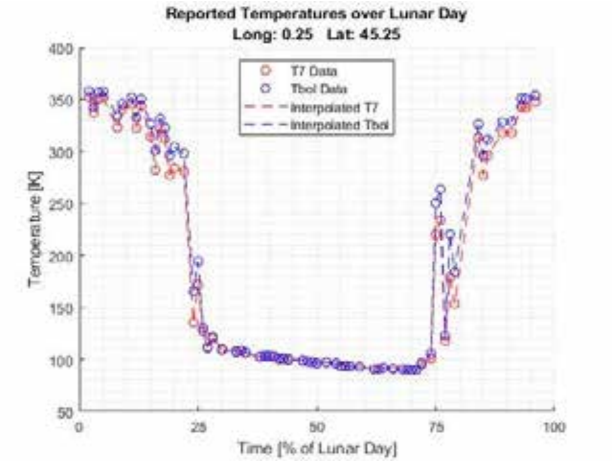
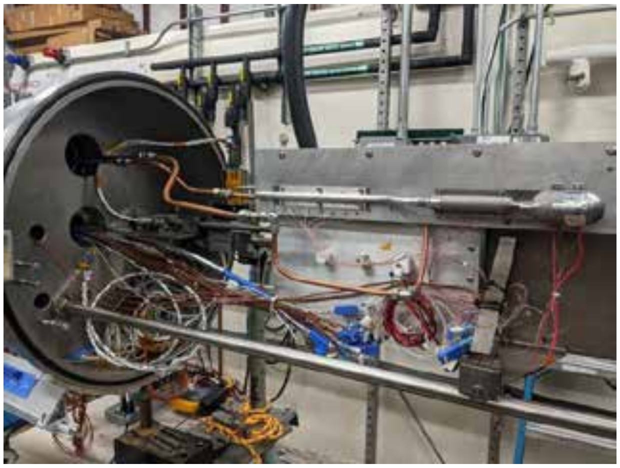
Introduction: NASA's return to the moon brings about many challenges, including issues with survival on the Lunar surface. In order to be sustainable, assets such as landers, rovers, and habitats must be usable for more than a single mission duration. One of the key challenges with sustainability is designing adequate thermal control systems that allow for surface systems to survive both during the day and the Lunar Night.

The extreme thermal environments on the Lunar surface are a challenging design space for thermal engineers. At equatorial regions the Lunar noon can be very hot, requiring systems with high heat rejection to the environment. At polar regions, such as those targeted by the return to the moon, the daytime temperatures are more moderate. During the Lunar night, however, temperatures plummet and can approach -200 degrees Celsius. Such temperatures are formidable and require specialized thermal control systems to allow surface assets to surface the long night.



Developments: Marshall Space Flight Center (MSFC) has been a leader in developing thermal control systems for surviving in the extreme thermal environments of the Moon. In coordination with partners such as Advanced Cooling Technologies (ACT) and Masten Space Systems, MSFC has been testing several thermal control devices that can be used to help solve the problem of surviving in extreme Lunar environments.

One major area of development is advanced heat pipes. MSFC works with ACT via Small Business Innovative Research (SBIR) and other funding sources to develop and test novel designs and applications of Variable Conductance Heat Pipes (VCHP) and Loop Heat Pipes (LHP). Several recent efforts include testing a warm-reservoir hybrid wick VCHP [1] and a LHP with Thermal Control Valve (TCV). Both of these heat pipes have the ability to provide passive modulation of the energy being rejected to the environment. A warm-resevoir hybrid wick VCHP will be flying on Astrobotic's Peregrine 1 mission to increase the Technology Readiness Level (TRL) and prove the technology on the surface. A new VCHP with advanced fluid handling is in development currently. [2]



MSFC has also been working with Masten Space Systems on development of a novel heat source for surviving in extremely cold Lunar environments. [3] Compared to traditional radioisotope heating sources, Masten's system does not have burdensome cost, availability, and regulatory issues. This system will be tested at MSFC in early 2023.

References: [1] Author J. D. (2022) *https://www.1-act.com/case-studies/non-integrated-warm-reservoir-variable-conductance-heat-pipes-vchps-with-hybrid-wicks-for-lunar-landers-and-rovers/*. [2] Author K. L. et al. (2021) *ICES-2021-242*. [3] *https://masten.aero/blog/surviving-the-lunar-night-with-mastens-nite-system/*

NASA MSFC Lunar Surface Simulator (LSS): A Facility for Lunar Relevant Environment Testing. W. E. King[1], P. Lynn[1], V. E. Pritchett[1], and the LSS Team,[1]NASA Marshall Space Flight Center (MSFC), 4600 Rideout Road, Huntsville, AL 35812, United States. (Contact: walter.e.king@nasa.gov)

Introduction: NASA will resume crewed visits to the lunar surface beginning in the mid-2020s. Environmental testing is essential to developing and validating the hardware that will enable a sustained presence on the lunar surface. Lunar dust is one of the most pressing challenges that threatens the longevity of mechanical systems as well as the health of astronauts living and working on the Moon. Facilities that allow large pieces of hardware to be exposed to both lunar dust and the temperature and vacuum of the lunar environment are invaluable to the agency as well as to the broader community of international, academic, and industry partners with which the agency collaborates. Marshall Space Flight Center has outfitted one of its largest test chambers with regolith simulant beds to create the Lunar Surface Simulator (LSS).

Figure 1. LSS Chamber and External Rail System

Facility: The LSS is located at the Environmental Testing Facility on MSFC's campus in Huntsville, AL. LSS extends the capability of the existing V20 thermal vacuum chamber (TVAC) maintained and operated by MSFC's Test Laboratory. V20 has supported projects from both internal and external partners, including Orion, ISS, and Space Shuttle.

To facilitate lunar environmental testing, the entrance to the V20 has been shrouded in a negative air pressure tent to contain regolith simulant. A rolling cart rides on external and internal rails to move test articles in and out of the chamber. A high-capacity overhead bridge crane and respirator trained technicians enable test articles to be safely handled.

The LSS complements other dirty chambers available or in development at MSFC such as the Lunar Environment Test System (LETS) [1] and the upcoming Planetary, Lunar, and Asteroid Natural Environment Testbed (PLANET) [2]. LSS also complements the MSFC's Lunar Regolith Terrain Field [3]. These facilities give MSFC partners access to a portfolio of simulated environments that bridge a wide range of scales and fidelities.

Figure 2. LSS Chamber with Regolith Bed Visible

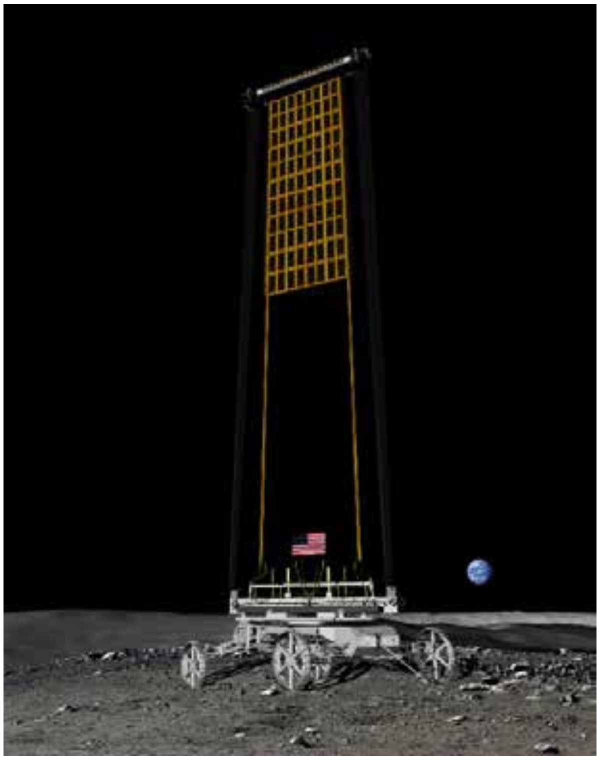
Capability: *The V20 Chamber.* The V20 chamber has a diameter of 20ft and a length of 28ft. A LN2 cryogenic shroud with 13 zones and heat lamps with 9 zones allow temperatures of -180 to 200 Celsius to be achieved. Two high-capacity diffusion pumps enable a hard vacuum of 1×10^{-6} torr to be attained in the chamber.

The Regolith Beds. The LSS's rolling cart can support 60,000lbs and a test bed footprint up to 9ft by 20ft. Currently, 9ft by14ft and 8ft by 4ft beds are operational and available for use. Regolith beds with depths up to 5ft are possible, as long as total weight remains within the capability of the cart.

Partnership: The LSS is currently online. Testing activities are managed by the MSFC Test Laboratory. Assistance with regolith simulant selection, acquisition, and preparation is available from the MSFC Materials and Processes Laboratory. Parties interested in utilizing the facility should contact Victor Pritchett (victor.e.pritchett@nasa.gov), Patrick Lynn (patrick.lynn@nasa.gov), or Shawn Maynor (shawn.b.maynor@nasa.gov) for more information.

References: [1] Craven P. et al. (2009) Third Lunar Regolith Simulant Workshop. [2] Hayward E. G. et al. (2022) ISME 15, Topic #14. [3] Summers A. W. and Zanetti M. R. (2022) LSIC Fall Meeting.

A Mobile Solar Array Designed for Prolonged Power Generation at the Lunar Poles. Troy Arbuckle[1] and J. Landreneau[1], [1]Astrobotic Technology, Inc. 1016 N. Lincoln Avenue, Pittsburgh, PA 15233, mike.provenzano@astrobotic.com



Astrobotic has developed under the NASA game changing development (GCD) program a solution to support a sustained presence on the lunar surface using its vertical solar array technology (VSAT). Astrobotic's VSAT is the foundational power source for its upcoming lunar surface power services that will enable continuous and sustained human and robotic presence on the Moon. Our VSAT will provide much needed surface power for landers, rovers, habitats, science suites, and other lunar surface systems to survive the lunar night and operate near the lunar poles. Astrobotic's VSAT technology is the future for NASA's near-term and long-term lunar missions and leverages strong partnerships with Redwire for solar power generation using the high TRL, 20 meter tall roll out solar array (ROSA), and Kennedy Space Center's (KSC) electrodynamic dust shield (EDS) for dust mitigation.

Astrobotic's VSAT offers a mobile power generation solution that is deployable on the lunar surface, and leverages highly mature technology developed from the CubeRover product line. At the base of the VSAT is the lunar infrastructure trailer (LIT), which can be remotely driven to known regions of near constant illumination, remain stable on slopes up to 15 degrees, provide sun-tracking for the ROSA using its gimbal control system, and has an advanced thermal management system that allows it to deliver high-power energy and tolerate the extreme cold temperatures of Lunar night. The onboard electrical architecture supports both high-power energy supply at long distance and wireless charging for local assets. High power can be transferred multiple kilometers over a hard-wired cable to establish a power grid or to support large assets like lunar habitats or excavation, construction, and processing equipment. Astrobotic's dust-tolerant wireless chargers can be used to deliver power to local assets without any concern for hardwired electrical connections. To make use of a wireless charger at a distance from the VSAT, a CubeRover-based wireless power station can be deployed to regions of interest.

The ROSA has space heritage on the International Space Station and is being modified and tested to show viable deployment operations under lunar gravity and in thermal vacuum extremes. The ROSA will supply more than 10kW of solar power over the minimum 10-year lifecycle of the VSAT mission profile.

KSC's EDS technology is also a critical element of Astrobotic's VSAT. Lunar horizon glow, observed by Apollo astronauts and supported by recent vacuum chamber experiments using electron beams, is the phenomenon of lunar dust lofting due to regolith electrostatic levitation and changing polarity in the terminator regions. The need for dust mitigation, at the LIT and at elevation on the ROSA, was identified early. The EDS technology offers a low power solution to maintaining a dust free surface on both the ROSA solar cells and the LIT radiators.

Astrobotic, Redwire, and KSC will complete testing to achieve TRL6 by early 2024. VSAT can be made available for delivery to the Moon as early as 2026 to support excavation, exploration, and scientific decadal missions. A 2026 delivery would support critical power needs for NASA's Lunar Terrain Vehicle.

Lunar Mine Reclamation Principles.

O. S. Lawlor[1], [1]U. Alaska, PO Box 756670 Fairbanks, Alaska 99775. (Contact: lawlor@alaska.edu)

Introduction: We propose that lunar mines [1] should be reclaimed to look like craters. Careless mining on Earth can degrade water and ecosystems for centuries, but erosion eventually covers up our mistakes. The lunar surface has no ecosystems but no rapid erosion, so every lost shovel or mine pit will remain for millions of years. Even though lunar permanently shadowed regions are never visible from Earth, in a few thousand years orbital mirror illumination and lunar polar orbital traffic may become common. Poor reclamation will endanger popular and political support for any use of space resources, so we should follow a long term holistic life-of-mine plan from day 1. This paper lays out these principles.

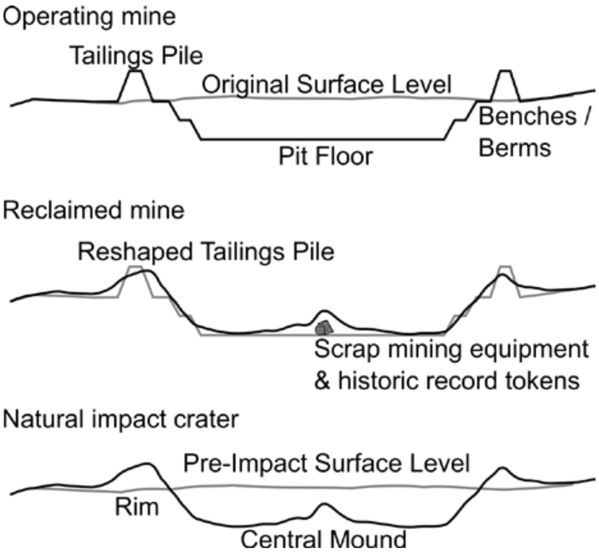
Principle 1: *Safety* over the long term. Deep pits or unstable slopes will remain hazardous indefinitely, so every excavation needs to respect the material slope limit, and ideally be easily traversable by a human in an EVA suit. This limits stepped bench heights to about 1 meter, and reclaimed slopes to about 45 degrees [2], preferably lower. Avoid leaving orbital debris, deep pit traps or hazardous waste on the surface.

Principle 2: The finished site should *look like a natural crater*. Using a circular pit with tailings stored around the rim can mimic a natural crater. For roughly circular orebodies, this is compatible with a terraced road open-pit excavation plan, with minimal backfill work needed to smooth the terraces during reclamation, leaving a shallow ramp out at least one wall to allow equipment or visitors to easily leave the finished crater. Scrap buried in unpredictable places would complicate future use, so any scrapped equipment should be buried in an artificial central mound, a unique location where it will be easy to locate in the distant future while still looking natural–see figure. Avoid leaving random robot tracks, dead robots, broken tools, random cables and other trash.

Principle 3: *Scientific exploration and mining* should be mutually beneficial. Large-scale excavations are likely to reveal scientifically useful stratigraphy and subsurface phenomena that would not have been found by small science oriented rovers: 3D variations in regolith composition, unusual mineral, impact and ejecta processes, and rare discoveries that could reshape our understanding of cosmic history. Scientific exploration can also help mining by better understanding the geology, finding nearby deposits and new materials in existing deposits. Scientific and mining organizations should share live access to mining robot telemetry, share analysis tools (XRF, drill cores), and collaborate on sampling, production, and site development in a synergistic way. We need to develop incentives to avoid science and mining becoming separate silos, working at cross purposes.

Principle 4: We should *use every part of the regolith*. Anything we excavate, we should either use, or store for future use. Icy regolith may contain a variety of volatiles including carbon, sulfur, and nitrogen species that will be critical for future lunar industry and agriculture. Nonvolatile tailings should be stacked neatly for future use, as ore for oxygen/metal/silicon/alkali extraction, or fill for construction. Avoid high grade extraction of a single target material, and dumping or venting volatiles as a mining comet plume.

Principle 5: Leave a durable *historic record* of site operations, at a minimum the original topography and processing undertaken. Scale model 3D maps and diagrams could be pressed or etched into glass tokens made from melted regolith and mixed into the central mound. Avoid offsite or few-copy records (lost), short lifetime technology and language (unreadable), or records made from rare materials (collected for scrap).



Acknowledgements: This paper began as our Excavation and Reclamation Plan for the NASA Break The Ice lunar challenge phase 1.

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The Inadvertent Modification of the Lunar Atmosphere Resulting from Increased and Prolonged Human Presence and Exploration. J. S. Levine, Department of Applied Science, The College of William and Mary, Williamsburg, VA 23187 (joelslevine@gmail.com)

Introduction: Surface Boundary Exospheres: The very thin lunar atmosphere is a rarefied planetary or satellite atmosphere called a Surface Boundary Exosphere (SBE). Other SBEs in the Solar System include Mercury, Io, Europa, and Callisto [1]. In an SBE, energetic atoms and molecules have only a small probability of experiencing a collision before escaping to space. SBEs are interesting due to the close connection between the planetary surface of a SBE and its atmosphere.

The Apollo Lunar Landings: An interesting observation of the Apollo lunar landings 50 years ago is that each landing mission deposited exhaust gases (from the lunar module descent and ascent rocket engines) and gases released from the pressurized lunar module totaling as much as about 0.2 of the total lunar atmosphere mass [1, 2, 3]. The Artemis landing missions will stay on the lunar for considerably longer times than the Apollo Mission and will involve extended exploration of the lunar surface and human activities on the lunar surface, e.g., building a permanent habitat, mining of the regolith for volatiles, such as water, etc. The time that the Apollo astronauts stayed on the surface of the Moon ranged from 22.2 hours for Apollo 11 to 75 hours for Apollo 17. In the Artemis Program, it is envisioned that the astronauts will spend weeks to months on the surface of the Moon. These human activities on the surface of the Moon may result in the release to the atmosphere of additional volatiles trapped in the regolith further increasing the impact of human presence and exploration in the production of gases to the atmosphere. The lunar SBE atmosphere is optically thin to the photons and charged particles that control the natural atmospheric loss process of lunar gases and their escape time is very short and hence, the short dissipation time of the Apollo-released atmospheric gases. Future human presence and exploration activities on the surface of the Moon could inadvertently alter the structure and composition of the lunar atmosphere [1, 2, 3]. The increased release of atmospheric gases by future human missions and activities could change the controlling lunar atmosphere loss mechanism from photoionization loss to Jeans thermal escape, with a consequent increase in characteristic loss time from tens of days to hundreds of years. Stern [1] cautions*: These considerations emphasize how fragile the native lunar environment is, and how easily human activities, even in the names of science, can affect this ancient wilderness.*

The Return of Humans to the Moon and Needed Measurements: As we begin the return of humans to the surface of the Moon, it is critical that we continuously monitor the density and chemical composition of the lunar atmosphere from both the lunar surface and from lunar orbit [4, 5]. Instruments similar to the Apollo Cold Cathode Gauge Experiment (CCGE) that measured the mass of the lunar atmosphere on the surface and the Apollo Lunar Atmosphere Composition Experiment (LACE) mass spectrometer that measured the chemical composition of the lunar atmosphere should become routine instruments on the Artemis Lunar Surface Experiments Package and on the lunar-orbiting command module. It is our responsibility and duty to understand the impact of human exploration and activities on structure and chemical composition of the lunar atmosphere from the very first Artemis human landing on the Moon.

References: [1] Stern, S. A. (1999) *Reviews of Geophysics,* 37, 453-491. [2] Vondrak, R. R. (1974) *Nature,* 248, 657-659. [3] Vondrak, R. R. (1988) Paper LBS-89-098, *Workshop on Lunar Bases and Space Activities in the 21st Century*, NASA Houston, TX.[4] Levine, J. S., and J. M. Zawodny (2007) *NASA Advisory Council (NAC) Workshop On Science Associated with the Lunar Exploration Architecture*, Tempe, AZ. [5] Levine, J. S. (2021) *The Impact of Lunar Dust on Human Exploration,* J. S. Levine, Editor, Cambridge Scholars Publishing, UK, 2012, 41-54.

CENTRIFUGAL DISASSOCIATED REGOLITH ELECTROLYSIS CELL/REACTOR FOR LUNAR OXYGEN AND METALS PRODUCTION

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Introduction: Oxygen is ubiquitous and exists everywhere on the Moon. Lunar oxygen is tightly bound with various other lunar elements (mostly Si, Al, Ca, Fe, Mg, Ti); thus, it abundantly exists in the form of various mineral oxides[1] – mineral oxides that make up the powdery meters-deep regolith layer that blankets the Moon. Indeed, freely available lunar regolith contains more than 40% oxygen by weight, which, if extracted, could be used in extraterrestrial life support systems and as a propellent for space travel [1].

Lunar Oxygen Corporation (d/b/a “LunOx” – Seattle, WA), a frontier extraterrestrial mining company, proposes a novel “centrifugal disassociated regolith electrolysis” approach that, when developed, will enable the continuous extraction of abundant oxygen (and separation and recovery of valuable metal alloys) from raw/unprocessed lunar regolith. In brief, LunOx is developing a novel co-rotating “shell and drum” centrifugal cell/reactor designed to electrolytically decompose, while under centrifugal action, molten and/or solubilized lunar regolith into oxygen, metals, and semiconductor materials. LunOx’s proposed lunar oxygen and metals production technology provides a viable alternative for enhanced in-situ resource utilization (ISRU), especially if water ice trapped at the lunar poles is scarce or proves difficult to harvest (as some selenologist argue [2]).

In LunOx’s novel cell/reactor design, the conventional static “multi-stack” electrodes (associated with traditional terrestrial-based electrolysis cells) are replaced in favor of a new-type of a co-rotating co-cylindrical (shell-shell/drum) cell design that, during operation, creates <u>artificial gravity up to 10 g</u>. Unlike conventional static electrolysis approaches (that all suffer from substantial O_2 gas bubble transport and removal problems, which problems are greatly exasperated in low g environments), LunOx’s new cell/reactor design consists of only two large cylindrical refractory metal alloy electrodes (~5 m^2 active area each); namely, (1) an outer rotating tubular shell that serves as the cathode (and as the reactor containment vessel), and (2) an inner concentrically positioned drum that serves as the anode. In this novel configuration, and because the shell and concentric drum are rotating about a central axis during operation, molten and/or solubilized regolith introduced into the top of the rotating cell/reactor (fed from an overhead solar-heated melt cauldron[2]) is flung against the inner wall of the outer shell and begins to undergo electrolysis and density separation (due to artificial gravity).

LunOx’s cylindrical electrodes are made from advanced metal alloys; and, as such, the cell/reactor may be inductively heated up to 2,000°C and operated continuously without significant deterioration. During electrolysis and because of the centrifugal action, the denser liquid metals reduced at the outer cathode form a thin liquid metal layer against the shell wall, whereas the buoyant/less dense oxygen gas evolved (at the anode) is efficiently removed (via rows of anode through-holes) and vacuum drawn inwardly and into a central oxygen removal tube (and out of the cell/reactor for subsequent liquefaction and storage). The rotating and downwardly flowing reduced liquid metal layer (consisting essentially of Fe, Si, Al, and Ti) is separated from the less dense remaining oxide slag overlayer by means of a concentric splitting ring.

CMRE Cell/Reactor Specifications:

<u>Inputs and energy requirements</u> [3],[4]

Feedstock = Lunar regolith (unprocessed)
Reactor size: H = 1.8 m, D = 0.9 m
Feed rate = 1,000 kg/24hrs (~11.5 grams/sec)
Operating temp. = ~1650 – 1850°C
Melt cond. = ~0.08 $cm^{-1}ohm^{-1}$ – 1 $cm^{-1}ohm^{-1}$
Electrode surface area, A = ~5 m^2 each
Electrode spacing, L = 0.635 cm
Electric potential energies = -0.7 V to -2 V
Oxygen production efficiency = ~60-90%

<u>Output products (per 1,000 kg of regolith/24hrs)</u>

O_2 production = ~170 kg; Volatiles = ~0.1 kg
Total metals (mongrel) production = ~370 kg
Total slag production = ~460 kg

References:

[1] G. H. Heiken et al., Lunar Sourcebook (1991).
[2] M. Nord, *Aerospace America* (April 2021).
[3] R. O. Colson, L. A. Haskins, *Space Resources* (1992).
[4] L. A. Haskins et al., NASA conf. paper (1992).

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[1] The oxide mineral class include those minerals in which the oxide anion is bonded to one or more metal alloys.

[2] The melt cauldron (energy absorber) is solar-heated by focused mirror arrays disposed about the base of a central melt cauldron support tower.

Active Phased Array for Ka-Band High Data Rate Communication. E. Luther[1], S. Erekson[1], D. Vreeland[1], [1]CesiumAstro, Inc., 13215 Bee Cave Pkwy, Suite A-300, Austin, TX 78738, USA. (Contact: erik.luther@cesiumastro.com)

Introduction: Communication to and from the Lunar surface will require innovative antenna solutions that support mobility and high data rates at greater scale and lower cost in extreme environments. Active phased arrays meet these demands and provide many advantages at Ka-band supporting the LunaNet Interoperability Specification.[1]

Lunar Surface Operations: Relay satellites are planned to provide connectivity to/from the Lunar surface when line-of-sight communication to Earth or a lander is limited by terrain features and for far-side-of-the-moon operations.[2] These orbiting relay points will require tracking and/or constant repositioning of Lunar ground antennas, made more complex if those endpoints are in motion.

Nightingale I Active Phased Array: Nightingale I provides a transmit (Tx) and receive (Rx) single-beam solution spanning 22.5–23.55 GHz and 25.5–27 GHz frequencies allowing it to serve as either side of a communications link. Each 8.5cm.sq. antenna tile contains 186 elements and weighs 400g. Multiple tiles can be combined to improve RF performance or to add redundancy to the system. The design leverages carefully selected ICs and radiation testing of automotive-grade components to reduce cost while ensuring reliability.

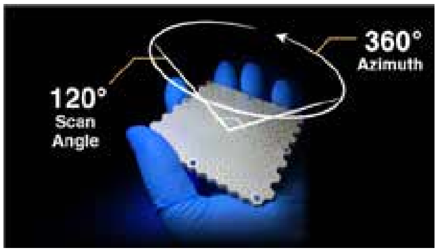

Figure 1: Nightingale I active phased array tile field of view, +/-60° scan at 360° azimuth

Active Phased Array Capabilities: Nightingale I supports near-instant tracking and repointing across the entire field of view with no moving parts, covering +/-60 degrees of scan in 360 degrees of azimuth with no keyhole effects. This enables high-gain connectivity to a moving satellite from both stationary and mobile ground stations. Multiple operating modes allow a single antenna to support multiple functions, including acquisition mode (scanning for a satellite), low-power communications, high-throughput communications, and ranging. Additional features include nulling to reduce multi-path reflections and other interference sources.

Figure 2: Fully integrated Nightingale I payload supporting LunaNet communications

Complete Payload Integration: The Nightingale active phased array tile combines with digital backend components, including a software-defined radio, up/down conversion, computing, and power conditioning, to form a complete communications payload. Paired with standard modulation and coding schemes such as CCSDS and DVB-S2X waveforms, the fully integrated Nightingale I can be mounted in (or on) a rover, lander, or satellite platform connecting only power and ethernet.

Demonstration and Availability: Nightingale I payload is available today at TRL 8 with Tx and Rx capabilities from 25.5–27 GHz with a LEO flight planned for Q4 2022. The second-generation Nightingale tile, with full 22.5–27 GHz frequency coverage, is in development and on track for flight in late 2023 to early 2024.

References: [1] NASA Goddard Spaceflight Center. (September 12, 2022), LunaNet Interoperability Specification. [2] Esper, J. (May 17, 2022) Lunar Communications Relay and Navigation Systems (LCRNS), ESC-LCRNS-REQ-0090.

Acknowledgments: This work is supported under the NASA Commercial-Scale Arrays for Lunar Exploration contract.

The Flexible Logistics & Exploration (FLEX) Rover and Robotic Arm with Modular Payload Capability. J. B. Matthews[1], R. D. Billing[1], A. J. Welter[1], [1]Venturi Astrolab, Inc., 12536 Chadron Ave Hawthorne, CA 90250 (Contact: jaret@astrolab.space)

Introduction: NASA and private industry investments will soon make it possible to land unprecedented amounts of cargo on the Moon at a regular cadence. Venturi Astrolab, Inc. (Astrolab) is developing the multi-functional Flexible Logistics & Exploration (FLEX) rover with this burgeoning environment in mind. The FLEX rover's unique commercial potential comes from its novel mobility system architecture, which gives it the ability to pick up and deposit modular payloads in support of human operations, robotic science, exploration, logistics, infrastructure deployment, site survey/preparation, construction, maintenance, & repair, resource utilization, and other activities critical to a sustained presence on the Moon and beyond (Figure 1).

Figure 1: FLEX's modular payload interface and novel mobility system enable it to perform a multitude of functions, including (left to right, top to bottom): crew transport, outpost logistics, robotic science, and infrastructure deployment

Adaptive Utility: FLEX is a Lunar Terrain Vehicle (LTV)-class, semi-autonomous, remotely-operable, rover that can carry two suited astronauts and all their associated equipment, tools, instruments, and samples. FLEX features a novel wheel-on-limb mobility system that can raise and lower the ground clearance of the chassis and adapt to variable terrain while maintaining stability. This system also allows the rover to lower attached instruments and equipment to the ground and/or independently collect and deploy modular payloads. FLEX can accommodate payloads with volumes in excess of 3m^3 and masses of up to 1,500 kg.

Robotic Arm & Payload Mezzanine: Astrolab recently completed the design and build of a ~2m long, six degree-of-freedom robotic arm that interfaces to FLEX. The arm includes a dust-tolerant quick disconnect end effector that is used to attach-to and extract payloads, instruments, and tools that are housed in a mezzanine below the arm. Each of the 15 payloads in the mezzanine can be as large as a 12U cubesat (22cm x 22cm x 36cm) and 25kgs. In addition to deployable customer payloads, the mezzanine can contain instruments or other implements such as a scoop for collecting samples or transferring regolith.

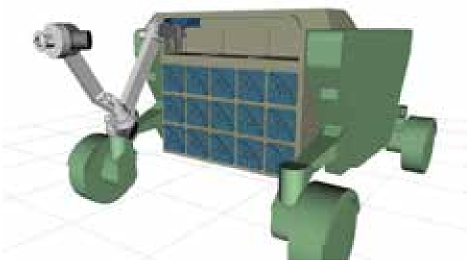

Figure 2: Astrolab's 6-DoF Robotic Arm and Payload Mezzanine attached to the FLEX rover.

Analog Testing: Astrolab has developed a full-scale, fully-functional terrestrial proof-of-concept FLEX rover and has conducted multiple field tests at analog sites in the California desert. At these field trials, FLEX was used to conduct demonstrations of various activities and operational scenarios that will be required on the Lunar surface [1].

Open Payload Interface Standards: Astrolab recently published an updated Payload Interface Guide to educate potential partners and customers on the capabilities of FLEX and the various ways it can accommodate payloads. The latest version of the guide contains information for making implements and payloads that are compatible with the robotic arm. Astrolab is now inviting government, academic, and commercial entities to partner with us in the design and field testing of payload concepts. We seek to foster a community of payload developers adhering to an open and standardized interface. The use of standardized payload interfaces is critical for diverse participation on the International Space Station, and the approach that Astrolab is advancing will be similarly vital for a sustained human presence on the Moon.

[1] NASA HEOMD-006: Human Exploration Operations & Utilization Plan (2021)

Trade Study of Impact-Resisting Structures on the Lunar Surface. A. Majlesi[1], A. Shahriar[2], and A.Montoya[3]. [1] School of Civil & Environmental Engineering, and Construction Management, The University of Texas at San Antonio, One UTSA Circe San Antonio, Texas, 78249. [2]Department of Mechanical Engineering, The University of Texas at San Antonio, One UTSA Circe San Antonio, Texas, 78249. [3]School of Civil & Environmental Engineering, and Construction Management, and Department of Mechanical Engineering, The University of Texas at San Antonio, One UTSA Circe San Antonio, Texas, 78249. (Contact: Arturo.Montoya@utsa.edu)

The design of habitats in extreme space environments requires analysts to identify materials that can resist several disturbances. These habitats are exposed to micrometeoroids that constantly impact the lunar surface with extreme velocities and high-temperature fluctuations. Moreover, the limited launch mass of NASA missions significantly influences the design of lunar habitats. Thus, trade studies that determine the best material options for space habitats can help guide the design of these structures. Solidified regolith and aluminum are two material alternatives that are being considered to design space habitats. A trade study was conducted to compare the performance of monolithic dome structures made of these two materials under the same applied load. Power consumption and repair time over twenty years were used to evaluate the performance of the domes.

The consumed power and repair time were proportional to the perforation depth caused by ejecta impact. An artificial neural network model (ANN) trained with finite element simulation results was used to predict the perforation depth of shields with a range of different ejecta diameters and velocities. Based on the trade-study assumptions, the following conclusions were obtained:

- Regolith structures consume less power to control the interior environment due to damage.
- The total accumulated repair time during a 20-year lifecycle is less for aluminum habitats.
- Regolith structures have higher performance uncertainty under ejecta impacts as damage is highly dependent on the ejecta characteristics.

Further refinements to the trade study procedure are being conducted to enable designers to find the most optimal long-term lunar habitat design.

Advancing Dust Tolerant Mechanisms for a Sustained Exploration of the Moon. J. I. Núñez[1,2], M. E. Perry[1,2], S. Hasnain[1,2], R. S. Miller[1,2], L. R. Tolis[1,2], B. A. Clyde[1,2], A. M. Fritz[3], A. J. Sanchez[4,5], and K. K. John[4], [1]Johns Hopkins University Applied Physics Laboratory; [2]Lunar Surface Innovation Consortium; [3]NASA Johnson Space Center; [4]NASA STMD, [5]Stellar Solutions, Inc. (Contact: jorge.nunez@jhuapl.edu)

Introduction: "I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."– Gene Cernan, Apollo 17 Technical Debrief

The Apollo missions revealed the impact of lunar dust on mechanisms. Lunar dust particles are jagged and electrostatically charged, giving them the ability to bind or damage mechanisms and alter thermal properties. Reports documented clogged equipment and jammed mechanisms in every mission, regardless of surface duration, as well as clogged mechanisms in the Extravehicular Mobility Suit (EMS), including zippers, wrist and hose locks, faceplates, and sunshades [1-2]. Several astronauts remarked they could not have sustained surface activity much longer because clogged joints would have frozen up completely [2]. Effective dust mitigation strategies are needed to support longer duration stays on the lunar surface [3-4].

State of the Art: Technology for mechanisms able to operate in dusty enviroments is advancing rapidly due to the needs of both Mars rovers and the Artemis program. Vacuum-tight connectors are essential for spacesuits and habitats, and their performance can be dependent on cleaning technologies, which have proven difficult on the lunar surface. Several TRL 3-5 technologies are undergoing tests with the expectation to reach TRL 6 within 1-2 years. Some mechanisms will be infused and tested on the VIPER (Volatiles Investigating Polar Exploration Rover) mission planned for mid-2020s.

NASA Funded Efforts: NASA has recognized the need for dust tolerant mechanisms, and has partnered with industry to advance the state-of-the-art. At NASA GRC, KSC, and JSC, the Dust Tolerant Mechanisms Project is working to develop advanced actuator seals for rotary joints and rotary bearing technologies for long-term sustained operation in lunar dust environments. Another NASA project at NASA GRC, partnered with GSFC, JPL, and KSC is Motors for Dusty & Extreme Cold Environments (MDECE). MDECE is developing an unheated magnetically-geared motor that can operate continuously for a long duration at an ambient temperature of -243 ºC (33 K). NASA GRC has the capability to characterize the effects of dust on seals, mechanisms, and other mating surfaces and components under lunar conditions [5].

Through the SBIR/STTR program, NASA has funded several companies to advance dust tolerant mechanisms via the Dust Tolerant Mechanisms sub-topic with applications in surface mobility, spacesuits, connectors, joints, and more.

LSIC and Community Efforts: The Lunar Surface Innovation Consortium (LSIC) Dust Mitigation focus group has fostered collaborations across NASA, industry, and academia to develop solutions that minimizes the impact of lunar dust on robotic and human systems. Community efforts have included topical meetings on dust tolerant mechanisms, featured technology presentations, and feedback to NASA on potential gaps and needs.

Testing: In 2021, NASA released NASA-STD-1008 [6]. This NASA Technical Standard establishes minimum requirements and provides guidance for testing systems and hardware to be exposed to dust in planetary environments. The standard has specific sections dedicated to Mechanisms Testing (e.g. bearings, gears) as well as Seals and Mating Surfaces Testing (e.g. hatches, docking systems).

Gaps and Needs: NASA is tracking dust tolerant mechanisms as a gap in a cross-directorate analysis of capability areas needed to enable future human space-flight architectures. Two high-priority gap areas include additional facilities for testing mechanisms in lunar-surface conditions, and a better understanding of vulnerabilities to the smallest, nanometer-scale dust particles.

Conclusion: Understanding and mitigating lunar dust is critical to successful, sustained operations on the lunar surface – whether autonomous or otherwise. This presentation will discuss both the state-of-the-art and open needs in lunar dust tolerant mechanisms, technology impacts, mitigation approaches, testing, LSIC community efforts, and more.

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Searching for evidence of water ice at the Lunar South Pole - The Puli Lunar Water Snooper on the IM-2 Mission. T. Pacher[1], T. Martin[2], and F. Meyen[3], [1]Puli Space Technologies Ltd, tibor.pacher@pulispace.com, [2]Intuitive Machines, LLC, tmartin@intuitivemachines.com, [3]Lunar Outpost Inc., forrest@lunaroutpost.com (Contact: tibor.pacher@pulispace.com)

Introduction: There is consensus on the importance of lunar volatiles, especially water ice, critical to sustaining a human presence on the Moon. Lunar Prospector NS [1], LRO LEND [2], LOLA and DIVINER [3], and LCROSS [4] observations provided indirect and direct evidence that enhanced hydrogen concentrations (significant amounts in H_2O and OH molecules) are found at the poles. Recent modeling indicates that water ice could even be found in micro-cold traps (scales from 1 km to 1 cm) [5]. However, the spatial resolution and precision of the measurements are low, and significant unknowns remain about the abundance, composition, distribution, and origin of lunar volatiles, especially in the smaller Permanently Shadowed Regions (PSR).

Per NASA Artemis III Science Definition Team Report, the highest priority objectives include detecting, characterizing, and mapping the geographic distribution of volatiles in the polar region and determining their physical state and abundance [6].

Neutron spectroscopy: One of the common methods to determine hydrogen content of the regolith is neutron spectroscopy. Low-energy albedo neutrons scatter upwards and emerge from the lunar regolith produced by high energy cosmic rays, with a final neutron energy distribution characteristic to the local soil composition,and highly depending on the hydrogen content [7].

The Puli Lunar Water Snooper (PLWS) is a lunar neutron spectrometer, which detects thermal and epithermal neutrons. The PLWS is a miniaturized (static envelope: 10 cm × 10 cm × 3.4 cm), lightweight (less than 382 gr), low-cost, COTS-based system. It consists of 3 modified off-the-shelf CMOS active pixel image sensors as detectors (a Thermal Neutron, an Epithermal Neutron and a Reference Sensor).

Developed in the framework of the ’Honey, I Shrunk the NASA Payload, The Sequel’ challenge by Puli Space Technologies, three identical, functioning PLWS prototype models have been already manufactured and delivered to NASA JPL in February 2022 [8].

IM-2 Mission: Intuitive Machines (IM) will fly the IM-2 mission to the South Pole of the Moon NET June 2023. The NASA sponsored payloads CLPS PRIME-1 and STMD Tipping Point IM µNova Hopper and Nokia LTE are manifested on this mission. The µNova will hop into a permanently shadowed region (PSR), currently targeted to be Marston Crater, and then hop out and transmit data back to the lander. In addition, IM will use a Lunar Outpost (LO) Mobile Autonomous Prospecting Platform (MAPP) rover to transport the Nokia LTE system up to 2km away from the Nova-C landing location. [9]

PLWS on the µNova on the IM-2 mission provides the unique opportunity to gather multiple dispersed measurements to estimate water-equivalent-hydrogen (WEH) concentration in illuminated and permanently shadowed terrains. Adding a PLWS to the MAPP rover is also a fairly straightforward procedure and would provide numerous data points during the long rover traverse as well. Comparison of these data would also give insight into potential hopper exhaust plume effects, caused by its hydrazine fuel.

IM has assessed the feasibility of integrating the PLWS both on µNova and MAPP.

PLWS flight units for IM-2 has been delivered to IM and LO, respectively, in August 2022.

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Lunar Subsurface Access and Exploration using REBELS Drill.

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Introduction: Lunar subsurface exploration has been limited to a 3-meter depth in previous missions to the Moon; Apollo 15, 16, and 17 captured lunar cores to a depth of 3-meters, while the Soviet Luna 24 sample return mission drilled to 2-meter and China's Chang'e 5 drilled to 1-meter. Future missions such as PRIME1 and VIPER are limited to 1-meter depth. Understanding the stratigraphy on the 10-meter scale in the mid-latitude and polar regions of the Moon would significantly enhance our understanding of the gardening as well as volatile distribution of the subsurface.

REBELS (Rapidly Excavated Borehole for Exploring Lunar Subsurface) is a drilling and instrumentation system designed for penetrating >10-meters below the lunar surface for in situ science investigation and/or ISRU applications. REBELS leverages concepts from three existing Honeybee Robotics:

- *RedWater:* a coiled-tubing drill for penetrating up to 25-meters below the surface of Mars,
- *LISTER:* a 3-meter pneumatic drill scheduled to fly to the Moon in 2023 and 2025, and
- *SMART:* an instrumented drill under development for the RESOURCE project funded by NASA SSERVI.

The primary advantage of REBELS is to bring the instruments to the sample – i.e., all the instruments in the Bottom-Hole Assembly (BHA) can be activated in real-time and collect subsurface data while drilling. In addition, the cuttings being pneumatically cleared out of the borehole can be collected and analyzed in real-time by surface-level instrumentation.

Various subsystems of REBELS are currently being developed to TRL ranging from 4 to 9 via various NASA projects. Redwater will achieve TRL6 in 2024, SMART will achieve TRL5 in 2023, and LISTER will achieve TRL9 in 2023.

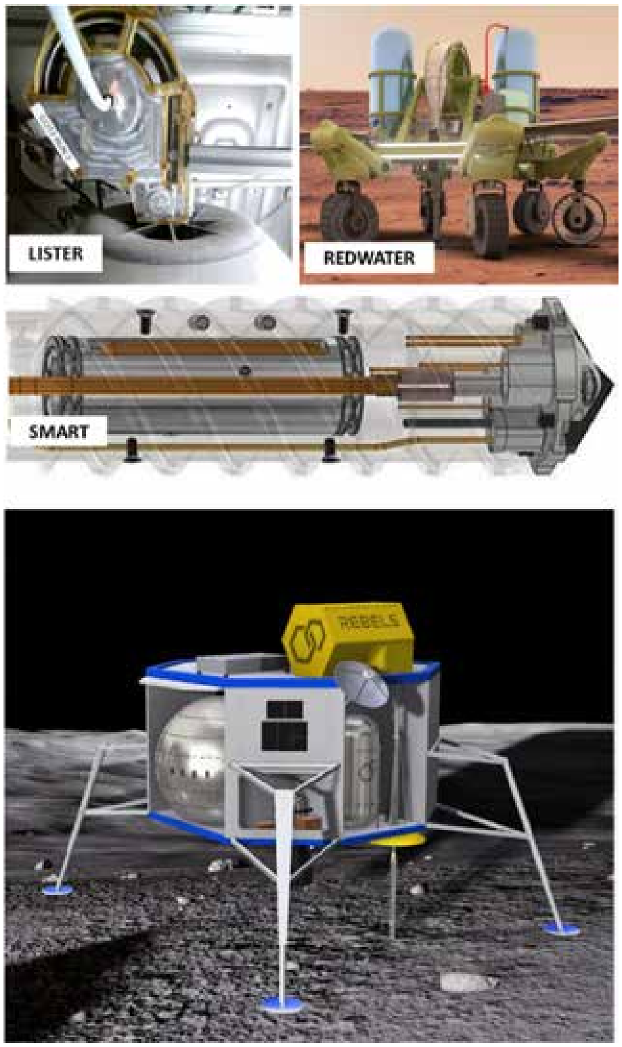

Figure 1. The integrated REBELS concept incorporates existing Honeybee technologies including the instrumented SMART drill (bottom right), the LISTER pneumatic drill (top center), and the Redwater coiled-tubing drill (top right). A 50-meter version of REBELS integrated with Blue Origin's Blue Moon lander is also being proposed for a mission to the Moon.

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Engineered Cold Plate with Additively Manufactured Cryogenic Heat Pipe and Periodic Ice Delamination for Lunar Ice Collection

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Introduction: The ongoing "Advanced Thermal Mining Approach for Extraction, Transportation, and Condensation of Lunar Ice" project at UTEP Aerospace Center funded under NASA LuSTR [1] is focused on the design, development and demonstration of a lab-scale advanced thermal mining prototype of 1 kg ice collection capacity that integrates engineered extraction, transportation, and desposition of water vapor from icy lunar regolith (Fig. 1). Due to the low power availability at the lunar PSRs, it is essential to develop ice re-capture cold trap with cryogenic heat pipe that requires no power to reject vapor deposition heat flux. Moreover, the poor thermal conductivity of ice imposes another challenge in continuous ice collection on cold plates. Therefore, this work focuses on developing an engineered cold plate with cryogenic heat pipe and periodic ice delamination mechanism.

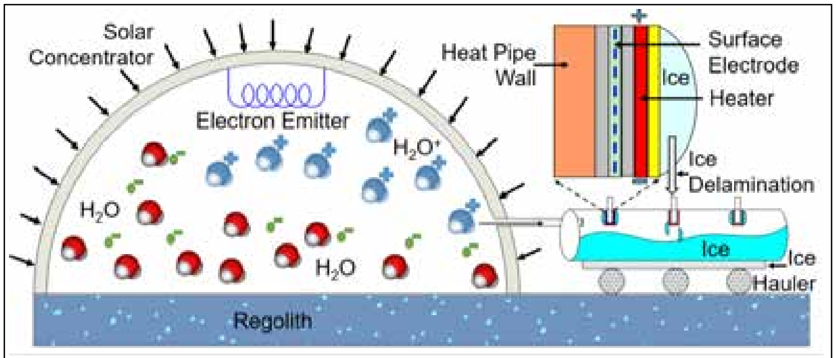

Figure 1: UTEP advanced thermal mining technology

Additively Manufactured Cryogenic Heat Pipe: The engineered heat pipe will collect the incoming water vapor by generating sub-cooling at the evaporator section of the heat pipe and reject heat to the lunar atmosphere. Additively manufactured Ti-64 micro-pillar arrays (Fig. 2) have been fabricated and experimentally characterized to maximize the heat transfer performance of evaporator and condenser sections of the heat pipe. The micro-scale features measure 400 μm square pillar width, 500 μm spacing and 600 μm height. More than 2.6 times heat absorption capacity has been experimentally demonstrated as compared to the lunar water processing mission requirements using saturated liquid nitrogen (~1.38 MPa, 110 K) as the heat pipe fluid.

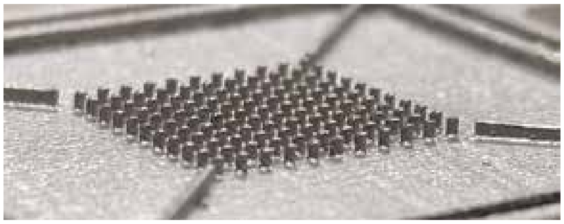

Figure 2: Additively manufactured micropillar arrays for engineered cryogenic heat pipe

Engineered Cold Plate: The engineered cold plate focuses on developing a sub-cooled surface for the incoming vapor deposition with periodic ice delamination mechanism. The ice delamination system utilizes a thin resistive heater to generate a thin vapor lubrication layer between the cold plate and the bulk ice resulting in gravity driven ice delamination. An ice collection rate of 2.6 g/hr. was achieved on a 4 × 4 cm^2 cold plate at a sub-cooling of 55.7 K and 2.0×10^{-3} Torr pressure in a cryogenic T-VAC (Fig. 3) for 4.54×10^{-5} kg/m^2s vapor sublimation flux. A perioid ice delamination (Fig. 3) has been experimentally demonstrated for a continuous ice collection.

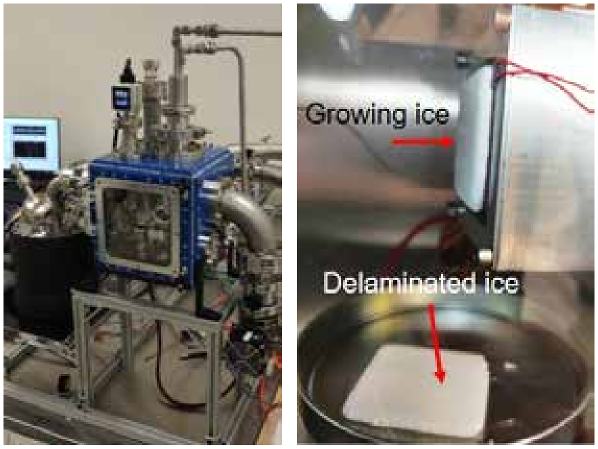

Figure 3: Modular thermal vacuum chamber (left) and periodic ice delamination (right)

In Summary, this work demonstrates an engineered cryogenic heat pipe with high heat transfer capacity, ice collection in cryogenic rarefied environment and periodic ice delamination for lunar water processing missions.

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Autonomy and Operations for Lunar Rover Prospecting Missions: A Highlight from the ESA-ESRIC Space Resources Challenge.

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Introduction: At previous LSIC Meetings, Mission Control has highlighted the suite of flight and ground software applications to allow lunar rovers to autonomously and intelligently understand the lunar surface environment and make key decisions in support of ISRU-relevant activities such as resource prospecting, excavation, and construction [1]. This is critical to allow vehicles and other systems operate with a high degree of supervised autonomy. At the LSIC Fall Meeting 2022, Mission Control will highlight a recent use, explained below.

Demonstration at the ESA-ESRIC Space Resources Challenge

In 2021, Mission Control was selected among 13 teams to compete in the Space Resources Challenge organized by the European Space Agency (ESA) and the European Space Resources Innovation Centre (ESRIC) in Luxembourg. The challenge took place close to ESA's ESTEC facility in the Netherlands, in November 2021. With a strong team well-versed with lunar rover operations, our team was selected among the top 5 teams to move on to the second phase of the challenge, which took place at ESTEC in Luxembourg in September 2022.

The second phase of the Challenge required a 2500 m^2 region of interest (ROI) to be explored, mapped, and prospected for resource potential within 4 hours. The ROI was set up as a south lunar pole analogue with challenging lighting conditions, and various features of interest to investigate. A 2.5-second latency in each direction and random communications drop-outs were incorporated to emulate a lunar mission scenario, allowing judges to evaluate the approaches taken by teams to handle the communications challenges.

As a software-focused company, Mission Control entered the Space Resources Challenge with a solution based on three elements:

- Focus on operations software technology and strategies based on our Mission Control Software platform
- Rigorous practice and operational readiness by the team, leveraging our easily accessible indoor lunar analogue testbed
- Leveraging reliable COTS hardware components, such as the Clearpath Robotics Husky, NVIDIA Xavier developer platform, a Pan-Tilt-Zoom camera, and Zed-2 stereo camera.

Mission Control also incorporated instruments from key partners:

- The mWABS, a compact, next generation, 2-axis scanning LiDAR, from Canadian space robotics and sensing company MDA, and
- The L3VIN LIBS (Laser Induced Breakdown Spectroscopy) from US-based Impossible Sensing.

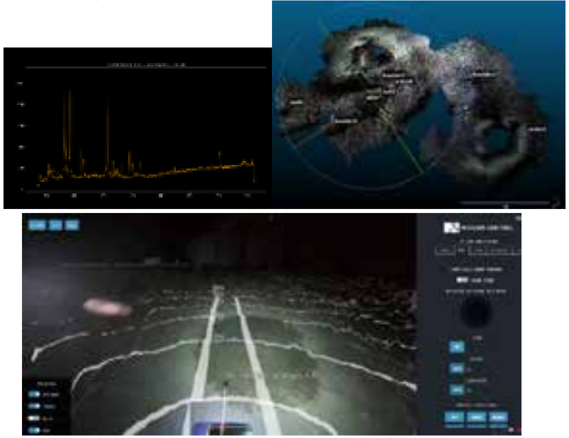

Figure 1. *Top; Left: LIBS spectra, Right: Map generated from traverse at ESRIC. Bottom: Mission Control Software UI used for rover and payload operations.*

Through this analogue demonstration, Mission Control has showcased the power of easy-to-use operations software with in-built tools for streamlining rover navigation and instrument operations alike in a lunar rover prospecting scenario.

Flight Demonstration: Mission Control will fly a payload on the first ispace mission M1 in 2022 and conduct the first demonstration of Deep Learning on the lunar surface, a historic milestone for space exploration. It will classify lunar surface features visible in images from the Rashid rover in the Emirates Lunar Mission (ELM). Mission Control will also participate in the international science collaboration of ELM, led by the Mohammed Bin Rashid Space Centre (MBRSC) [2]. Following this critical demonstration of AI-based autonomy, Mission Control is eager to deploy this technology for future lunar surface prospecting and ISRU missions.

Acknowledgments: We acknowledge the support of the Canadian Space Agency for technology development and for the lunar capability demonstration [3CAPDEMO21].

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Title of Abstract: Sub-nanosecond 2-way Time Transfer and Signal Generation Payload for Lunar Applications

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[2]Agalti Corporation

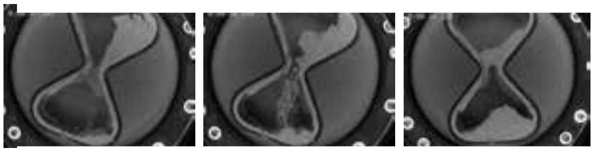
Introduction: CACI has developed a scalable, low-SWAP, space-qualified TRL-8 time transfer capability to provide a space-qualified timing service and signal generation capability to SWAP-constrained orbital vehicles. The core component is a software-defined radio that has been systematically characterized for transmit and receive delays. The primary application for demonstrating precision timing is a 2-way time transfer modem using short-burst communications that are inherently energy efficient. The communication technique features on-demand waveform versatility and tunability. Onboard processing includes advanced modeling for clock state estimation, prediction, and corrections for dynamics that provide a foundation for synchronization with remote clocks Additionally the hardware is optimitzed for generating on-time waveform emissions and precision time-tagging of received signals at the sample level. This technology allows small embedded systems to obtain laboratory-quality timing performance using commercially available oscillators without sacrificing short-term stability. Prototypes in TVAC testing show sub-nanosecond performance for typical link conditions. CACI has invested IR&D to build and launch a smallsat demonstration payload into a low-earth orbit in the first quarter of 2023.

Elucidation of Mechanical Behaviors of Lunar Regolith in Microgravity.

Jason Ramsey[1] and Brian Vattiat[1] and Cesar Gonzalez[1] and Evan Jensen[1] and Eamon Carrig[1] and Cody Bressler[1] and Thao Nguyen[1] and Martyn Staalsyn[1] and Kevin Cannon[2] and Jennifer Edmunson[3] and Karen Whitson[3], [1]ICON Technology Inc., 444 E St Elmo Rd Suite B, Austin, TX 78745, [2]Colorado School of Mines, 1500 Illinois St, Golden, CO 80401, [4]NASA MSFC, Martin Rd SW, Huntsville, AL 35808 (Contact: jramsey@iconbuild.com)

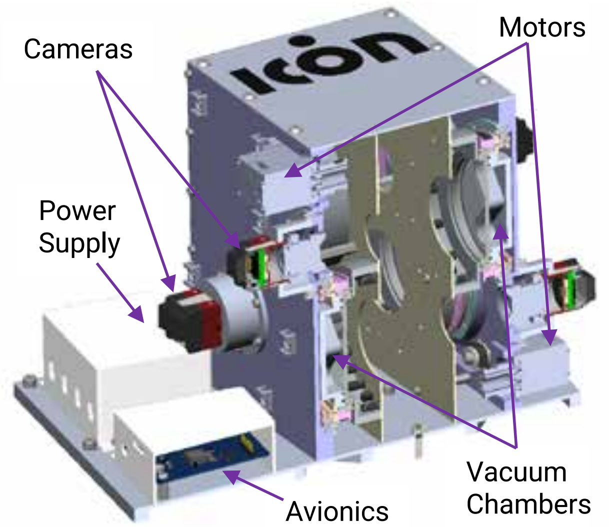
Introduction: Lunar soil, regolith [1], returned to Earth by the Apollo missions provides a glimpse of the construction material we must work with when humans return to the moon to stay. However, the basic principles of manipulation, conveyance [2], forming, packing, and solidifying regolith in the vacuum and minimal gravity afforded to lunar construction in situ remain fundamental unknowns over half a century later. For most of us, that means moon dust has been on Earth longer than we have and we still know very little of how to turn this material into a viable lunar construction material.

The Duneflow experiment aims to implement an array of mechatronic vacuum chambers which will drive the flow of lunar regolith, various terrestrial simulants, and one or more control samples from one side of an hourglass vessel to the other by manipulating the system relative to the gravity vector aboard a microgravity flight.



Mission: The experiment captures several comparative metrics for the flow dynamics of regolith and simulants including angle of repose as well as bulk density estimates through post-mission image and video analysis. This will narrow the gap in our understanding of how this material will respond to conventional approaches to conveyance, tune the gravity component in our present models of powder flow, shed light on the mechanical viability of our Earthly simulants, and in turn yield some perspective on potential new technologies for the manipulation of lunar soil as a building material.

Challenges: The logistics of acquiring and handling Apollo samples of lunar regolith may impair the mission's ability to provide a firm comparative basis for the various simulants. An experiment limited to direct comparison between simulants remains a viable endeavor. Launch vibrations will induce a packing and separation effect in the samples with an unknown impact on relevant mission data fidelity.



Design: The core of the design, relevant to the experiment, is the shape of the vacuum chamber and the calibration of the software and cameras to the induced gravity vector, and mission time components. The flow of material in each chamber is captured by independent machine vision cameras simultaneously read and recorded by the payload avionics system. The array of chambers, coupled mechanically in pairs of 3 to two motors, are observed by the cameras while the system is driven through varying position and velocity parameters.

Future: The teams at ICON and CSM are continuing to iterate on the optimal vessel design and motion strategies using a single cell prototype while building the first article qualifying unit between the submission of this abstract and the Nov. 2, 2022, LSIC meeting. The team intends to have the qualifying unit ready for testing in early November 2022 and remains ready to support a Spring 2023 flight opportunity.

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Fission surface power scalability for sustained lunar activity, B. T. Rearden, D. J. Rhodes, J. C. Kennedy, and A. J. Fallgren X Energy, LLC., 801 Thompson Ave., Rockville MD. 20852. (Contact: brad.rearden@x-energy.us)

X Energy, LLC (X-energy) presents its series of scaled design concepts for fission surface power (FSP). Three different scales are addressed (1-10 kWe, 10-100 kWe, and 100-1000 kWe), each with unique applications. The baseline concept, in the middle range, is a 40 kWe design presently being developed in a joint venture between Intuitive Machines and X-energy (IX), under NASA's FSP Phase 1 award. We open this presentation with an overview of the baseline design concept and enabling technologies (e.g. X-energy's proprietary TRISO-X fuel), and proceed to showcase two scaled adaptations.

The 40 kWe baseline is designed to support sustained robotic and human activity for 10+ years of autonomous operation. We discuss how this pilot FSP design project, and its follow on demonstration in Phase 2, will pave the way – in both the technical and regulatory sense – toward expanded nuclear power capabilities on the Moon and in space. The presentation addresses the planned site setup and application on the lunar surface, and touches into envisioned future integration into a lunar surface power grid. We also provide an overview of the supply chain developed for this effort, and the primary T/MRL challenges.

The downscaled system, in the 1-10 kWe range, supports most planned near term NASA activities, such as *survive the night* capabilities and exploration of permanently shadowed regions (PSRs). It applies to all upcoming uncrewed missions, as well as the early stage of upcoming crewed missions [1]. Its power system leverages well established design concepts proven by NASA's successful Kilopower experiment. At this scale of size, power and technological maturity, it is feasible to develop a generic "nuclear battery" that could be duplicated as needed to support a variety of near term lunar surface exploration missions. While the baseline design includes a limited degree of mobility (i.e. transferred from one site to another), this smaller unit could be integrated with a rover to travel across large distances, day or night, and facilitate prospecting for water and other volatiles, as well as potential structural material distributions in the lunar regolith. The compact structure also allows for easier launch under more mature lunar lander technology (e.g. Nova-C lander by Intuitive Machines). Lastly, we review the advantages of a controllable nuclear reactor system over the classic RTG approach, both of which compete for the ~1 kWe design space.

The upscaled system, 100-1000 kWe, supports long term lunar surface activity and in situ resource utilization (ISRU). These include power demand for a broad range of human civilization commodities for consumables, habitats, manufacturing and transportation [2]. The power demand for such pursuits is anticipated to grow exponentially in the coming decades [3]. At this scale launch and landing become unfeasible with today's space technology, and a higher degree of in-space or lunar surface assembly is required. We discuss some of the tradeoffs between a larger size reactor versus a fleet of smaller units, including usage of in-situ materials for site infrastructure and shielding.

This presentation will conclude with an overview of the unique capabilities of X-energy's R&D team. A verified and validated Multiphysics tool suite and its expert users enable rapid design prototyping for advanced nuclear systems. We discuss how these tools and related design processes support the fine balance between agile workflow and nuclear industry level quality (NQA-1). The high degree of computational fidelity allows X-energy to build confidence in the unprecedented level of autonomous operation in these first-of-a-kind space nuclear systems.

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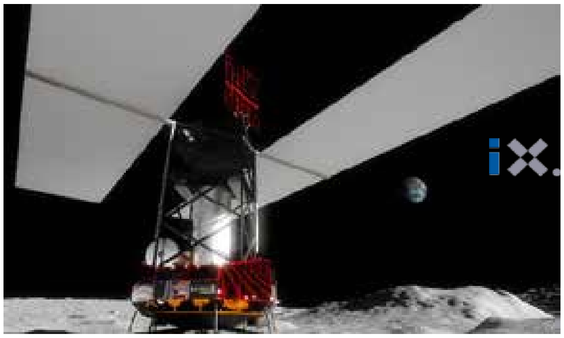

The Lunar Mobility Vehicle as a Key Enabler in the Cislunar Economy. R. M. Rickards, Lockheed Martin Space, 12257 S Wadsworth Blvd, Littleton, CO 80127. (Contact: Ross.M.Rickards@lmco.com)

Figure 1: The Lunar Mobility Vehicle

Introduction: On Earth, explorers of ages past could not conquer the vast expanse of the world's oceans without investment and development in vessels to ferry them over great distances. Similarly, the settlement of the western United States and the ensuing gold rush was first enabled by primitive roads and covered wagons and then the vast network of railways strewn across the country. Increased speed and mobility is a hallmark of any successful exploration campaign. This is especially true where goods and services ultimately flow back to the source of investment. The Moon will be no different and requires early investment in transportation to enable all things yet to come both on the lunar surface and in cislunar space. Lockheed Martin in partnership with General Motors is investing in a mobility solution capable of meeting the need for comprehensive exploration of the lunar surface and transportation of everything from surface samples to habitation modules.

Capabilities: The Lunar Mobility Vehicle (LMV) is the most capable rover designed to-date for use on another planetary body. Capable of speeds up to 20 kph and travelling for periods in excess of 8 hours, this vehicle will go further and faster than any of its predecessors. Further, the vehicle will be capable of autonomous driving, which means it can traverse the lunar surface safely without real-time mission operations oversight.

LMV can carry with it two human passengers in their xEMU suits as well as their tools and instruments, or it can carry a comparable amount of scientific payloads for resource characterization and cataloging. LMV is capable itself of surviving the full-duration lunar night, and it will also provide power and data services to enable payloads to do the same. LMV has a 4-DOF robotic arm capable of collecting samples or adding and removing payloads from the payload bed. With LMV's understanding of its precise location and its suite of on-board cameras, a robust set of mapping data with layers of information will be captured and telemetered back to Earth for commercial use.

Additionally, the chassis and core functionality are scalable and extensible. This means LMV can support a wide array of mission kits or grow to carry a habitation module. Some of the mission kits envisioned include a blade attached to the front of the vehicle for grading the lunar surface and a printintg head attached to the robotic arm to bind lunar regolith for roads or landing pads. The LMV is capable of supporting other infrastructure development as well, such as transporting or assembling power stations and running power cables.

Progress to-date: The LMV Team has already begun to make progress with the intention of arriving on the lunar surface in time to support Artemis III. One of the great enablers of progress has been the collaboration between several partners that are industry leaders in their respective areas of expertise. For example, Goodyear is responsible for developing the vehicle's tires, and has made great strides in developing a modern design and material suitable for our targeted environment and operational life. MDA is developing the robotic manipulator, and is taking advantage of their space heritage to inform the development of an arm with the right reach, packaging, and capabilities to support the mission use cases. General Motors is bringing their history of automotive experience as well as new gains in the electric vehicle market to support core mobility functionality, key aspects of the electrical system, and autonomous driving. Lockheed Martin is developing the rest of the system and is contributing systems integration support, as well as cutting edge composite manufacturing experience from Orion, and a history of landing spacecraft successfully on other planetary bodies.

Lockheed Martin is committed to helping build the infrastructure required to realize a cis-lunar economy that will relieve burdens on Earth, inspire future generations, and enable the human leap to a multi-planetary species. The LMV coupled with Lockheed Martin's Parsec lunar communication and navigation services enable customer opportunities never before realizable. To that end, the team has been developing universal interfaces to connect with other external systems on the lunar surface and refining frequencies and bandwidth allocations for cislunar communications traffic.

Radiation Protection by Varied Densities of Lunar Regolith

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In anticipation for future, long duration lunar civilizations, a study of radiation shielding using lunar regolith is presented in this paper. With a future focused on Moon and Mars exploration and long-term sustainability, protective habitats will need to be designed. However, cost efficiency is a huge concern. As the moon is 238,900 miles from the Earth, shipping housing infrastructure from the earth to the moon will be an expensive endeavor. Fortunately, the usage of lunar regolith has become a popular alternative for the building process and radiation protection. For long term missions on the moon, radiation exposure is the largest concern for an astronaut's health. Currently, NASA has a 30-day exposure limit of 250 mSv for astronauts [1]. On the moon, future NASA missions require to stay under 150 mSv for a six-month mission [1]. To meet this requirement, this paper studies different densities of compacted regolith with several ratios of additives. The additives investigated are powdered polyethylene and powdered lithium hydride. The samples were tested against different types of radiation on the moon to include Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR). Analytical simulations using NASA's OLTARIS tool effectively indicate the radiation dosage that is both shielded and transmitted through the lunar regolith samples. The OLTARIS tool postulates that SPEs penetrate less with the additive of polyethylene. GCRs penetrate less with the additive of lithium hydride. Both radiation sources penetrate less when the samples are layered with the 50:50 ratio. Unexpectedly, OLTARIS concluded that as density increased, dose exposure stayed constant. For further investigation, the numerical simulations were physically constructed using a lunar regolith simulant mixed with either powdered polyethylene or powdered lithium hydride. The permutations of the experiment design were tested at Kirtland Air Force Base's Cobalt-60 radiation lab. The results indicate that with a constant thickness, density does make a difference in radiation protection. With an incremental increase in vibration amplitude (method for acquiring a certain density), the dose rate decreased. This illustrates vividly how compacting regolith is an effective technique for dose reductions given constant thickness [1]. Furthermore, the study underscored the significance of material homogeneity on radiation dissipation capacity of the compacted regolith simulants. The results however showed negligible influence of selected additives on the attenuation of the radiation. A plausible explanation could be attributed to the nonhomogeneous nature of the regolith simulants mixtures containing granulated additives. The best dose rate was obtained using a two-inch block of polyethylene and a 2.5 inch sample of lunar regolith. This sample significantly outperformed other permutations of the experiment matrix in terms of dose rate. Therefore, the authors concluded that systematic layering of the additives results in superior dissipation performance compared to samples with dispersed mixture of granulated additives. Concerning the lithium hydride, it was concluded that the ratio was too small to make a significant difference. However, this was nothing to lose sleep over after discovering that lithium hydride is a very toxic chemical that should not meet water let alone be aboard a rocket during space travel. After months of testing, it has been concluded that the best infrastructure to reduce radiation to astronauts on the moon would be a layered infrastructure including compacted lunar regolith with an added layer of polyethylene. As to how thick these layers should be is for future investigation.

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Disclaimer:

E-Powered Micro Vehicles™ for use on Moon/Mars xEVA's.

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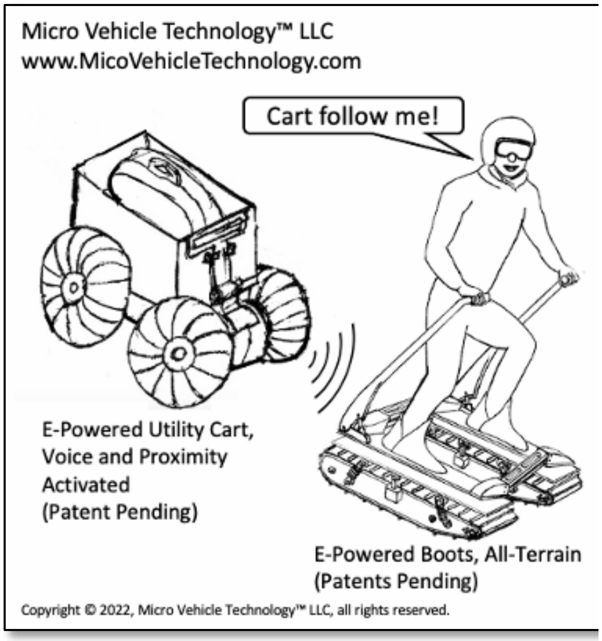
Introduction: Micro Vehicle Technology™ LLC is developing the astronaut's "Go-To" mobility vehicles for human and equipment transport on the Moon and Mars. E-Powered Boots followed by an E-Powered Hands-Free Utility Cart, will prove to be an obvious choice for getting around, instead of, or in addition to, walking or driving a large 4-wheeled multi person lunar buggy. "Consider Ants. Ants convoy. They don't carpool."

Micro Vehicle Technology™ LLC is seeking patent licensee and manufacturing partners to help develop and tailor Micro Vehicles™ to NASA's Artemis xEVA ConOps, as well as other SBIR/STTR topics of need.

The Innovation:

What are Powered Boots? As electric motors, batteries, and electronics become smaller, lighter in weight, and more power dense, it becomes possible to package these components compactly within an envelope essentially the size of a pair of boots. For stability and safety, the pair of boots includes a four-bar linkage connecting chassis and handlebars that allow carving through turns. The result is an easy to learn, yet rugged multi-terrain Micro Vehicle™.[1]

What is an E-Powered Hands-Free Utility Cart? The E-Powered Hands-Free Utility Cart follows a person by voice commands and proximity sensing. The E-Powered Hands-Free Utility Cart includes a standard base with propulsion and control unit, and a quickly changeable carrying bin for the many different uses that will be realized.[2]



Benefits of Micro Vehicles: How do Micro Vehicles compare with the state of the art?

- Launch weight may be much less for multiple personal Micro Vehicles™ compared to a single multi-passenger rover.
- Multiple personal Micro Vehicles™ may be easier to package, distribute weight, and subsequently deploy from a surface lander or cargo vehicle compared to a single multi-passenger rover.
- Powered Boots Micro Vehicles™ reduce the need for astronauts to walk and sit, thus mitigate health and constricted spacesuit concerns.
- Use of Powered Boots Micro Vehicles™ will cut out much time from the already planned Artemis III xEVA Con Ops walking range or may allow additional activity and greater exploration distances than currently planned.
- Multi-passenger rovers can be equipped with Micro Vehicles™, therefore, in case of rover failure, mitigate a lengthy and physically exhausting walk back scenario.
- With each astronaut using their own personal Micro Vehicle™ like ants, surface travel routes, colonization, and operations can be expedited and optimized for efficiency and fault tolerance.

[1] Rudofsky K.M. (2021) *United States Patent and Trademark Office, Application No. 17238202 - Powered Boots*

[2] Rudofsky K.M. (2021) *United States Patent and Trademark Office, Application No. 17241060 Utility Cart, Electric Powered, Voice and Proximity Activated.*

Wireless Power Transfer as a Dust Mitigation Solution for Mobile Surface Assets. J. D. Schapiro[1] and S. M. Garman[2], [1]Astrobotic Technology, Pittsburgh, PA, [2]Department of Electrical & Computer Engineering, University of Washington, Seattle, WA. (Contact: joshua.schapiro@astrobotic.com)

Introduction: Astrobotic recommends the inclusion of magnetic resonance based wireless chargers as a viable option for dust mitigation in the field of lunar excavation and construction. Certain lunar activities are inherently prone to dust intrusion and accumulation. Using traditional solar panels to charge these assets may be extremely inefficient at best, and in many applications completely impractical. Furthermore, charging with physical connectors is challenging due to dust intrusion and limited dexterity of glove-encumbered astronauts. By installing a wireless charger to a rover, it may dock to a stationary lander or other power source and recharge even with an accumulation of lunar dust coating the power transfer coils.

Technology: The wireless charger is comprised of two smaller systems. The transmitter system is integrated with a host asset and transmits power to the onboard charger system which is integrated with the rover or surface asset. Each system has a small avionics enclosure as well as a coil for transferring the energy. While the avionics are most sensitive to extreme temperatures, the transmitter and receiver coils are designed to be completely exposed and can operate from -200 to 175C without a decrease of efficiency or failure [2].

The current wireless charger can sustain charging rates of 400W, which is suitable for mid to large range battery powered vehicles. Being based on magnetic resonance allows these systems to achieve an end-to-end transfer efficiency up to 85%. They also have effectively operated through tests in the presence of various lunar regolith simulants and temperature conditions simulating lunar night [1, 2]. With the use of rovers and teleoperated robotic systems, it is imperative the system be forgiving with respect to alignment while charging. Magnetic resonance technology is much more tolerant to misalignment and offset compared to the traditional counterpart of inductive charging.

Demonstration: One development initiative that NASA and others are pursuing is regolith excavation. For the purpose of In-Situ Resource Utilization (ISRU), they hope to extract resources to create things such as building materials, propellants and breathable air [3]. One such development is the Regolith Advanced Surface System Operations Robot (RASSOR) excavator, designed and built by the Kennedy Space Center (KSC).

Astrobotic and WiBotic have worked with KSC to demonstrate the effectiveness of the charger in an assortment of design reference mission scenarios. After quickly integrating a commercial grade system onto RASSOR, power transfer was easily demonstrated. The KSC team successfully demonstrated the effectiveness of the wireless charger system in the presence of 8 different lunar regolith simulants.

It should be noted that most simulants, including those tested here, have no iron content, though lunar regolith is known to contain iron. Subsequent tests using pure iron powders were conducted and shown to have minimal impact to efficiency [1]. Future work includes collaboration with manufacturers to develop simulants to more accurately represent electromagnetic properties of lunar regolith.

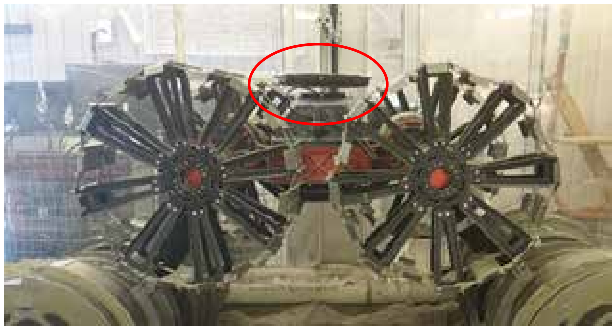


Figure 1. RASSOR charging demonstrations performed at KSC's Granular Mechanics and Regolith Operations (GMRO) Lab. Charger is highlighted with red circle.

Acknowledgments: This work was conducted as part of NASA's Tipping Point and SBIR programs in partnership with Bosch Research, WiBotic, Inc., NASA Glenn Research Center, and Kennedy Space Center. 80LARC21CA001. 80NSSC20C0345.

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Application of Cold-Welding for Construction of Lunar Base Camp Infrastructure. M. B. Sefer[1] and J. W. Sowards[2], [1]Iowa State University, 537 Bissell Rd, Ames, IA 50011, [2]NASA Marshall Space Flight Center, Huntsville, AL, 35812. (Contact: sefer@iastate.edu)

Introduction: With the large involvement of private companies and NASA's flagship space mission Artemis, the space industry has focused on habitats supporting sustainable human existence in space and on celestial bodies rather than sample return missions. Among the reasons for this are the experience gained on the International Space Station and the fact that private companies have gained the capacity to perform advanced manned space missions. These advanced space missions include the Artemis Base Camp planned by NASA's Artemis mission, SpaceX's Mars program, and large space station projects for space tourism. With the upcoming Artemis missions, the Artemis Base Camp can be the first habitat we can see on a celestial body in outer space. These large habitats have to be assembled on the surface, as the internal volume of the launch systems limits the size of these structures. [1] Unlike robotic systems, such habitats require airtight seals. Strength of bonds, accessibility of necessary equipment, and safety are important factors in determining the space construction method for these habitations.

Existing Methods: Welding, fastener-based assembly techniques, and docking systems are examples of existing in-space construction technologies. Docking systems constrain the size of the interior channel between the two structures. They are required for spacecraft that must detach but are unnecessary complications for building permanent lunar habitats. Fastener-based assembly techniques call for the painstaking assembly of several individual parts in a harsh space environment to establish the hermetic level seal necessary for livable chambers. [2] Building large structures with fastener-based methods by astronauts can be time-consuming and increase extravehicular activities. Welding is a more approachable method for in-space construction applications in terms of joint strength, simplicity, and adaptability. The most advantageous benefit of in-space welding is that it naturally addresses the hermetic sealing problem better than mechanical joints. [2] While welding makes it simple to produce joint hermeticity at zero or negligible mass, mechanical joints struggle with increased joint mass as they need fasteners and gaskets to achieve the required hermeticity. [2] However, current hot-work techniques require extra effort as they demand additional equipment, power sources and involve risky labor. [3] The industry must address hot-welding techniques' drawbacks and safety issues before deploying them on a lunar base.

Proposed Method: Cold welding is proposed as an alternative way of joining structures on the lunar surface to overcome these limitations and increase the bond's simplicity, integrity, and strength. Unlike other welding techniques, cold welding does not require large equipment and does not possess notable safety concerns since it does not require heat to join.

Image 1. Cold-welding test specimen before the coating is applied on the surface

Pre-designated joint surfaces of structures can be prepared for cold-welding by applying additional coating on Earth using oxygen-free environments and vacuum systems. After the surface is prepared, a protective shielding layer can be applied. Once the components have been launched to the lunar surface, the shielding layer can be removed, and two pre-designated joint surfaces can be brought together. At that point, two surfaces will start diffusing together. If the proposed technology is used effectively, it can make in-situ space construction and assembly on the Moon easier and safer than ever. Current work by Space Construction Technologies, a former L'SPACE team of research students across the country, is focused on developing a laboratory approach to study cold welding. The approach includes surface preparation in the inert gas glovebox, deformation, and testing of various materials in a vacuum chamber. Existing in-space welding methods and the methodology used for cold welding will be presented.

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LSIC Technical Focus Area: Surface Power

Overview of Silicon Carbide Power Devices for Lunar Surface Power Applications

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Introduction: NASA's Artemis Program aims to set up a Base Camp at the Shackleton Crater on the moon which will include a modern lunar cabin, a rover and even a mobile home. However, setting up such an infrastructure on the lunar surface has a major challenge in the form of generation, storage, and distribution of power [1]. Silicon (Si) power devices, which are used for power conversion and control in older generation spacecrafts, will not be ideal to meet the power requirements for lunar surface exploration due to their material limitations. Silicon Carbide (SiC) makes a desirable candidate choice for such high density and high-efficiency power electronics in the medium DC voltage range because of its favorable material properties such as wide band-gap, higher breakdown voltage, lower intrinsic carrier concentration, and better thermal conductivity, as shown in Fig. 1 [2]. Various SiC vertical and lateral, discrete, or integrable device structures have been fabricated and investigated for more than two decades now for terrestrial applications and a wide range of such devices are available commercially now [3].

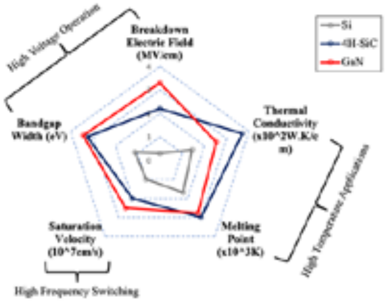

Fig. 1. Summary of Si, SiC, and GaN material properties, after [2]

Reliability Concerns for Silicon Carbide Power Devices: Commercial-off-the-shelf (COTS) SiC devices may be susceptible to parametric degradation or catastrophic damage caused by the passage of a single energetic ion through a sensitive device region. The catastrophic damage mechanisms include Single-Event Burnout (SEB) and Single-Event Gate Rupture (SEGR). In a commercial 1200V device, SEB is observed at about 40% of the rated voltage [3,4]. On top of that, Single-Event Leakage Current (SELC) induced degradation is observed even below the SEB threshold, as shown in Fig. 2, which is also not desirable in lunar missions [5].

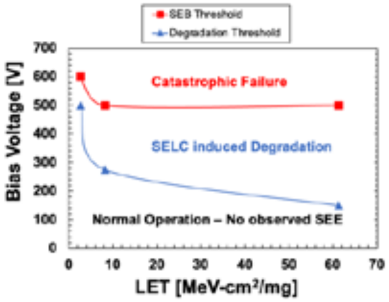

Fig. 2. SEB and SELC induced degradation thresholds observed for 1200 V rated devices, tested at TAMU Cyclotron Institute

Considerations for Lunar Surface Power Applications: Radiation hardness assurance of SiC devices for Lunar surface application should consider heavy ion induced permanent degradation effects, in addition to catastrophic SEB and SEGR. Latent gate damage and SELC are cumulative and depend upon both the device bias condition and the properties of the ions striking the device [6]. SELC can be experimentally determined by the same heavy-ion irradiation testing as SEB. A joint effort by NASA, Vanderbilt, and General Electric is in place to characterize the SEE response of existing GE 3.3 kV SiC power devices with respect to ion energy and off state bias, and the design of new devices that are intended to be SEB-immune, but also preserve most of the desirable electrical characteristics of SiC devices. The project is part of the NASA Lunar Surface Technology and Research (LuSTR) program, launched in 2021, to close technology gaps that hinder the exploration and development of the moon, and to support the development of high-voltage, high-power power systems such as micro-grids, highly capable rovers, and human habitation and transport systems in the lunar environment.

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[5] C. Martinella et al., (2019) *IEEE TNS.*
[6] J.M. Lauenstein *et al.*, (*2021) IEEE IRPS.*

Removal of lunar regolith simulants from Electrodynamic Dust Shield devices with chemically modified reduced graphene oxide electrodes.

K. G. Sjolund[1], M. J. Schaible[1], E. A. Ryan[1], M. L. Shofner[1], J. R. Reynolds[1], T. M. Orlando[1], and J. S. Linsey[1], [1]Georgia Institute of Technology, 901 Atlantic Dr., Atlanta GA 30332. (Contact: julie.linsey@me.gatech.edu)

Introduction: For manned missions on the lunar surface to be sustainable, dust mitigation techniques must be developed to maintain desired performance levels for spacesuits and protect delicate surfaces exposed to the lunar environment. Electrodynamic Dust Shielding (EDS) has been shown to be an effective tool to actively repel lunar regolith [1]. However, further developments are required to apply EDS to flexible surfaces and for use with spacesuits. This work documents ongoing effort by members of the SSERVI REVEALS team at Georgia Institute of Technology to develop an effective EDS device using chemically modified reduced graphene oxide (CMrGO) embedded into the surface of thermoplastics, thereby creating a flexible dust mitigation surface. These systems have also shown that photoelectric charging of particles using UV radiation allows for the EDS system to adequately clean surfaces at lower voltages.

EDS systems using Chemically Modified reduced Graphene Oxide: The SSERVI REVEALS team at Georgia Institute of Technology developed CMrGO to serve as a conductor that could be implemented for space applications [2,3]. Its primary advantage over other conductive materials is the ability to be embedded or laminated into thermoplastics and withstand significant deformation while still maintaining its conductivity [4]. Implementation of this material system within an EDS system demonstrates a novel application for CMrGO nanocomposites as well as an expansion of the materials palette that can be used for EDS systems. Figure 1 shows a two-phase CMrGO based EDS system before and after cleaning.

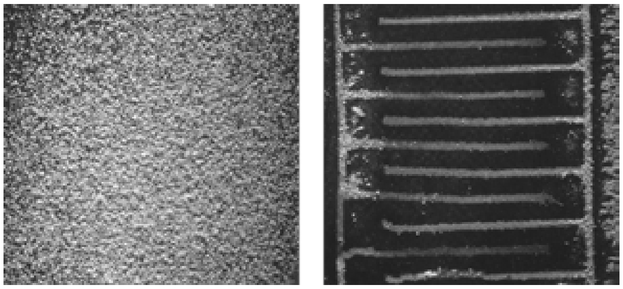

Figure 1: (left) An EDS sample covered with LHS-1 lunar simulant. (right) the same sample after cleaning. A 10 Hz square wave with 1000 Volts peak-to-peak was used.

UV Photoelectric charging to improve EDS: Dust mitigation through UV exposure has been documented to be possible [5] but has only been researched as a standalone technology. By combining UV and EDS, significant improvements in necessary voltage for operation are observed, as seen in Figure 2. The most important result is that UV exposure produced high levels of cleanliness at half the voltage required for cases where only EDS was used. The processing of the data from this experiment is currently ongoing with refinements being made to the method. Further experiments are to be conducted with three-phase EDS systems using CMrGO to determine if further system improvements are possible.

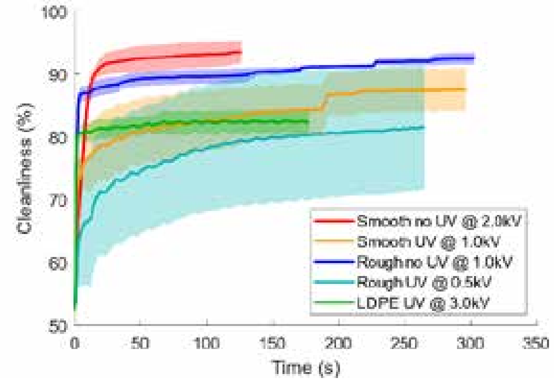

Figure 2: Time versus cleanliness plots for EDS samples under different conditions. Rough and Smooth refer to the surface finish of the CMrGO. The LDPE case had a thin layer of LDPE over the exposed CMrGO.

Acknowledgements:

This work was directly supported by the NASA Solar System Exploration Research Virtual Institute (SSERVI) under Cooperative Agreement #NNA17BF68A (REVEALS). It was also a part of the 2021 NASA's BIG Idea Challenge as a part of team Shoot for the Moon from Georgia Institute of Technology.

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TAKING FRICTION OUT OF THE ISRU VALUE CHAIN: SPACE KINETIC'S NOVEL SYSTEM FOR LUNAR LOGISTICS, S.J. Ziegler, R.S. Sullivan, Space Kinetic Corporation, 3720 Sundale Rd., Lafayette CA 94549. (Contact: ryansullivan@spacekinetic.com).

Introduction: Private sector standard-bearers, government agencies, and thought leaders in the space development field have cohered around the importance of the lunar ISRU value chain for both deep space exploration and economic development. As such, PwC predicts that the lunar ISRU economy will be worth $63 billion by 2040 [1]. To capture this market, startups and established players around the world are developing novel technologies for excavating and refining lunar regolith. These developments are exciting and worth commending.

However, relatively little attention has been paid to the surface logistics sector. To date, many transportation architectures for the lunar surface rely exclusively on rovers. Rovers are rugged and well-adapted for short-range transportation on the Moon. They will undoubtedly play a vital role in sustaining operations and providing last-mile delivery on the lunar surface. However, they are not optimized for the long-haul logistics services required to kickstart the ISRU economy, especially when factoring in the harsh terrain associated with lunar permanently shadowed regions.

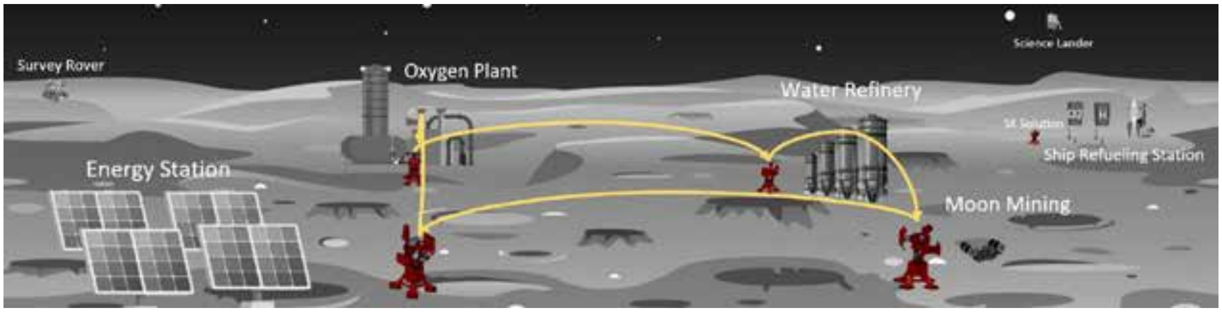
Against this backdrop, Space Kinetic has developed a novel logistics system to efficiently transport material resources across the lunar surface. Ultimately, our distribution network will complement rover-based architectures by seamlessly connecting far-reaching operating sites.

Technology Description: Our system launches and receives payloads through an electrical actuation system. Each launcher/receiver module in our network is equipped with a robotic arm, which launches capsules containing resources (e.g. regolith, propellant, metal, spare parts, etc.) on a predetermined ballistic flight trajectory toward a receiving module. After the receiving module catches inbound capsules, they are released via an automatic unloading system. Our system is payload-agnostic and can load, transfer, and unload the inputs and finished products that will sustain the ISRU value chain.

System Capabilities: Our distribution system has an 80-kilometer point-to-point range and a throughput rate of 150 kilograms of materials per hour. By deploying a relay system of launcher/receiver modules, we can extend our logistics chain indefinitely. Furthermore, our system is lightweight (each module will weigh 150 kilograms), reducing lift costs and making the movement of resources on the lunar surface affordable for more participants.

Conclusion: Our technology will support more efficient ISRU production and manufacturing on the lunar surface. By facilitating seamless long-range logistics services between upstream and midstream operations, Space Kinetic can enable a more cost-effective, centralized industrialization architecture. Furthermore, using our system will reduce wear-and-tear for rovers on the lunar surface, extending operating timelines and decreasing costs for our partners. Ultimately, our technology can also support surface-to-orbit transfers, further reducing the costs associated with accessing ISRU resources in cislunar space.

References: [1] Scatteia, L., & Perrot, Y. (2021). Lunar market assessment: market trends and challenges in the development of a lunar economy. PwC Space, 30–31.



Dust Tolerant Connector (DTC). J. Herman, M. Maksymuk, L. Carlson, C. Santoro, P. Fink, H. Williams, K.F. Bywaters, M. Szczesiak, Honeybee Robotics Spacecraft Mechanisms Corporation, 2408 Lincoln Avenue Altadena, CA 91001. (Contact: hjwilliams@honeybeerobotics.com)

Introduction: DTC (Dust Tolerant Connector) is a reusable, electro-mechanical connector designed to carry power and signal and be both resistant and tolerant to the presence of lunar regolith.

Lunar dust is a significant challenge for ISRU (In Situ Resource Utilization) and future exploration missions. Following the Apollo 16 mission, mission commander John Young commented that “Dust is the number one concern in returning to the moon.” In addition to posing contamination and health risks for human explorers, the interlocking, angular nature of lunar dust and its grain size distribution make it detrimental to any mechanisms with which it comes into contact. All Apollo Lunar missions experienced some equipment failure due to dust, including electrical/data connector failure in the tool changer mechanism on the Apollo 17 drilling tool.

To address these problems for future Lunar missions of all types, DTC was designed as a highly scalable, dust tolerant, data and electrical connector. The connector comes in two variants: manual version, suitable for astronaut operation, and a mechanized version for robotic coupling **(Figure 1)**.

Figure 1: Manual, left, and mechanized, right, versions of the Dust Tolerant Connector.

The connectors use a preloaded membrane capable of performing under dust choked conditions to remove dust on the surface of male pins. The pins extend, penetrate the self-healing membrane on both sides, and mate with the corresponding sockets on the female connector. The dust is trapped and remains between the two membranes. The connectors integrate cone-like centering and keying features guaranteeing fine alignment and kinematic coupling. Moreover, the mechanized version of the connector comes with gross alignment features. The alignment cones support ±10° angular and radial, as well as ±0.75 cm radial misalignment during mating. The mechanical connection is provided by three finger-like features which latch onto the female side ensuring locking and preload.

Testing and Demonstration: Both versions of the connector were tested in a vacuum chamber between 10-5 and 10-6 mbar at room temperature **(Figure 2)**. Before testing began, JSC-1AF lunar simulant was baked out at >100° C for 24 hours and plasma cleaned in the vacuum chamber for 1.5 hours. This was done to clean the surface of the simulant and increase its adhesion and cohesion effects. Over 100 mate/de-mate cycles at high vacuum were completed, covering both sides of the connectors with approximately half a tablespoon of simulant every five cycles. The connector successfully mated every time, and no major degradation in the electrical resistance of the pins was recorded.

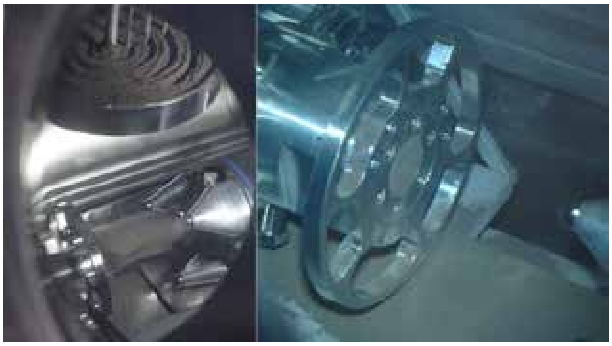


Figure 2: DTC vacuum testing in the presence of JSC-1AF lunar simulant. Left, DTC and the regolith dispenser before the test. Right, dust covered female side of the connector during testing.

The design specification document for the DTC has been publicly released under the Creative Commons Attribution-NoDerivatives 4.0 International License. A new version of the connector, specifically designed to meet the power requirements of the LAMPS (Lunar Array Mast and Power System), is currently being developed.

Acknowledgements: The research and the development of the DTC was done under the SBIR (Small Business Innovation Research) Contract No. NNX09CA50C, NNX09CE51P, and NNX10CB09C.

Observations of Working with Lunar Simulant in a Dusty Thermal Vacuum Chamber. P.J. van Susante[1], [1]Michigan Technological University, 1400 Townsend Dr., Houghton, MI, 49931. (Contact: pjvansus@mtu.edu)

Introduction: Going back to the lunar surface will mean operating daily in the lunar environment and interacting constantly with the lunar regolith. To simulate this on Earth, tests are being done with lunar regolith simulants from various producers and under varying levels of relevant environments. Test under ambient pressure and temperature, tests in (dusty) (thermal) vacuum chambers are all used to test various aspects of lunar operations and processes. At Michigan Technological University (MTU) we have been testing and comparing thermal and flow behaviors of lunar regolith simulant under ambient pressure and temperature conditions and under vacuum conditions.

Test purpose: Lunar regolith excavation, transportation for In-Situ Resource Utilization (ISRU), construction and ice extraction are major short term goals for lunar activities. MTU's Planetary Surface Technology Development Lab (PSTDL) is developing regolith compaction, (icy) regolith excavation, regolith construction, regolith transfer mechanisms and testing durability and behavior of these systems in atmosphere and vacuum conditions. We have observed some key differences in behavior that need to be better understood to properly design hardware that will function well. The main concern is trapped air in the lunar simulant after vacuum levels are achieved, affecting various behaviors thought to be under vacuum, but due to trapped air behave differently.

Observations and effects: Depending on the test that is run, the effect varies from minimal to very different behavior:

Regolith storage hopper flow testing

During testing of regolith storage hoppers in vacuum conditions, it was found that air was trapped in the pre-compacted regolith inside the hopper and when the hatch was opened to allow the regolith flow to start the whole hopper emptied in a second or two being blown out by the trapped air which suddenly had a way out. This made any flow study meaningless in a vacuum chamber if air was trapped.

Thermal testing

During thermal testing of (icy) regolith it was observed that a liquid phase change occurred while the chamber pressure was below the triple point which indicates that inside the regolith grain structure a higher pressure was present which allowed ice to melt instead of sublime. This complicates the study of icy regolith extraction etc. since the thermal composite properties of the icy regolith are different with air trapped than without as well as allowing a phase change to occur that would not occur when no air would be present.

Compaction

For construction purposes, a location covered in loose regolith, craters and rocks would need to undergo site-prep before any construction could take place. When moving regolith around in atmospheric conditions, air gets trapped and the granular material behaves almost like a fluid in some cases. In addition, in vacuum the trapped air would be released when disturbing the equilibrium in the regolith layers, complicating the study of the forces and behavior of tools in construction or excavation/mining. Vibratory compaction sometimes allows this trapped air to escape and results in rearranged particles as expected during compaction. In vacuum conditions, the vibration allows a path for the deeper trapped air to escape but it can lead to blowouts.

Large test bed preparation

The trapped air complicates large test bed prep for vacuum use since it is difficult to vibrate the entire bed to allow air to escape. This can get even harder when ice cemented regolith is used that can trap air in a regolith/ice matrix which would be trapped unless the matrix would be broken and an air escape path would be created. This affects the final mechanical properties of the test bed and thus any excavation force or other measurements.

Possible Mitigation measures: To avoid the trapped air situation during vacuum testing, we have created a two-step process where the regolith simulant is stored on slanted trays or in a large screw conveyor. After/during the vacuum pulling of the chamber, the tray is vibrated to move the regolith simulant to the actual test setup. The vibration eliminates the trapped air and the regolith deposited into the actual test setup without air present. Then the test setup needs to be vibrated to achieve any desired compaction of the regolith in the test setup. A similar process can be used for icy regolith, but this cannot be applied to ice-cemented regolith since it would break the cementation or if the water would be liquid it would sublime away resulting in much lower ice content than intended.

DESIGNING THE BORON DISTRIBUTION IN POLYETHYLENE COMPOSITES TO OPTIMIZE SHIELDING OF LUNAR NEUTRONS

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Recently, there has been an interest in integrating boron-based materials into critical radiation shielding and sensing components for space applications [1,2].The isotope ^{10}B (19% of natural boron) has a large capture cross section for thermal neutrons, converting them into alphas and lithium ions, which are stopped within a few microns of material. With high density polyethylene (HDPE) as a thermalization medium and hexagonal boron nitride (hBN) as a capture medium, we aim to maximize shielding effectiveness by optimizing the boron distribution within polyethylene composites using Monte Carlo (MC) simulations, specifically Geant4. The shielding materials are optimized for the distribution of neutrons near the Moon's surface, which are ubiquitous due to interactions of high-energy galactic cosmic radiation with the Lunar regolith.

For both personal shielding and habitats on the Moon or beyond, mass is a critical consideration due to the high cost of transporting materials and the limitations of in-situ resource utilization. In the design of shielding solutions, it is worth considering the detailed distribution of elements within the shield, to optimize its effectiveness for minimal mass. We study a range of shielding thicknesses (mass/area), in order to include solutions that could be incorporated into radiation shielding for a variety of space applications, from spacesuits to Lunar habitats. These polymer materials also would be well-suited for additive manufacturing, which is proposed to be a central tool for construction on the Moon [3].

Fig. 1 shows the effective dose per fluence, which is used as a figure of merit (smaller values mean better shielding), as a function of the mass per unit area. We explore three configurations for the distribution of boron within HDPE: (1) a blend of HDPE and h^{10}BN (blended, yellow), (2) HDPE layered with pure h^{10}BN (ideal layered, green), and (3) HDPE layered with a blend of HDPE and h^{10}BN (manufacturable, purple). From the simulations, our main finding and prediction is that multiple millimeter-thick layers of HDPE and hBN provide better shielding than a homogenous blend, **improving shielding effectiveness by 4x to 30x over Al and 1.5x to 2x over HDPE,** which would significantly reduce the radiation exposure that astronauts receive for a mission to the Moon. We also observe an interesting feature: the ideal layered and manufacturable configurations have a cross-over where the optimal shielding changes from being trilayer to multilayer. In this presentation, we present a detailed overview of the Geant4 results of optimal boron distribution within polyethylene composites.

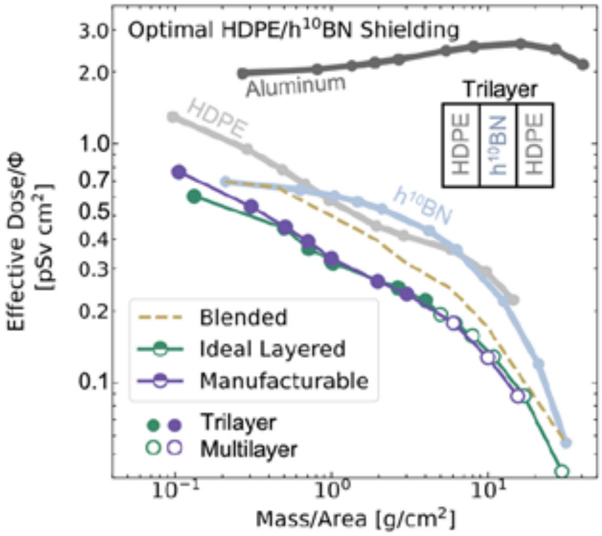

FIG 1. Effective dose per fluence (pSv cm^2) as mass per area (g/cm^2) for the optimal configurations of HDPE/h^{10}BN composites.

Acknowledgements: This work was supported by the NASA Solar System Exploration Research Virtual Institute cooperative agreement number NNA17BF68A and by NASA grant 80NSSC21M0271, a cooperative agreement with Marshall Space Flight Center.

References: [1] Maity, A., et al. (2016), Appl. Phys. Lett. 109, 072101. [2] Shang, Y., et al. (2020), Compo. Commun. 19, 147-153. [3] Clinton, R. G., et al. (2021), ASCEND 2021, 4072.

Solar-Melted and Printed Regolith Glass for Lunar Landing Pad (LLP) Construction.

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Introduction: Under NASA SBIR funding, the auhors have investigated a new and versatile method for the additive manufacture (AM) of structures *in situ* on the moon from locally available lunar regolith. The concept takes advantage of recent technology developments in the form of (1) concentrated solar power at intensities designed to melt regolith, and (2) additive manufacturing (AM) (printing) with metal oxide (glassy) materials. In this method, lunar regolith is solar-heated by the Molten Regolith Printing (MRP) system to its melting point (~1450–1700°C), and then extruded continuously (and onto previous layers) to form arbitrary structures of programmed shapes. The method aims for highest efficiency *in situ* resource utilization (ISRU) in both power and materials.

Modeling and experimental efforts performed in this project were aimed at bounding the flow rate, power requirements, and annealing requirements to help deduce an optimized approach. A pivotal question centers around whether it is more advantageous to produce a single monolithic structure or to construct the landing pad out of modular elements. The subtleties of fabricating with a glass (or more challenging still, a glassy material with a tendency to crystallize) dictate that good temperature control is wanted over the cooling process after extrusion (during forming), as well as the subsequent period of relaxation to ambient temperature. The first step (quenching) wants to be quick enough to avoid crystallization (weak spots in the glass matrix), while the second step (annealing) wants to be long enough at a temperature above the glass transition temperature to relax internal stresses left by temperature gradients through the material during forming. These factors dictate that a mobile glass-deposition approach is impractical for robust materials. We conclude that the logical strategy is to build from pavers.

Based on the modular build approach, it will be most effective to keep the manufacturing system static at a building site or located at a lunar industrial center and that regolith glass components will robotically be transported and assembled to create the LLP superstructure. Continuous production of pavers can be matched with continuous annealing and removal of pavers, no matter what anneal parameters settle out as optimal. General scale assumptions for the regolith glass printer are on the order of a 5kg/hr production rate, requiring ~10kW solar power. The key risk associated with creating a modular (paver-like) landing pad is the added challenge of joinery. Paver connection by a (mobile) regolith glass 'welder' could be an important accessory for many lunar structures. A bonding approach with melted regolith is to be investigated in future work. **Figure 1** illustrates the system concept.

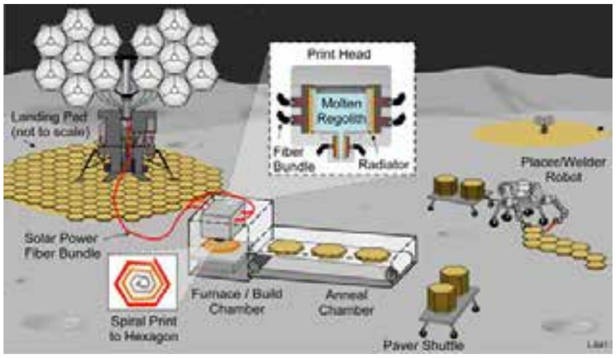

Figure 1. Solar thermal melted regolith printer (MRP) concept.

Technical Development: Investigative efforts in the project focused on both: 1) full-physics modeling of the melt and flow process of regolith through the fabricator machine; and 2) experimental efforts aimed at demonstrating the utility of AM with this challenging material as well as the molten and solid properties of the regolith glass. To this end, **Figure 2** illustrates a demonstration printed 'donut' shape with melted regolith simulant, while flexural tests on regolith glass rod samples illustrate that the material is quite robust, with an approximate elastic modulus of 85GPa.

Figure 2. Image captured from a video of a circular 2.5D print with LHS-1 regolith simulant.

Thermal, chemical, and mineralogical properties of lunar simulants.

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Introduction: High-temperature processing techniques for construction using lunar regolith are developed using simulants that vary in their chemical and mineralogical properties. Lunar regolith also varies in composition, most notably between basaltic mare and anorthositic highlands terranes, but with additional complexities due to regional-scale internal chemical anomalies (e.g. the Th-rich Procellarum-KREEP terrane) and lateral mixing via impacts. We previously studied the melting behavior of mixtures of JSC-1A basalt and Stillwater anorthosite [1]. Here we characterize the properties of several mare (JSC-1A, JSC-2A, OPRL2NT, LMS-1, LMT-1, LCATS-1) and highland (CSM-LHT-1, LHS-1, NU-LHT-2M, NU-LHT-5M, Stillwater norite, Stillwater anorthosite, Shawmere anorthosite and agglutinate-LHT) simulants, to assess their variability as a function of chemical and mineralogical composition over a much wider range.

Methods: Samples were characterized using X-Ray Diffraction (XRD) for mineralogy, X-ray Fluorescence (XRF) for chemical composition, helium pycnometry for density, and Differential Scanning Calorimetry (DSC) for heat capacity and enthalpy of fusion.

Results: Most simulants contain a combination of plagioclase, olivine, and pyroxene, the most abundant minerals on the Moon, and some fraction of basaltic glass. The anorthosites are dominated by plagioclase feldspar, and contain no glass. Highlands simulants are generally a mixture of basaltic and anorthositic material.

When heated at 30˚C/minute, most mare simulants show a small glass transition bump at ~700˚C, a small release of latent heat of crystallization around 800-900˚C, and melting between ~1100 and 1300˚C with the peak around 1150-1200˚C (Fig. 1). LMS-1 peaks at about 1300˚C and requires a higher temperature than other simulants to achieve complete melting, and apparently contains little glass.

When heated at 30˚C/minute, most highland simulants show a barely detectable glass transition around 750˚C, a barely detectable crystallization trough above that, and undergo melting between ~1200 and 1400˚C with a peak around 1300˚C (Fig. 2). The agglutinate-LHT is very glassy, shows a strong glass transition feature around 750˚C, followed by crystallization at ~1000˚C, and remelting beyween 1150-1450˚C, peaking around 1250˚C. The crystalline Stillwater and Shawmere anorthosite samples only start melting at about 1400˚C, and melt completely at ~1500˚C.

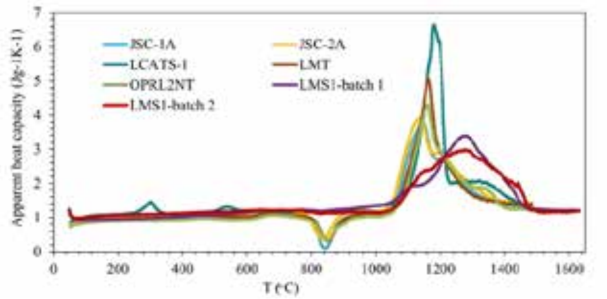

Figure 1. Apparent heat capacity data for mare simulants

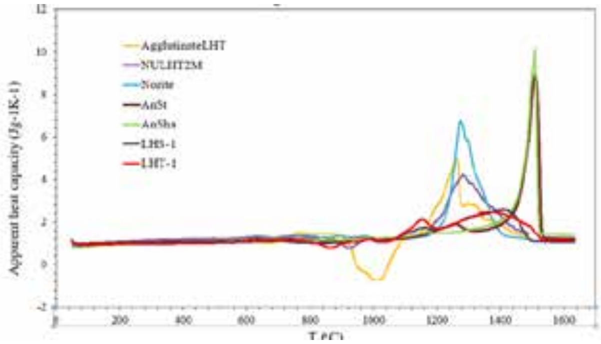

Figure 2. Apparent heat capacity data for highland simulants

Conclusions: Thermal properties of simulants vary considerably as a function of composition and glass content. Variability within each group (compare JSC-2A or LMT-1 vs. LMS-1 for mare; and NU-LHT-2M vs anorthosite for highlands) is as great as differences between these groups. Differences between fully crystalline and substantially glassy starting materials also affect melting behavior bvery strongly (compare NU-LHT-2M vs agglutinate-LHT for highlands).

Processes that can work for materials encompassing the range of glassy basalt to crystalline anorthosite should accommodate most lunar regolith, although some aspects of lunar chemistry (e.g. low K) cannot be replicated with terrestrial rocks.

References: [1] Whittington A.G. and Parsapoor A. (2022) *New Space,* doi: 10.1089/space.2021.0055

The Lunar Payload Development Program at Honeybee Robotics.

Hunter Williams, Kris Zacny [1]Honeybee Robotics, 2408 Lincoln Ave, Altadena, CA (Contact: hjwilliams@honeybeerobotics.com)

Introduction: NASA's Commercial Lunar Payload Services (CLPS) program has opened up a new paradigm in NASA contracting practices and risk posture. Highly risk tolerant, low cost, rapid development missions are now a key part of NASA's Lunar technology portfolio development. NASA has also renewed its commitment to encourage new and nontraditional Principal Investigators. To enable these PIs to perform sample-intimate science on the Lunar surface and develop new payloads under this low cost, low mass, risk tolerant paradigm, Honeybee has created the Lunar Payload Development Program. The Program seeks to answer the question, "How do we support and contribute to low cost, risk tolerant scientific exploration of the Lunar surface?" A key finding of the Program is the need for 2 distinct methods of support:

1) A highly accessible suite of low cost, low mass excavators and sample handling systems designed specifically for CLPS missions.
2) Established facilities, personnel, and institutional knowledge needed for progress in the TRL advancement process.

This article provides an overview of the elements of this two part solution, where they came from and how they are implemented.

CLPS oriented excavators and sample handling systems: the cost and mass constraints on payloads flying on CLPS landers, particularly for those funded through the Payloads and Research Investigations on the Surface of the Moon (PRISM) program, has precluded traditional excavators and sample handling systems such as those requiring robotic arms or those relying on complex actuation. Having built such traditional excavators and sample handling systems for NASA's Mars missions (ISAD, RAT, SMS), Honeybee recognized the need for new kinds of low mass and cost systems for CLPS missions. Pneumatic excavation was determined to be the simplest, most effective excavation method, moving kilograms of regolith per gram of gas [1], and requiring as little as one actuator and one solenoid for operations. A series of pneumatic excavators and sample handlers were developed specifically to meet the needs of sample intimate instruments flying on CLPS missions. These systems are providing sample to Lunar instruments as part of every CLPS mission to date.

TRL progression assistance: taking Lunar payload technology through the TRL pipeline from 1-9 requires a variety of processes, facilities, and organizational knowledge. It was found through the Program that PIs and their institutions are not homogeneously lacking in particular facilities or forms of organizational knowledge; an institution with a new suite of Lunar simulating test facilities may be lacking in validation and verification procedural knowledge, while a PI with significant flight experience may need assistance with design and simulation. Common among many PIs was difficulty in progressing from TRL 5 to 6 and from 6 to flight due to lack of relevant test facilities, documentation knowledge, and skilled staffing. While facilities can often be secured through rental or partnership, the jump in staffing, documentation, and test requirements at TRL 5-6 is a common reason for small business failure and have caused the stage to be known as the "TRL Valley of Death". To enable rapid TRL progression, particularly through the TRL Valley of Death, the Program identified the following as needed capabilities:

- Early design support to avoid costly mistakes in flight-level designs
- Realistic budget and timeline assessments to prevent overruns
- Comprehensive systems engineering and risk assessments
- Low cost fabrication facilities for both prototyping and flight hardware development
- Large and/or rapidly reconfigurable dirty thermal vacuum chambers
- A variety of regolith simulants for geophyisical edge case testing
- Short term contractor support to meet shifting staffing requirements, particularly in avionics, software, and simulation
- Documentation support for flight builds, test, and integration

The Lunar Payload Development Program identified these as key elements for enabling new PIs to perform sample intimate Lunar science under tight cost and schedule constraints.

References:

[1] Zacny, Kris, et al. "Application of Pneumatics to Sample Acquisition and Delivery for Planetary Surface Missions." EPSC-DPS Joint Meeting 2019. Vol. 2019. 2019.

High-power solid-state microwave combining technology for deep space communications

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Introduction: High-capacity communication technology is needed for current and future exploratory and scientific missions targeting lunar/cis-lunar and beyond. Recent semiconductor devices based on wide-bandgap materials such as GaN and SiC enable the prospects of full solid-state transmitter systems for deep space communication architectures. Power combining these GaN/SiC power amplifiers may provide a competitive alternative to the traditional klystron and traveling-wave tube technology and may possess the merits of scalability, grace-full degradation and long-term micro-electronic supply-chain sustainability for NASA missions [1].

This work: We present the technological research efforts of cavity-based spatial and on-chip planar monolithic microwave integrated circuit (MMIC) power combining results in the X and Ka-band for deep space communications and planetary radar applications.

Figure 1 showed the conceptual diagram of the Spatial Power Combining Amplifier (SPCA) and the on-chip planar power combined with an MMIC. Figure 2 (left) showed the X-band 1kW SPCA demonstrated in the laboratory environment. The unit combines 16x 80Watt MMIC for a total output of 1.1kW. We used an output resonant cavity for "spatial" power combining to provide high-power, low-loss combining in a small footprint. Each MMIC module has a computer-controlled board to provide biasing, amplitude and phase control, real-time monitoring of MMIC's health and performance, and a graphical user interface for control and monitoring of the entire SPCA unit.

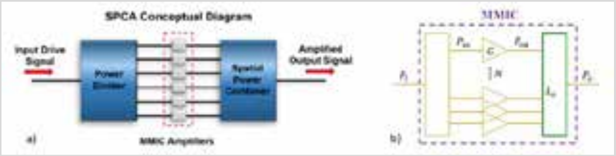


Figure 1. a) Spatial Power Combining Amplifier Diagram (SPCA). b) MMIC on-chip power combining diagram. P_i: input power, P_o: output power, L_o: output load.

We designed and fabricate a 4-way TXR combiner, with the goal to achieve 4kW total output using the 1kW unit. The measured results are shown in Figure 3 with a photo of the actual 4-way combiner in Figure 2(right). The S-parameters showed that the insertion loss is at 0.1dB with 500MHz 1dB bandwidth.

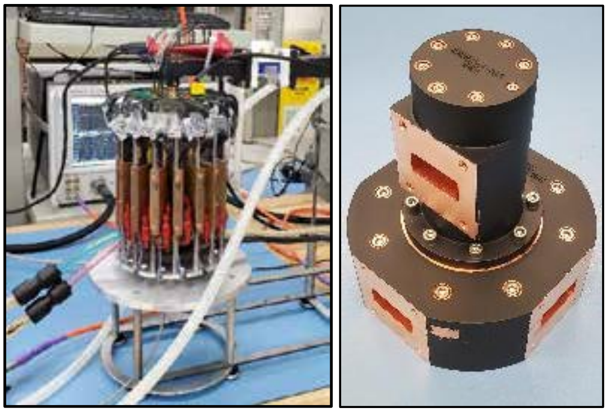


Figure 2. 1kW SPCA and 4-way combiner

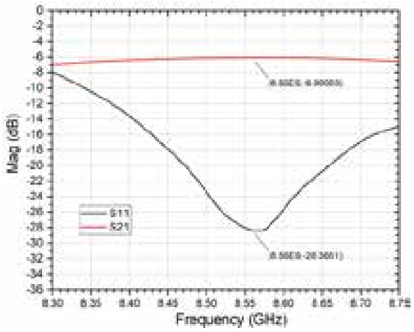


Figure 3. 4-way combiner performance.

We also designed the MMIC solid-state power amplifier using the GaN technology (150nm GaN/SiC, Wolfspeed) for the X-band downlink in the deep space network (DSN), with the devices shown in Figure 4. Simulated performance shows PAE is as high as 58% and the power output is 5 Watt.

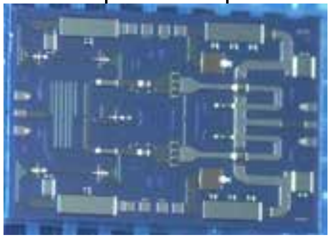


Figure 4. GaN MMIC for DSN X-band

Acknowledgments: Copyright 2022 California Institute of Technology. United States Government Sponsorship acknowledged. The work described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics Space Administration.

References:

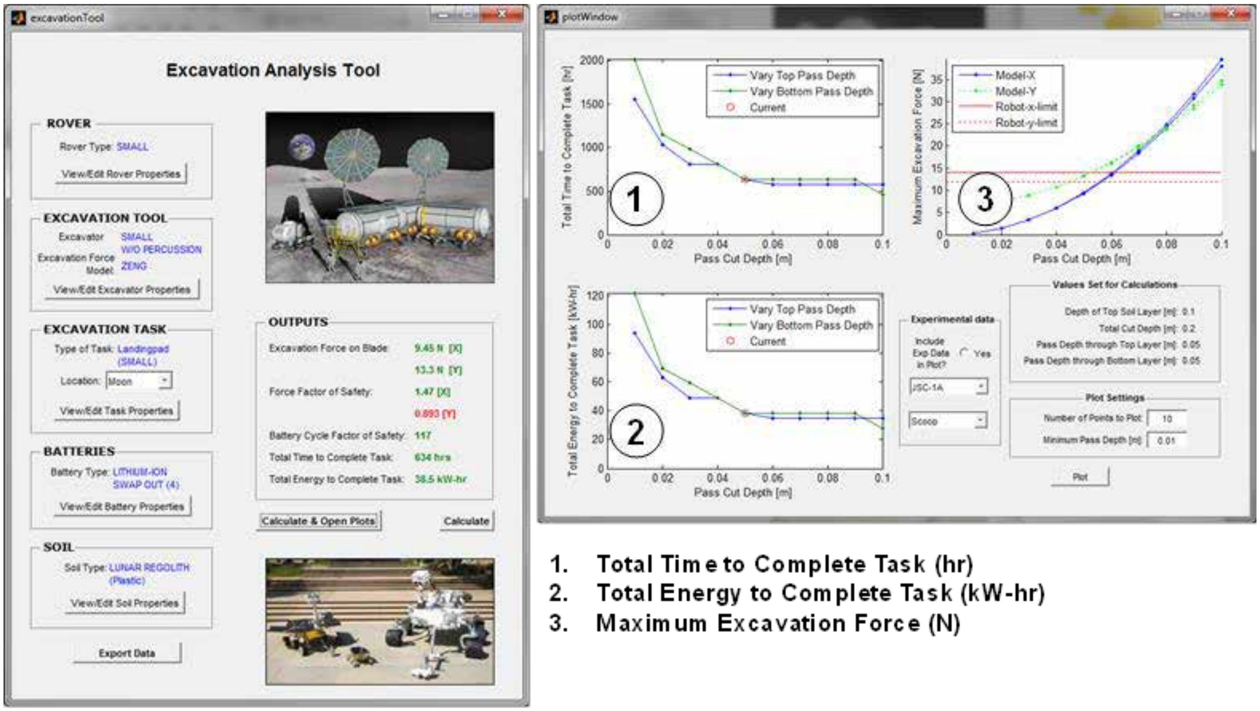
[1] Velazco, J., and Mark Taylor. "Spatial Power Combining Amplifier for Ground and Flight Applications." *Int. Planetary Network Prog. Rep.* (2016).

Parametric Optimization and Prediction Tool for Excavation and Prospecting Tasks. K. Zacny, H. Williams, T. Mathison, D. Bergman, I. King, Honeybee Robotics, 2408 Lincol Avenya, Altadena, CA 91001 (kazacny@honeybeerobotics.com)

Introduction: We developed a software tool for facilitating prospecting and excavation system trades in support of selecting an optimal architecture for the Moon, and demonstrated the calculations for a limited test case [1, 2]. The tool could serve as a starting platform for excavation software for Mars or asteroids. The tool will provide engineers with the ability to quickly examine "What if?" scenarios within a trade space by specifying a surface system architecture (e.g. lander or rover based, digging for ice or building berms) and receiving reliable data and graphs evaluating that architecture's performance in terms relevant metrics, such as total energy used or total duration. The software tool includes theoretical soil excavation models as well as empirically derived data from quasi static, percussive, and vibratory exaction tests.

Excavation Software: The excavation architecture analysis tool described here is the latest in a series of iterations. Throughout the development, the goal has been for this tool to be: 1) user friendly, 2) relevant, and 3) accurate. The initial version, constructed during the 2009 study, essentially consisted of a complicated arrangement of interdependent MS Excel spreadsheets. The SBIR Phase I work included porting the existing equations to Matlab, constructing a Graphical User Interface (GUI), and improving the rigor with which the underlying soil mechanics and civil engineering calculations were treated. The SBIR Phase II work built upon Phase I, adding the Qinsen and Shuren (1994), Zeng (2007) and Balovnev (1963) models for rippers, buckets and blade excavators, defining a format and adding the capability to import empirical data from a MS Excel database, and adding the capability to compare calculated values to appropriate sets of empirical results in the generated plots.

Screenshots of the software is shown in Figure 1. One of the most important attributes of the software is that additional empirical data from actual digging tests can be added for comparison with the modeled results. This will make it ever more accurate and effective to evaluate model results as additional experimental data is added. This is envisioned to be an ever-growing body of data, with new results added as they become available.



ROVER
Rover Type: SMALL

EXCAVATION TOOL
Excavator: SMALL W/O PERCUSSION
Excavation Force Model: ZENG

EXCAVATION TASK
Type of Task: Landingpad (SMALL)
Location: Moon

BATTERIES
Battery Type: LITHIUM-ION SWAP OUT (4)

SOIL
Soil Type: LUNAR REGOLITH (Plastic)

OUTPUTS
Excavation Force on Blade: 9.45 N [X] 13.3 N [Y]
Force Factor of Safety: 1.47 [X] 0.893 [Y]
Battery Cycle Factor of Safety: 117
Total Time to Complete Task: 634 hrs
Total Energy to Complete Task: 38.5 kW-hr

Experimental data
Include Exp Data in Plot? ○ Yes
JSC-1A
Scoop

Values Set for Calculations
Depth of Top Soil Layer [m]: 0.1
Total Cut Depth [m]: 0.2
Pass Depth through Top Layer [m]: 0.05
Pass Depth through Bottom Layer [m]: 0.05

Plot Settings
Number of Points to Plot: 10
Minimum Pass Depth [m]: 0.01

1. **Total Time to Complete Task (hr)**
2. **Total Energy to Complete Task (kW-hr)**
3. **Maximum Excavation Force (N)**

Figure 1. Matlab Excavation Prediction Tool – Main Menu and Model Calculation Result Plots

References: [1] Zacny et al., 2010, Earth and Space; [2] Zacny et al., (2013), AIAA.

The Lunar Regolith Terrain (LRT) Field: A New Lunar Surface Planetary Analog Facility at NASA Marshall Space Flight Center (MSFC).

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Introduction: NASA is moving toward a new age of exploration and resource utilization of the lunar surface. Challenges related to exploration, resource utilization, and construction at the Lunar South Pole will require advanced technology and well-designed mission concepts and operations. NASA Marshall Space Flight Center (MSFC) has added new capabilities to support surface mobility and construction activities to meet industry, academia, and NASA research and development goals for lunar applications. The Lunar Regolith Terrain (LRT) field is a new, large-area, lunar regolith planetary analog testing ground for users interested in surface mobility and lunar construction activities. The LRT complements NASA MSFC's other lunar environment testing facilities such as the Lunar Surface Simulator (V20 dirty vacuum chamber), the Lunar Environment Testing System (LETS), among many others.

Lunar Regolith Terrain (LTR) Description: The Lunar Regolith Terrain field is an outdoor planetary analog environment facility located on base at MSFC. The lunar regolith simulant is JSC-1A feedstock material (volcanic cinder sand sourced from Meriam Crater, Flagstaff, AZ). The field contains more than 500 tons of lunar regolith simulant confined within a 125 ft x 125 ft (38 m x 38 m) area. The field is placed ~50% over paved parking lot and ~50% over a natural ground. Currently, the depth of regolith ranges between ~5 in - ~4 ft (~13 cm – 1.2m) but can be modified to suite user needs. The lunar regolith simulant that makes up the field has representative geotechnical, geochemical, and optical properties of lunar mare basalt. An area within the LRT of lunar highlands terrain simulant is planned.

Additional Features of the LRT: The LRT was designed to allow rapid modification of the terrain's topography obstacles in the field. The terrain can be reshaped to suite specific testing requirements that may require flat-expanses, steep hills, or heavily cratered and rocky landscapes. Large rocky obstacles in Fig. 1 are artificial landscape boulders (faux-rocks) that can be easily placed by users or removed entirely. Areas of the field also contain buried fiducials, large sheets, bar stock, and pipes of various composition and dimensions to allow for possible ground penetrating radar and shallow seismic studies. Rapid modification capabilities will also allow for burial of additional user-specific materials to enable in-situ resource utilization detection (e.g., burial of hydrogen sources for neutron detection or other materials). The field is also equipped with on-site office space with an air-conditioned and heated trailer with 120/240V power and lighting. The site has Wi-Fi and Cellular signal coverage. Direct radio frequency communication with the Huntsville Operations Support Center (HOSC) is in development. Additional on-site workspace and secure equipment storage is available in adjacent buildings. Accessibility to the field is straightforward with on-site parking and access for delivery of instruments, payloads, and additional equipment.

Community Availability: The LRTF provides an accessible planetary analog surface environment for surface mobility testing, autonomous roving operations, developing advanced navigation techniques and operations development. Interested parties can contact the abstract authors for additional details, tours, and scheduling.

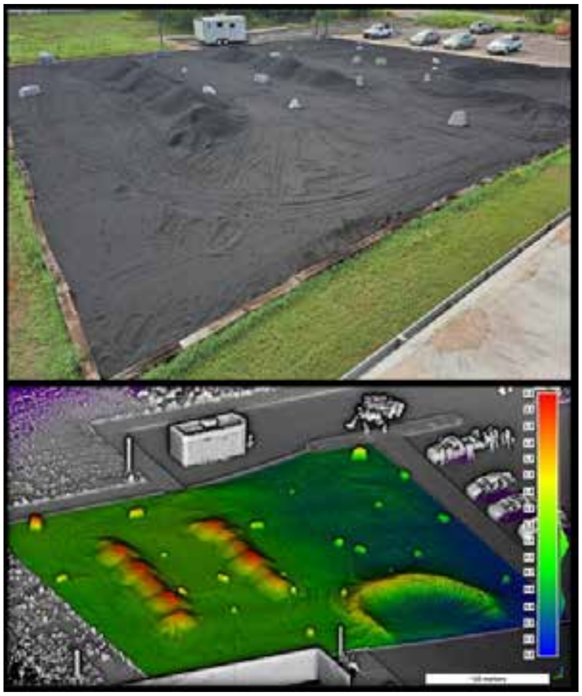

Figure 1: (Top) view of the Lunar Regolith Terrain (LRT) field, a 125ft x 125ft (38m x 38m) planetary analog surface mobility environment at NASA MSFC (M. Zanetti). (Bottom) A digital elevation model from MSFC's Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR system showing current topography of the LRT (M. Zanetti)