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Breakthrough Materials for Space Applications Workshop

T. Prater, W. Tilson, J. Vickers, and S. Singhal
Marshall Space Flight Center, Huntsville, Alabama

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Proceedings of a Workshop held at the
Jackson Center, Huntsville, Alabama,
Hosted by Jacobs Engineering,
April 23–24, 2019

January 2020

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National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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CONFERENCE PUBLICATION

BREAKTHROUGH MATERIALS FOR SPACE APPLICATIONS WORKSHOP

INTRODUCTION

In the course of its 60 year history, the National Aeronautics and Space Administration (NASA) has blazed trails in the development and advancement of aerospace materials and the transition of these advancements to industry. The Agency has overseen the infusion of new high-performance materials into a diverse array of mission applications, including aeronautics, planetary science, and human spaceflight. The next generation of demanding exploration missions, including a return to the lunar surface with humans in the 2020s, will present new and unprecedented material challenges. Selecting or developing materials to survive the environments of launch and the high temperatures present in propulsion systems, operate in a microgravity and/or a vacuum environment (which includes exposure to radiation), and/or survive years on a planetary surface is an immense challenge. In addition to functioning in their intended use environment, materials for space must also possess extremely high-performance characteristics. The anecdotal Von Braun quote “space is weightlifting” reminds us of the need to minimize the mass of a space system while still meeting safety margins. The cost of launching a kg to orbit is estimated currently at $10,000; barring a drastic reduction in launch costs, lightweight and high-strength materials will remain the most sought-after spaceflight materials for the foreseeable future. Other primary considerations for materials in spaceflight applications include affordability, compatibility with other systems and materials, and manufacturability. The emergence of new advanced manufacturing processes such as friction stir welding and additive manufacturing have revolutionized the aerospace industry in recent years. Additive manufacturing in particular allows for rapid fabrication of components and greater design freedom. With the advent of these new processes, however, comes the need to develop new specifications, process control approaches (including material modeling), testing, and nondestructive evaluation techniques to ensure that parts meet the stringent functional requirements for spaceflight.

The aerospace community stands at the dawn of a new age in materials, with emerging materials and processes offering potential solutions to recognized historical challenges. Government, industry, and academia are continuously working together to develop new materials and realize the potential of existing materials for aerospace applications through their technology maturation efforts. New materials and processes may offer answers to historical questions: How do we process and use materials on a planetary surface to build infrastructure? What can we can learn about processing of materials and thermophysical properties from operation in the microgravity environment? What testing, modeling, and characterization techniques do nontraditional manufacturing processes require? How can supercomputing and machine learning be leveraged to design better materials and reduce iterative optimization efforts?

In response to this highly dynamic aerospace materials research environment, NASA organized a workshop on "Breakthrough Materials for Space Applications" in the spring of 2019. The purpose of this two-day event, held on April 23 and 24 at the Jackson Center in Huntsville, AL, was to bring together researchers conducting groundbreaking work in materials in six identified focus areas:

(1) Metals.
(2) Nonmetals.
(3) Computational modeling.
(4) Testing and characterization.
(5) Emerging materials (includes materials at a low technology readiness level, materials for future advanced space applications such as nuclear propulsion, and topics on in situ resource utilization).
(6) International Space Station (ISS) microgravity materials research (focus on translational research and using the ISS to improve modeling of materials and processing of materials on Earth).

The workshop was sponsored by Jacobs Engineering and combined a mix of plenary talks on high level programmatic needs and Agency-level research efforts with breakout sessions in each of the six focus areas which featured more detailed technical talks. The agenda for the workshop is included in appendix A, and the over 200 attendees who participated in the event are listed in appendix B. Attendees represent a diverse group of stakeholders from industry, academia, and government. The workshop provided NASA with an opportunity to share lessons learned from its history of materials development work, updates on current activities, and future needs regarding materials for space applications.

The format of this Conference Publication (CP) provides an overview of each presentation included in the workshop. The biography of the presenter is followed by a more detailed discussion of the content in a particular talk. This CP serves as a record of the first annual Breakthrough Materials Workshop and highlights materials and research areas of interest to NASA as the Agency embarks on new and ever-more challenging missions.

DAY 1—APRIL 23, 2019

WELCOME AND OPENING REMARKS

The welcoming and opening remarks for the meeting were provided by the workshop chair, Dr. Suren Singhal of NASA Marshall Space Flight Center (MSFC), Huntsville, Alabama. Other speakers included Dr. Lisa Watson-Morgan (MSFC), John Vickers (MSFC and Space Technology Mission Directorate principal technologist for advanced manufacturing), and Randy Lycans (vice president of Jacobs Space Exploration Group). In their opening comments, all speakers emphasized the critical role materials play in enabling exploration systems. The speakers tasked the attendees with continued advancement of state-of-the-art materials with the goal of meeting NASA's programmatic challenges. NASA is currently focused on a return to the Moon through the Agency's Artemis program, which will return humans to the Moon by 2024 and establish a sustained human presence on the Moon by 2028. Elements of the Agency's portfolio with specific material challenges highlighted during these remarks included habitation elements, landers, propulsion systems, thermal protection systems, and in situ resource utilization activities.

Dr. Suren Singhal is the Director of Materials and Processes Laboratory at NASA Marshall Space Flight Center. His Laboratory leads strategic space exploration technologies including additive manufacturing, composites, digital manufacturing, materials diagnostics and testing, fracture, non-destructive evaluation, metals and nonmetals, and materials informatics. He joined the Materials & Processes Laboratory as Assistant Manager at MSFC where he led several Center and Agencywide projects from Space Shuttle, International Space Station, and materials and manufacturing of space systems. Prior to coming to MSFC, Dr. Singhal led NASA Glenn Research Center's onsite engineering contract as Director of Structures & Materials, Director of Aero-Propulsion, Director of Space Technology, and Director of Test Engineering, and then as the Deputy General Manager for the $180M engineering support services contract. Prior to working at NASA Centers, he started his professional career in the oil and offshore industry in Texas and Oklahoma. He is a Fellow of the American Society of Mechanical Engineers; a Fellow of the American Society of Materials, International; a Fellow of the Society of Mobility Engineers, International; and an Associate Fellow of the American Institute of Aeronautics and Astronautics. He has received numerous awards including the NASA Exceptional Achievement Medal. He earned a B.S. in Mechanical Engineering from Indian Institute of Technology, Kanpur, India, followed by an M.S. in Fluid, Thermal, and Aerospace Sciences from Case Western Reserve University, MBA from the University of Houston, and an M.S. as well as a Ph.D. in Mechanical Engineering from the University of Wisconsin, Madison.

Dr. Lisa Watson-Morgan is the associate director of operations in the Engineering Directorate at NASA Marshall Space Flight Center. The directorate is engaged in the design, testing, evaluation, and operation of hardware and software associated with space transportation, spacecraft systems, science instruments, and payloads in development at Marshall. In 2013, she was appointed to the Senior Executive Service as manager of Marshall's Chief Engineer's office.

Watson-Morgan was named chief engineer of Marshall's Flight Programs and Partnerships Office in 2011. From 2008 to 2011, Watson-Morgan worked in Marshall's Science and Mission Systems Office in various leadership positions, responsible for the strategic planning and project management, including the integration of and process for all International Space Station Engineering Research & Technology Demonstrations for the Center. She began her career at Marshall in 1989 as a cooperative education student, and worked in the Mission Operations Laboratory as a data management controller for the ATLAS-3 Spacelab mission.

Mr. John Vickers serves as the principal technologist within the area of advanced materials and manufacturing in the Space Technology Mission Directorate at NASA Headquarters. He also serves as the associate director of the Materials and Processes Laboratory at NASA Marshall Space Flight Center and as the manager of the NASA National Center for Advanced Manufacturing with operations in Huntsville, Alabama and New Orleans, Louisiana. He has over 35 years of experience in materials, manufacturing research and development, engineering, and production operations for propulsion, spacecraft, and scientific systems. He serves as the Agency primary representative to the National Science and Technology Council's Subcommittee on Advanced Manufacturing and the Subcommittee on Critical and Strategic Mineral Supply Chains. He also serves as the Agency representative to the Manufacturing USA network and the Interagency Advanced Manufacturing National Program Office.

Mr. Randy Lycans is Vice President and Program Manager of the Jacobs Space Exploration Group (JSEG) at NASA Marshall Space Flight Center (MSFC). In this role, he manages the scientific, engineering, and technical support contract (ESSCA) for Jacobs at MSFC. Primary customers include the Engineering Directorate, Science and Technology Office, Flight Programs and Partnerships Office, the Space Launch System Program Office as well as future programs and projects. Randy has led Jacobs support at MSFC since 2006. Prior to serving as JSEG PM, Randy was the Deputy General Manager, and before that oversaw the Jacobs Engineering Directorate where he supported programs such as the Space Shuttle Return-to-Flight, the International Space Station assembly and activation, and the development of microgravity materials science experiments. Randy has 38 years of experience, the bulk of which has been spent supporting the human space flight program at MSFC in various leadership and technical roles. He has experience in heat transfer and thermal analysis, wind tunnel test support, development of advanced thermal protection systems, and launch vehicle design and development. Randy received the Holger Toftoy award from the American Institute of Aeronautics and Astronautics (AIAA) for excellence in program management in 2015, and was a NASA Space Flight Launch Honoree in 2003. He has authored a number of technical papers and journal articles and has served on several AIAA Technical Committees. He is a past chairman of the National Space Club—Huntsville. Randy received an M.S. degree in Mechanical Engineering (1985) and a B.S. degree in Mechanical Engineering (1981) from the University of Akron. He is a registered Professional Engineer in the state of Alabama, and an Associate Fellow of the AIAA.

KEYNOTE SESSION I—APRIL 23, 2019

Keynote session I featured high-level talks on composites, energy storage devices, advanced manufacturing, the Materials Genome Initiative, and nanostructured materials. These talks provided a foundational understanding of the current thrust of advanced materials research in industry, government, and academia.

■ Revolutionary Composites—Dr. Keith Young, Boeing

Dr. Keith Young is currently the Composites & Metals Director for BR&T Materials and Manufacturing Technology, located in Boeing Charleston. He is responsible for leading a team of 350+ engineers and technologists across the Enterprise, located in California, Alabama, South Carolina, Missouri, Washington, and 11 International Centers. The primary objectives are developing and implementing Composites, Metals, and Fasteners, Fabrication and Materials Technology. Keith also serves as the Enterprise Functional Executive for Materials, Processes and Physics (MP&P), and the executive focal for the University of South Carolina.

Dr. Young began his talk with a discussion of the long history of the Boeing and NASA partnership, which dates to the earliest days of the Space Agency. Boeing has provided engineering support and designed, built, and tested hardware for virtually all flagship NASA human exploration programs: Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, and Space Shuttle. Boeing's current work includes the International Space Station, Commercial Crew (CST-100 capsule), and the Space Launch System. Boeing's space division is focused on rapid and advanced access to space, lunar lander development, and spacesuit development. All of these programs come with a unique set of material challenges. In particular, Dr. Young noted the need to build confidence in composite structures for crewed spaceflight. Boeing uses composites extensively in its aviation business segment (777 and 787 structures) and is working to transition these materials to human spaceflight applications where they can reduce weight of systems and improve performance in some use scenarios (Figure 1). Boeing previously manufactured a composite cryogenic tank demonstration for NASA, which was tested at MSFC.

Figure 1. Composites manufacturing at Boeing. Image credit: Dr. Keith Young, Boeing.

Dr. Young highlighted other areas of Boeing's materials research, including work on new high-temperature composites (similar to benzoxazines) which are less detrimental to the environment than historical formulations. Boeing makes extensive use of additive manufacturing in aircraft and spaceflight hardware. Researchers are working to use AM techniques to improve the strength of aluminum by modifying it at the nanoscale. Other AM work includes development of metal AM processes for space hardware, topologically optimized structures, AM of ultra-lightweight materials (microlattice structures), and hybrid systems which also include a machining capability for part finishing.

As keynote presenter Dr. Byron Pipes also noted in his talk, that there are many challenges in automating composites manufacturing processes, which sometimes limits the use of these materials in high-rate mass production scenarios. Boeing has done significant work on automating the fabrication of ceramic matrix composites. Boeing produces over 200 million pounds of composite material per month. While these techniques were developed for aircraft, they can also be leveraged for space exploration applications. Boeing has also developed a full suite of thermal protection system (TPS) solutions for spacecraft: TPS blankets, metal TPS, refractory alloys, TPS tiles, C-SiC and SiC-SiC, and ultra high temperature composites (UHTCs). Boeing also conducts research in computational modeling, seeking to accelerate and optimize materials development and manufacturing through analytical models on every scale. Dr. Young concluded his talk by emphasizing the materials challenges of a mission to Mars. The sustained work of the materials community is essential to seeing astronauts one day set foot on the Red Planet.

■ Forging a Path for Materials Revolution—Dr. Melissa K. Rhoads, Lockheed Martin

Dr. Melissa Rhoads is the Sr. Manager of the Advanced Electronics & Materials department at Lockheed Martin Space's Advanced Technology Center. Her team includes Advanced Manufacturing, Electronics, Materials, and Test & Characterization. Melissa is also the advocate for Synthetic Biology at Lockheed Martin. Prior to this role, Melissa supported Space Advanced Programs, spanning engineering and business development for technical strategy and architecture solutions. Melissa earned a B.S. in Electrical Engineering from Bucknell University, an M.S. in Engineering (Telecommunications and Networking) from the University of Pennsylvania, an MBA from the W.P. Carey School at Arizona State University, and a Ph.D. in Bioengineering from the University of Maryland.

Dr. Rhoads emphasized the importance of advanced manufacturing, and specifically, additive manufacturing (AM), to enable design of materials at the molecular level and more rapid fabrication. While AM has been widely accepted for some materials and applications, there are many new/emerging materials (for example, composites) which show high potential with AM processes but need to be verified and characterized to transition them into production. Digital integration of design and manufacturing will be needed to understand the repeatability of a process and enable prediction of the final properties of a part based on data collected during manufacturing. Other materials research areas Lockheed Martin is currently working in include: nanotechnology, graphene, nano-copper, and CNTs. Lockheed Martin is working to maintain its supply base for materials while ensuring 'eco-friendly' domestic production. LM leverages small business domestic suppliers extensively in its supply chain. Dr. Rhoads also spoke about synthetic biology, which can include altering living tissue at the genetic level to obtain a specific functionality or making materials using organisms that could also construct the material at the nanoscale (molecular manufacturing). Work in this field also enables an enhanced molecular understanding of material properties (Figure 2).

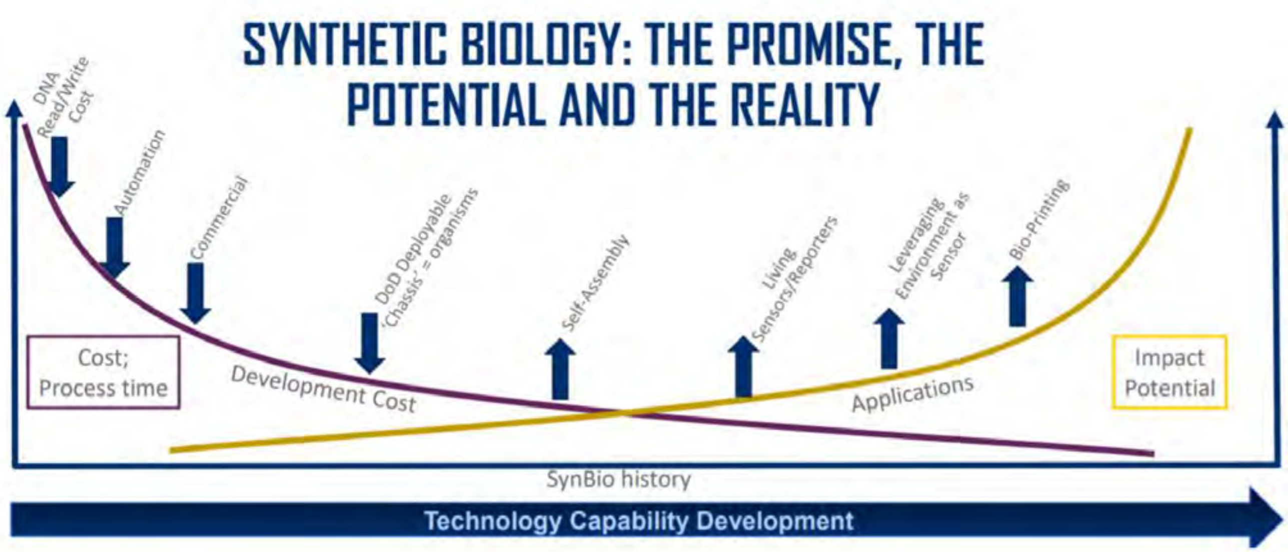


Figure 2. Synthetic biology history and impact potential. Image credit: Dr. Melissa Rhoads, Lockheed Martin.

■ Nanostructured Materials for Energy Capture, Storage, and Delivery in Space-Based Applications—Dr. Jud Ready, Georgia Institute of Technology Institute for Materials

Dr. W. Jud Ready is the Deputy Director, Innovation Initiatives for the Georgia Tech 'Institute for Materials.' He has also been an Adjunct Professor in the School of Materials Science & Engineering at Georgia Tech and a Principal Research Engineer on the research faculty of Georgia Tech Research Institute (GTRI) for 15 years. Prior to joining the Georgia Tech faculty, he worked for a major military contractor (General Dynamics) as well as in small business (Micro-Coating Technologies). He has served as PI or co-PI for grants totaling ~$18M awarded by the Army, Navy, Air Force, DARPA, NASA, NSF, NIST, industry, charitable foundations, private citizens, and the States of Georgia and Florida. His current research focuses primarily on energy, aerospace, nanomaterial applications, and electronics reliability.

Energy capture, storage, and delivery is crucial for space flight. Carbon nanotubes (CNTs) can be used in 3D solar cells, ultra-capacitors, and field emission arrays (Figure 3). This talk discussed potential nanostructured solutions for each:

(1) Energy capture—'3D' photovoltaic cells made from an Earth-abundant photoabsorber (Cu2ZnSnS4 -- CZTS) are deposited atop a light trapping array of carbon nanotubes and exposed on the International Space Station.

Figure 3. 3D photovoltaic cells made from CNTs on MISSE 11.
Image credit: Georgia Institute of Technology.

3D photovoltaic cells made with CNTs permit multiple impingements of a single photon, significantly increasing absorption probability. To fabricate these cells, CNT towers are formed in a chemical vapor deposition (CVD) furnace (pattern is generated on Si substrate via photolithography). P-type materials are applied by Molecular Beam Epitaxy (MBE) and n-stype materials are applied via MBE or CVD. A transparent conductive oxide is also applied to the device. CZTS is a light absorber that is deposited to complete the cell material system. Eighteen 3D photovoltaic cells were flown on a 4U Cubesat mission in 2016 and exposed to the space environment for 12 months. No in situ data were obtained due to payload malfunction, but cells were reflown on Materials International Space Station Experiment (MISSE) 11 and 12 to test their performance in the space environment (thermal transients, ultraviolet radiation and atomic oxygen exposure). Research is underway in pursuing additional CZTS compositions, multiple solar cells, and new geometries in multi-junction solar cells to improve performance. This technology has been commercialized by Bloo Solar.

(2) Energy storage—Electrochemical double layer capacitors incorporating room temperature ionic liquid electrolytes, graphenation, and pseudocapacitive functionalization of carbon nanotube forests.

CNT energy storage devices provide very high power density, very low energy density, and a virtually unlimited cycle life. Helmholtz double-layer capacitors provide a high surface area and small charge separation which dramatically increases energy storage capacity. Devices tested represent material systems with graphene and pseudeocapacitive materials (for example, g-CNT + TiO2).

(3) Energy delivery—Robust Spindt-style electron emitters are made by embedding carbon nanotubes within etched cavities in silicon wafers.

CNT field emission arrays (CFEAs) reduce electrode spacing and provide geometric field enhancement (potential gradient increases with curvature). CFEAs minimize electrostatic screening. CFEAs are fabricated using photolithography and deposition techniques and packaged. A set of CFEAs flew on a Cubesat as part of an Air Force Institute of Technology CNT experiment. The payload characterized field emission in the space environment via an integrated electrostatic analyzer (device which determines the electron energy distribution). The payload (known as ALICE) was launched on NROL-39. CFEAs also have potential applications in hall thrusters (in-space electric propulsion) and electrodynamic tethers (interact with the Earth's magnetosphere to generate thrust/propulsion without consuming propellant).

■ High Rate Composites Manufacturing for Aerospace—Dr. Byron Pipes, Purdue University

Dr. R. Byron Pipes is Executive Director of the Composites Manufacturing and Simulation Center of Purdue University. He was elected to membership of the National Academy of Engineering (1987) and the Royal Society of Engineering Sciences of Sweden (1995). Dr Pipes is recognized for his leadership in creating partnerships for university research with the private sector, government, and academia. He served as President of Rensselaer Polytechnic Institute from 1993–1998 and was Provost and Vice President for Academic Affairs at the University of Delaware from 1991–1993. He served as Dean of the College of Engineering and Director of the Center for Composite Materials during 1977–1991 at the same institution. He was appointed John L. Bray Distinguished Professor of Engineering at Purdue University in 2004.

Composites manufacturing has undergone a substantial revolution since the first flights of air vehicles made up of high-performance, carbon fiber systems in the 1970s. The evolution of computing power/cost, processing speed, and processing power has improved rapidly (a factor of one billion in the past 50 years). PAN carbon fiber helped revolutionize the airframe industry in the 1970s and 1980s. The defense industry also led the composites revolution by integrating composite materials into high-performance flight systems such as fighter jets and bombers. Commercial aerospace composites were used on the Boeing 777, 787, and Airbus 350. High-performance composites are also used in leisure products (boats, bicycles) and the automotive industry. In 2008, 50 million pounds of carbon fiber composites were used in various industries. The cost per pound of carbon fiber composites has decreased dramatically from $150/lb (in 1970) to $5/lb (2008).

While continuous fiber thermoset prepregs were developed and tape lay machines were already in use for surfaces of modest curvature in the 1980s, much of the airframe components were manufactured with hand layup. Product certification required large data sets in the 'building block' approach and manufacturing processes followed 'recipes' with little or no feedback until quality control measures were made in the final step. Single-sided, low-pressure tooling was and remains the dominant approach to aerospace composites manufacturing, especially for large area applications. During the past two decades, the automobile industry has advanced the manufacturing of composites to high rate processes for vehicle light-weighting and developed approaches that largely focus high pressure, two-sided tooling and intermediate scales. Further, the combination of continuous and discontinuous fiber materials systems in hybrid molding has shown significant promise for new integrated manufacturing systems that yield high performance with rapid manufacturing rates. The challenge ahead for composites manufacturing in aerospace will be the adoption and modification of the lessons learned in automotive composites to provide for the enhanced manufacturing rates and economy required for future aerospace products. The air mobility applications currently under development provide a platform for these important developments.

Perhaps the greatest current challenge in aerospace composites manufacturing (alongside cost and risk) is the achievable rate of production. While there are many technical challenges to increasing manufacturing production rates for composite structures, the complexity of the aerospace supply chain imposes an additional barrier. One way to address this issue is to create a digital thread that interconnects suppliers and manufacturers. The Composites Manufacturing and Simulation Center has developed a cloud-based virtual factory hub that provides access to commercial design programs, simulation programs, and databases—within this framework, design modifications can move between groups freely. The hub provides browser access to powerful integrated simulation tools with cloud-based computing and is hosted through Amazon Web services.

The overarching goal of the platform is to accelerate innovation by sharing modeling and simulation tools. The future of simulation in composites is in work flow apps (Figure 4) which simulate and track composites manufacturing at each stage of processing, resulting in a 'digital twin' of the manufactured part: Additive 3D, Prepreg3D, Preform 3D, Autoclave 3D, Infusion 3D, Overmold 3D, SMC-BMC3D, and COST3D. Simulations for all aspects of part manufacturing are combined into the integrated work flow app. Testing of the work flow apps with real builds of composites (such as with the Cincinnati Big Area Additive Manufacturing (BAAM)) has provided key data to validate simulations. Dr. Pipes indicated that the work of the Composites Manufacturing and Simulation Center is strongly aligned with the NASA *Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems*, which envisions an "ecosystem...tailorable to roles and skill levels so that models, methods, best practices, tools, workflows, and information are widely accessible and available to appropriately skilled engineers and non-engineers including manufacturers, compliance officers, academic students, and supply-chain specialists." Dr. Pipes concluded by emphasizing that simulation is the language for manufacturing innovation and simulation ecosystem of 2040 must have the following characteristics (as indicated in the NASA *Vision 2040* document): accessibility, adaptability, interoperability, traceabiliy, user friendliness, and pervasiveness.

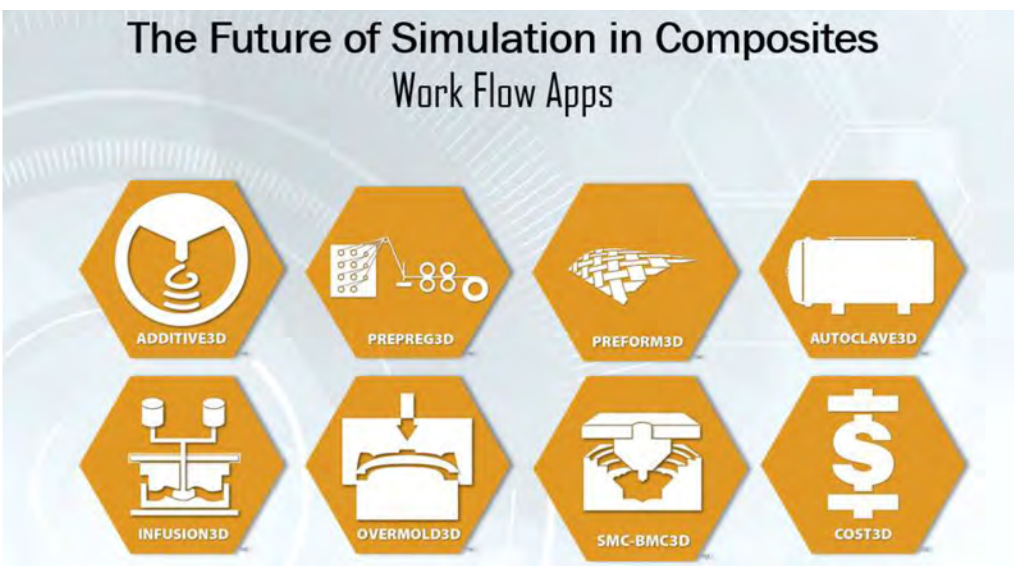


Figure 4. Work flow apps for simulation in composites manufacturing.
Image credit: Purdue University.

■ Advancing Technology Through Measurement Science: The Materials Genome Initiative 2.0 —Dr. Eric Lin, National Institute of Standards and Technology

Dr. Eric Lin is Director of the Material Measurement Laboratory (MML) at the National Institute of Standards and Technology (NIST). MML serves as the Nation's reference laboratory for measurements in the chemical, biological, and materials sciences. MML activities include fundamental research in the composition, structure, and properties of industrial, biological, and environmental materials and processes, to the development and dissemination of certified reference materials, critically evaluated data, and other measurement quality assurance programs. Dr Lin received a B.S.E. from Princeton University, and M.S. and Ph.D. degrees from Stanford, all in chemical engineering.

The advancement of many important technologies for economic growth in the United States is dependent upon the availability of the technical infrastructure. For example, the spectacular success in the transformation of semiconductor technology into an industry was aided by technical developments in electron microscopy, advanced electrical measurements, and lithographic process control. The mission of the NIST is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. NIST operates metrology labs (material measurement, physical measurement), technology labs (engineering, information technology, communication), and national user facilities (CNST, NIST center for neutron research). Programmatic priorities include advanced manufacturing, cybersecurity, disaster resilience, documentary standards, technology transfer, and measurement. NIST has a broad range of materials science activities that span topics from the Materials Genome Initiative (MGI) (Figure 5) to Advanced Manufacturing. This presentation provided an overview of ongoing programs and priorities in materials science and engineering at NIST, such as flexible electronics, directed self-assembly for advanced lithography, and additive manufacturing. Opportunities to engage with NIST were also presented, including the nSoft consortium and activities under the Materials Genome Initiative.

The MGI 1.0 sought to develop a materials innovation infrastructure of computational tools, experiment tools, and digital data; achieve national goals in energy security and human welfare with advanced materials; and equip the next generation of the materials workforce. MGI 2.0 focuses on accelerating the progress of machine learning and artificial intelligence (AI) approaches to improve validation times and increase accuracy in pattern recognition and classification. The development of these technologies through MGI could lead to a form of 'autonomous materials science' to efficiently develop new materials. Three key challenges in employing AI techniques to materials are: choosing effective descriptors for materials, choosing algorithm/work flow during AI design, and understanding the uncertainty in AI predictions. Dr. Lin highlighted materials modeling software, tools, and materials data resources which are managed by NIST as part of MGI. These resources, which include material property databases and algorithms to aid in materials selection and optimization, are available at http://mgi.nist.gov. To date, MGI has a number of success stories in accelerating materials development, including aiding in the design of new superalloy, materials with targeted properties, and a new material for a U.S. Mint coin. MGI also seeks to democratize manufacturing by making tools and data available to both large and small suppliers, facilitating and enhancing data science, and data exchange across the manufacturing base.

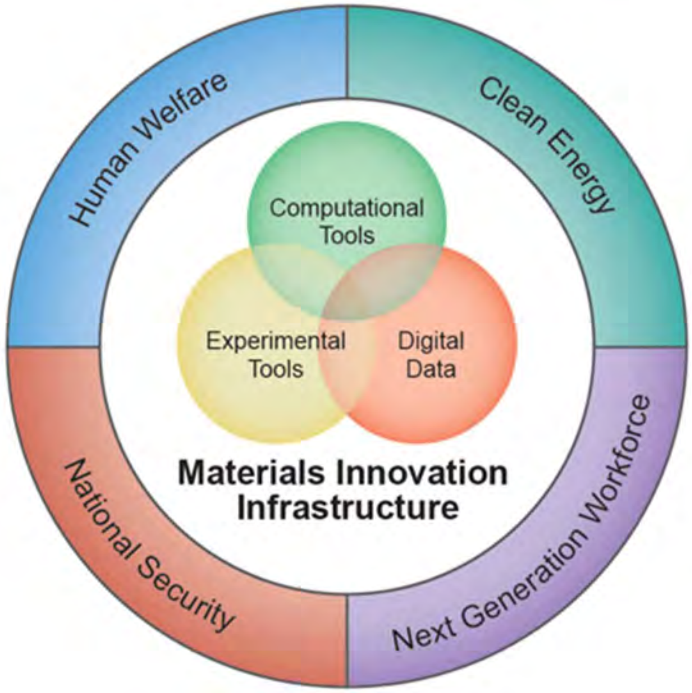


Figure 5. Materials Genome Initiative Infrastructure. Image credit: NIST.

■ Optimized Geometries Meet Optimized Materials: 3D Printing of Nanostructured Metals —Dr. Christopher Schuh, Massachusetts Institute of Technology

Christopher A. Schuh is the Department Head and the Danae and Vasilis Salapatas Professor of Metallurgy in the Department of Materials Science and Engineering at MIT. Schuh's academic training in Materials Science and Engineering focused on metals, including their processing, microstructure, and mechanics. He earned his B.S. degree from the University of Illinois at Urbana-Champaign in 1997, and his Ph.D. from Northwestern University in 2001. He held the Ernest O. Lawrence postdoctoral fellowship at Lawrence Livermore National Laboratory in 2001 before moving to join the faculty at MIT in 2002.

Nanocrystalline metals enable lightweighting of structures through material efficiency. 3D printing enables lightweighting of structures by geometric efficiency (i.e., depositing material only where it is needed). For additive manufacturing (AM), it is desirable to work with powder particles on the micron scale, but with crystal grains much finer on the nanoscale, to take advantage of both geometrical and material efficiencies simultaneously. While powders for metal AM can be made to incorporate nanostructure, typically this nanostructure is erased by melting and is not recovered in solidification. Sintering (pressureless) also leads to undesirable coarsening and slumping.

With materials and manufacturing processes developed by MIT and Veloxint, alloying elements can be added to stabilize grain boundaries and to sinter nanostructured materials without degrading the nanostructure. This is accomplished through material design which lowers the driving force for grain growth and also lowers the required temperatures for sintering. Accelerated sintering of nanostructured metals in a functional printed part is realized in the materials systems of Veloxint (which produces stabilized nanostructured powder) and the Desktop Metal 3D printing system (which extrudes this powder in filament form with a binder and sinters the resulting part). Research presented by Dr. Schuh showed that parts produced with nanostructured powders in the Desktop Metal unit displayed excellent material consolidation with minimal deformation during the sintering process. Shape retention after firing was favorable (there is a small but measurable loss of tolerances for some prints), as isotropic shrinkage is observed with this manufacturing process; parts can be designed with dimensions inflated in a predictable manner to account for shrinkage. Additionally, the rigidity of the feedstock material and the solid-state nature of the nano-phase separation sintering process prevents distortion in parts without support structures. Sintered parts produced with this process are shown in Figure 6. In materials design for this process, Veloxint has developed a stainless Cr-based alloy with a characteristic density of 7 g/cc, Young's modulus of 250 GPa, yield strength of 1.7 GPa, and a uniaxial strength greater than 2 GPa. Looking to the future, an MIT/NASA Marshall Space Flight Center collaboration explored nanocrystalline Nickel alloys designed for thermal stability and nanophase separation rapid sintering.

Figure 6. Jar with threaded cap (top image)—shows functionality immediately after sintering. Hollow core geometrically lightweighted step drill bit (bottom image). Image credit: Massachusetts Institute of Technology.

BREAKOUT SESSION 1—METALS

The metals section included presentations on lightweight metal composites made with additive manufacturing, development of lightweight Aluminum alloys for launch vehicle fuel tank applications, high-temperature materials and coatings for propulsion, and large-scale additive manufacturing with the MELD process.

■ Additive Manufacturing of Lightweight Metal Composites—Dr. Ethan Parsons and Dr. Todd Mower, MIT Lincoln Laboratory

Dr. Ethan Parsons is a Staff Scientist in the Applied Mechanics group at MIT Lincoln Laboratory and a Lecturer in the Department of Mechanical Engineering at MIT. Since receiving his Ph.D. from the Mechanics & Materials group at MIT, he has also worked as a Research Scientist at Schlumberger-Doll Research Center and several departments at MIT. His research focuses on additive manufacturing and the mechanics of composite materials.

MIT Lincoln Laboratory has developed lightweight metal composites and associated manufacturing techniques for numerous applications: Seeker radar, ISR sensing, satellites, space telescopes, and laser communication platforms. In any application, the prototype functional performance depends on the performance of its structural materials. Specific stiffness and thermal stability are critical performance indices for evaluating the use of a material. Minimizing weight, maximizing natural frequency, and minimizing thermal expansion are important for pieces of equipment sensitive to shifts in alignment. Cellular metal composites with tunable thermal expansion properties can be created using layered materials, such as those produced by ultrasonic additive manufacturing (UAM). The superposition of two metals with dissimilar coefficients of thermal expansion (CTE) can result in a zero effective CE. In these cellular materials, bending and rotation of cell walls counteracts thermal strain (positive delta T). In layered composites, the Poisson contraction offsets the thermal strain. In an Aluminum and Titanium layered composite, the materials have a CTE ratio of 3:1. In a tessellated structure, the macroscopic CTE is identical to the response of the triangular unit cell for Al-Ti. Ultrasonic AM was used to manufacture an Al and Ti material system. Subsequently, parts were machined from the AM-produced stock (Figure 7). Testing showed a negative CTE for the Aluminum and Titanium system with a tessellation pattern, matching model predictions. Specific stiffness in bending exceeded stiffnesses of solid Invar and aluminum.

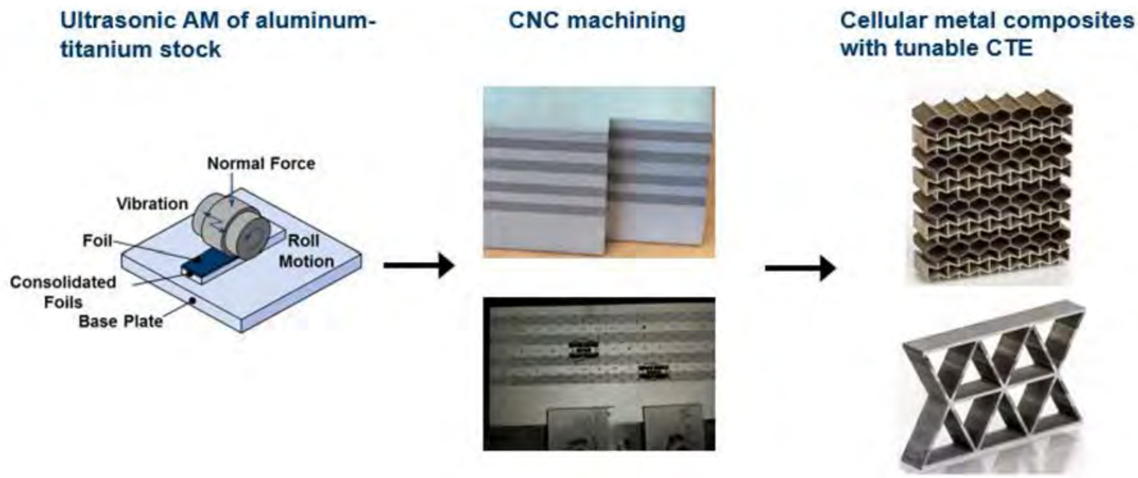


Figure 7. Ultrasonic AM of cellular metal composites with tunable CTE. Image credit: Massachusetts Institute of Technology Lincoln Laboratory.

Other 'tunable' materials include metal matrix composites (MMCs) produced with selection laser melting (SLM). To produce MMC powder feedstock, a stiff, strong, brittle ceramic powder (0.5–10 µm, the reinforcement material) is combined with a ductile Aluminum alloy pattern (40 µm, the matrix material) via novel powder processing methods. Powders are consolidated with SLM, resulting in a stiff, strong, and ductile composite with a complex geometry in a single manufacturing operation. Composite feedstock powder was ball milled to improve wettability and flowability in the SLM system. Volume fractions of 40% reinforcement are achievable with this technique. The Hall flow test demonstrated the composite powders flow as well as Al-Si10-Mg, which is an alloy commonly used as SLM feedstock. The power was able to be spread by the SLM recoater at a thickness of 30 µ (about the thickness of a human hair and a typical layer height for SLM processes). The composite tracks were smooth and continuous but narrower than Al-Si10-Mg.

Characteristic density of the fused powder was measured at 97% and was defect free at the scale of the reinforcement particles. As materials which are very difficult to machine and weld but have a very high strength-to-weight ratio, the ability to produce net-shape parts from MMCs with AM could enable their use in many aerospace and defense applications. Future goals for this research include refinement of powder properties and laser parameters and development of materials and methods for production of MMCs with commercial SLM systems.

■ Emergence of AirWare2050 for Space Applications—Mr. Michael Niedzinski, Constellium

Mr. Michael Niedzinski is responsible for introduction of aerospace and defense-related products and technologies developed by the Constellium Group to industry and government agencies such as MMPDS, SAE, AA, and Air Force. These range from the latest aluminum structural components, latest generation of aluminum alloys, and manufacturing technologies, which optimize and facilitate assembly techniques. Ultimately, these products become visible to Boeing, Lockheed Martin, Bombardier, and other aerospace companies. Michael has been involved with space programs such as Space Shuttle, Space Launch System, SpaceX, Blue Origin, ULA, Ariane 6, and Orion since 1994.

Constellium supplies aerospace plates, sheets, extrusions and forging stock to all major airframers and their tiers. Constellium has a wide product mix of standard alloys, high-performance/advanced alloys, and low density Airware® Al-Li solutions. Constellium is the market leader in Al-Li, offering the widest selection of mature products and forms in our Airware® family of products. Airware uses an AlCuLiZr family of advanced aluminum alloys offering weight reduction and corrosion and fatigue resistance.

Over 20 years ago, Airware 2195 was selected for the cryogenic sections of the Space Shuttle external tank. Airware 2195 provided over 3,000 kg in weight savings and payload improvements in this application. The material offered higher strength/modulus, improvements in stress corrosion cracking, and 5% lower density when compared to legacy 2219 plate. Current applications of Airware 2195 in various launch vehicles include: dome caps, barrel panels, stiffeners, adapters, gores/domes, and intertanks. Airware 2195 is intended for structures which require plate not exceeding 60 mm in thickness. To address requirements for structures in the thickness of 60–150 mm, Airware 2050 was developed as an evolution of Airware 2195. It offers the same improvements in strength and modulus with an A rating for stress corrosion cracking.

Over the past 10 years, Airware alloy 2050 has joined Airware alloy 2195 as a preferred plate material for both pressurized and non-pressurized structural components of space launchers and crew modules. The thickness range for 2050 can be expanded to match the applicable gauge ranges in alloy 2219 and 7050. Significant improvements in cryogenic toughness, a key requirement, have been demonstrated by multiple users. Drop-in replacements allow 5% weight reduction due to the lower density of Airware 2050 when compared to 2219. Reengineered structures demonstrate up to 10% weight reduction through thinner stiffeners with wider pocket spacing. As with Airware 2195, the product is readily joined via the friction stir welding process. Mature longitudinal, radial and mixed mode FSW joining has been fully demonstrated. Additionally, joining of dissimilar base materials such as 2050 and 2219 indicated a nugget strength higher than base 2219 plate. High ductility (elongation in excess of 20%) in T34 temper permits production of barrel and cone sections (Figure 8) through conventional forming processes such as roll and bump forming on plates up to 150 mm thick. This allows the production of monolithic, integrally machined grids and stiffeners. Constellium has also developed the AMS 4372 specification covering 2050-T34 temper and T82 aging capability response.

Figure 8. Airware 2050 panel machined and formed in T34 temper and aged to T84 temper. Image credit: Michael Niedzinski, Constellium.

Airware 2050 has been baselined for the upper (second) stages of two major space launch programs, while trade studies indicate that core stages of launch vehicles are also a suitable candidate for conversion from legacy 2219. Numerous other noncryogenic applications such as intertanks, adapters, and engine sections are currently being studied for conversion. The Airware 2050 material is readily available in commercial quantities, as significant amounts are currently being produced to support several commercial/military aircraft programs.

■ A Survey of High-Temperature Materials and Processes Development Through NASA's Small Business Innovative Research Program at Plasma Processes—Mr. Tim McKechnie, Plasma Processes

Tim McKechnie is President of Plasma Processes LLC. He has B.S. and M.S. degrees in Mechanical and Materials Engineering from Vanderbilt University. Tim has 35 years experience with advanced materials at Rocketdyne and Plasma Processes. He is a Fellow of ASM International.

Plasma Processes is a small business established in Huntsville, Alabama, in 1993. The firm specializes in high-temperature materials, refractory metals, metal alloys, ceramics, and coatings for the aerospace, defense, medical, and energy sectors. Plasma Processes has developed and improved upon a number of specialized processes to support high-temperature material fabrication and coatings work: vacuum plasma spray, EL-Form® Electrochemical Deposition, plasma spray, wire arc spray, powder alloying and spheroidization, silicide (diffusion process), and high-pressure cold spray. These breakthrough materials and processes have been significantly enabled by NASA's small business innovative research (SBIR) program. Plasma Processes first government contract was with NASA MSFC in 1993. Since then, the firm has leveraged over 25 SBIRs with MSFC, GRC, GSFC, LaRC, KSC, and JSC to advance the state of its coatings technology for aerospace applications. The presentation highlighted technology advancements from SBIR work with a focus on advanced propulsion applications (some examples are pictured in Figure 9). Some contract numbers appear in parentheses and can be used to reference the work in the public-facing SBIR database at www.sbir.nasa.gov:

- Rhenium thrust chambers for in-space propulsion (yield strength of 40 KSI and 10% elongation). Potential applications include apogee insertion, attitude control, orbit maintenance, repositioning of satellites/spacecraft, planetary descent/ascent, reaction control systems. (SBIR contract number NNX11CE22P)

- Advanced composite thrust chambers. Radiation-cooled, bipropellant thrusters are being considered for future lunar and Mars missions. Currently, Ir-Re combustion chambers are state-of-the-art. This work sought replacement of the Re structural wall of these chambers with a C-C composite to save mass. An innovative C-C composite thrust chamber was developed that incorporated advanced HfO2 and Ir liners. Vacuum Plasma Spray (VPS) and electroforming (EL-Form®) fabrication methods were developed for deposition of advanced hafnium oxide thermal barrier coatings and iridium oxidation protection coatings for thrust chambers. (SBIR contract number NNX10CB51C)

- High emissivity metallic nozzle extensions for radiation cooling.

  Nontoxic HydroxylAmmoniumNitrate- (HAN-) based Monopropellant Propulsion. Plasma Processes developed non-toxic HAN AF-M315E monopropellant as a potential replacement for in-space thruster systems which use toxic hydrazine as a chemical propellant. As demonstrated in testing, this propellant has a 12% higher ISP and 60% higher density-ISP than hydrazine. (SBIR contract number NNX12CA29C)

- Testing of a combustion chamber (100 lbf) for nontoxic ('green') propellant formulations.
  A mono-propellant chamber for HAN was developed in support of the Green Propellant Infusion Mission, an in-space demonstration of this green propellant for a satellite thruster system,

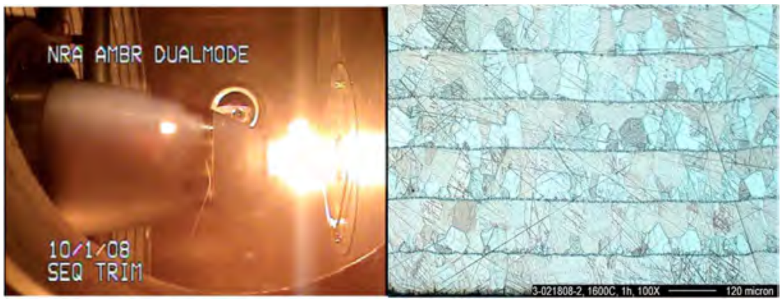


Figure 9. (left) Hot-fire testing of Advanced Material Bipropellant Rocket (AMBR) engine produced by Plasma and Aerojet. (right) Engineered Re structure after annealing at 1,600 °C for 1 hr. Pinning layers have prevented grain growth between the ductile rhenium layers. Image credit: Plasma Processes.

which launches in 2019 on a Falcon Heavy. The Ir/Re thrust chamber material (developed under a previous SBIR) was supplied to Aerojet Rocketdyne for five GPIM thrusters. (contract number NNX15CC18C).

- Spray-formed Mo-Re cartridges with alumina liners and TaC emissivity coatings for sample containment in a microgravity furnace. Leak test showed samples were vacuum-tight.

- Development of simulated fuel segments for Nuclear Thermal Propulsion. A critical aspect of the program is to develop a robust, stable nuclear fuel such as cermets comprised of uranium dioxide (UO2) particles encased in a tungsten matrix (W). Improved claddings are needed to prevent excessive fuel loss from reaction with the hot hydrogen gas and uranium hydride formation. Phase I demonstrated the feasibility to produce fine-grained W claddings using EL-Form® and VPS processing techniques. Both techniques were suitable for producing W claddings on preformed W-oxide based cermets. (SBIR contract number NNX13CM07P)

- High surface iridium anodes for electrochemical processing of lunar regolith. The developed anode allows melting of regolith simulant and sustained electrolysis with temperatures up to 1,650 ºC. Plasma Processes demonstrated the electrolysis of lunar regolith simulant JSC-1A using a containerless technique with self-heating iridium anodes to produce an iron-silicon alloy. (SBIR contract number NNX10CB20C)

- A highly wear-resistant coating, that when electrically activated, can repel/remove deleterious lunar dust. (SBIR contract number NNX10CA47C)

- Ceramic-matrix-composites (CMCs) for flight systems. Integration of CMCs into a material system is a challenge due to the CTE mismatch between the CMC and adjacent metal components. Innovative joining technology was developed to overcome the CTE mismatch while maintaining the structural integrity of the hardware. (SBIR contract number NNX16CM11C)

- Testing of composite radiation shielding materials using the Materials International Space Station Experiment (MISSE) platform. Plasma Processes coated the Parker Solar Probe heat shield (10 ft × 10 ft carbon composite heat shield that was plasma coated; closest man-made material to the Sun). (SBIR contract number 80NSSC18C0169)

■ MELD Manufacturing of Functionally Graded and Advanced Materials—Dr. Paul Allison, The University of Alabama

Dr. Paul Allison is an Associate Professor in the Mechanical Engineering Department at The University of Alabama, Tuscaloosa, AL. Dr. Allison is pioneering computational and experimental research on the Additive Friction Stir Deposition (AFS-D) solid-state additive manufacturing process, and is involved in characterizing the structure-property-processing relations of a variety of material systems to support basic and applied research projects. Prior to joining UA, Dr. Allison worked in the areas of force protection and force projection at the US Army Engineer Research and Development Center (ERDC) where Dr. Allison received the US Army ERDC - Research and Development Achievement Award for 2013 and 2014, the 2014 Department of the Army Commander's Award for Civilian Service, the 2011 Department of the Army Achievement Medal for Civilian Service, and the 2013 Department of the Army Research & Development Achievement Award for Technical Excellence.

Additive Friction Stir Deposition (AFS-D), commercially known as MELD, is a solid state layer-by-layer additive manufacturing process that provides a new path for repair, coating, joining and additively manufacturing materials such as functionally graded metal matrix composites (MMC). The AFS-D additive manufacturing process shares similar physics to traditional friction stir welding (FSW). However, a significant difference from FSW is that in AFS-D, metal powder, machine chips, or solid rod is fed through a non-consumable rotating cylindrical tool, generating heat and plastically deforming the feedstock material through controlled pressure from the tool as successive layers are built upon a substrate. The AFS-D process is illustrated in Figure 10. Additionally, this solid-state process does not require the use of lasers or electron beams to melt the material during deposition, eliminating fusion related defects. The AFS-D process produces fully-dense near net shape parts of high quality material at fast deposition rates with equiaxed and refined grains, can be operated in an open atmosphere environment at room temperature, and has low power consumption relative to other AM processes (47 J/mm^3). The AFS-D process is compatible with a wide array of materials, including Aluminum alloys, Magnesium, Titanium, Steel, superalloys, Copper, and MMCs. In MMC fabrication, two powders (a metal matrix and reinforcing material powder) are dispensed from dual hoppers. With this approach, the ratio of matrix/reinforcement can be carefully controlled, creating a functionally graded MMC. For the technical analyses presented, an aluminum powder was mixed with iron particles and deposited on an 1100 aluminum alloy substrate (commercially pure Aluminum) with the iron content varying from 2%-iron at the base to 24%-iron at the top of the build.

Subsequent material analysis was used to characterize the Fe area fraction, particle size, and hardness throughout the build. Asymmetrical hardness profiles were noted, as hardness decreases as material flows outward from the tool during manufacturing. Increasing iron content in the upper layers of the build corresponds to increased hardness.

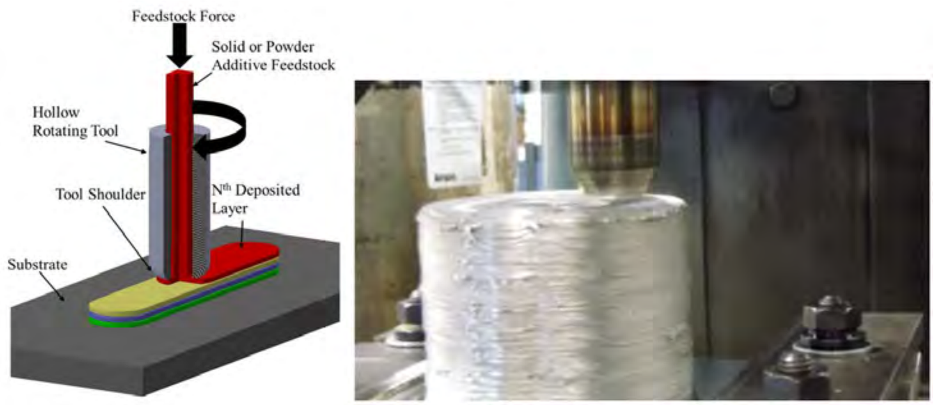


Figure 10. (left) Schematic of the MELD process. (right) MELD being used to produce a part. Image credit: The University of Alabama.

One objective of the AFS-D research at The University of Alabama is to develop a capability for repair of components with a minimal logistical footprint for aerospace applications. To enable repair in the field and/or logistically remote locations, UA characterizes process-structure-property relationships to calibrate and validate physics-based multiscale modeling of AFS-D components. This includes a smooth particle hydrodynamics (SPH) AFS-D process model, crystal plasticity modeling, physics-based internal state variable (ISV) plasticity-damage models, and multistage fatigue model (MSF). SPH provides a path to model the dispersion of reinforcing particles in the matrix material. Additionally, this presentation provided an overview of the experimental and computational investigation on the direct recycling of two waste streams: (1) machine chips and (2) field-damaged stacked strips deposited via AFS-D. X-ray Computed Tomography (CT) analyses shows fully dense depositions, while isotropic mechanical behavior is observed in large test articles. There was little difference in microstructure between material manufactured from a solid rod deposit and a recycled strip deposit. The AFS-D technique may thus be appropriate for in situ resource utilization of waste products.

BREAKOUT SESSION 2—NONMETALS

Breakout session 2 highlighted state-of-the-art work in thermoplastic material development, aerogel development (including examples of aerogel use in flight applications). The session concluded with high-level overviews of next-generation approaches to composites manufacturing, testing, and simulation under the helm of a national manufacturing institute.

■ Design and Manufacture of High-Performance Thermoplastic Compounds for Technically Demanding Applications—Mr. Alan Franc, Techmer

Mr. Alan Franc is Product Development Manager for Techmer PM in Clinton, TN. He received his B.S. in Chemical Engineering from Penn State University in 1995. He has worked for over 24 years in research and development, technical service and sales in various plastics industries. He has spent 19 of those years in technical management roles. He has authored two patents relating to crosslinked polyolefin foams and has led teams developing and commercializing products ranging from industrial intermediates to consumer goods. He is currently leading technical activities for additive manufacturing at Techmer PM.

Engineered thermoplastic compounds can provide many wide-ranging performance attributes to an application. There are many performance criteria to consider when designing and developing an engineered thermoplastic compound; among these are density, color/appearance, water/moisture absorption, barrier properties, shrinkage, coefficient of friction, hardness, chemical resistance, UV stability, radiation resistance, and odor.

Thermal property specific inputs include low or elevated temperature profiles, thermal conductivity, heat capacity, coefficient of thermal expansion, flammability, and heat aging. Other performance considerations in material design include: tensile, flexural, and compressive strengths; electrical properties (surface resistivity, shielding, dielectric properties); and processing characteristics (viscosity, thermal stability, shrinkage, and cooling rate). This presentation discussed how these inputs translate into materials design, formulation and manufacturing solutions available to meet identified performance criteria, and case studies in the emerging market of large part additive manufacturing demonstrating the successful implementation of these steps.

The raw materials for design of thermoplastic compounds are resins, fillers and reinforcements, flame retardants, conductivity additives, and friction and wear additives. A base polymer is either amorphous (random molecular structure, gradual transition to flow at glass transition temperature) or semi-crystalline (ordered molecular structure, sharp transition to flow at melting temperature). Within each class of base polymers, a polymer may be further classified as a standard polymer (lowest strength), an engineering polymer (higher strength relative to standard polymers), or a high-performance engineering polymer (highest strength). Fillers are materials intended to displace a resin in an application, which can lower the cost of the material. Reinforcements are materials that improve strength properties. Common fillers and reinforcements include Calcium Carbonate, clay, talc, Wollastonite, glass fiber (E-glass and S-glass), basalt fiber, aramid fiber (generally not used as a reinforcement for thermoplastics), and carbon fiber (PAN-based). Figure 11 shows the effect of fiber type and reinforcement percentage on the strength of PA66, a semi-crystalline engineering polymer. Depending on the additives used, engineered thermoplastic compounds have a wide array of electric conductivity. High-performance engineering polymers are inherently flame retardant. To enhance flammability resistance in other material classifications, halogenated and non-halogenated additives may be included in the material formulation.

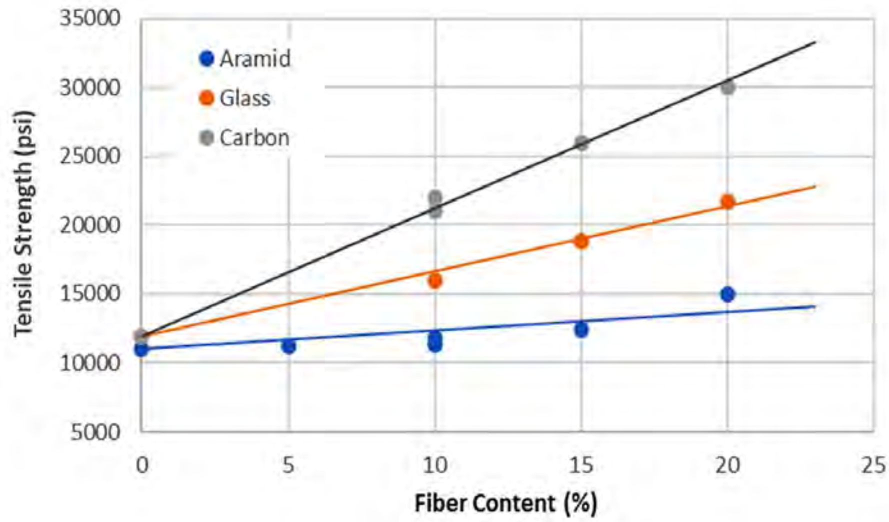


Figure 11. Tensile strength versus fiber content. Image credit: Techmer.

Properties of thermoplastic compounds are validated via testing to the relevant ASTM standard. Common tests include tensile, flexural, and impact resistance; surface resistivity and dielectric strength; deflection temperature under load; flammability via UL-94 or ASTM E-84; and tribology/wear rate.

The presentation included case studies of materials development to support a large-scale AM process. One such materials development activity was in support of a company competing in the NASA 3D Printed Habitat Challenge, a multi-phase competition focused on technology and materials development to enable large-scale AM for planetary surface construction. HiFill PETG 1706 3DP – PETG is a resin with exceptionally high loading of basalt and extremely high strength. The material contributed to the winning entry from Branch Technology and Foster + Partners in the phase II 3D Printed Habitat Challenge. Techmer also developed Electrafil PESU 1810 3DP, which has the properties of a resin- based composite material, but is able to be processed with 3D printing systems. The material was used in one application to manufacture thermoplastic tooling for autoclave curing of composite parts. HiFill FR PA6 G/CF25 FR-N IM BK002 was designed to meet standards for protection of personnel in explosive environments. Glass in the formulation provides stiffness and the carbon fiber dissipates electrical charges. The formulation was used in a self-contained breathing apparatus (SCUBA) frame for firefighters.

■ Aerogels: Ultralightweight Materials With Multiple Applications—Ms. Jessica Cashman and Dr. Frances Hurwitz, Glenn Research Center

Ms. Jessica Cashman is a Chemical Engineer at NASA Glenn Research Center working in the Materials and Structures Division where her primary focus has been on aerogels. She graduated from Rochester Institute of Technology with a B.S. in Chemical Engineering in May 2018.

Dr. Frances Hurwitz is a Senior Materials Research Engineer in the Materials and Structures Division at NASA Glenn Research Center. Fran has 39 years of experience in materials research, spanning polymer composites, carbon/carbon, ceramic matrix composites, polymer-derived ceramics, thermal protection systems and high-temperature aerogels and their composites. She participated in the Columbia Accident Investigation and the study of shuttle wing leading edge materials aging. She also supported an MSFC-led team to study space environmental effects on ceramic matrix composites.

Aerogels are extremely porous, lightweight solids comprised of a skeletal nanostructure and nanoscale pores. The nanoporous architecture is typically formed as a gel, and through super-critical fluid extraction or other methods, the solvent is removed and replaced with air. Aerogels have extremely low densities, high porosity, and high surface areas. These characteristics lead to materials with very low thermal and electrical conductivities as well as extremely small dielectric constants, approaching one as density decreases. Both inorganic and polymer-based aerogels were discussed with a focus on their unique space applications, including radioisotope thermoelectric radiation insulation, thermal barrier insulation, inflatable decelerators, multilayer insulation, and lightweight antenna substrates.

The primary application space for aerogels are as insulators; aerogel materials can be an order of magnitude better insulators than fiberglass materials. Silica aerogels are limited to 600–700 °C and higher operating temperature ranges are desirable. Past research efforts have focused on the use of Boehmite precursors to form alumina and aluminosilicate aerogels capable of maximum temperatures up to 1,200 °C. More recent efforts have focused on aerogels made from yttria-stabilized zirconia (YSZ) which is commonly used for thermal insulation. YSZ already has low thermal conductivity, but would perform even better as an aerogel as the structure is effective at limiting gas convection, and provides a tortuous path for conduction.

Polyimide aerogels use polymer chains as a precursor for the aerogel. These aerogels exhibit superior mechanical properties compared to the inorganic aerogels at the expense of high-temperature operation, with maximum temperature capability capped at about 400 °C. These aerogels are more durable and can be flexible while still maintaining low density and high surface area.

Aerogels have many potential spaceflight applications where decreased thermal conductivity or lower weight are desirable. High-temperature inorganic aerogels could be used for insulation in next-generation radioisotope thermoelectric generators for unmanned missions. They could also be used in composites for thermal barriers, such as seals and gaskets (Figure 12).

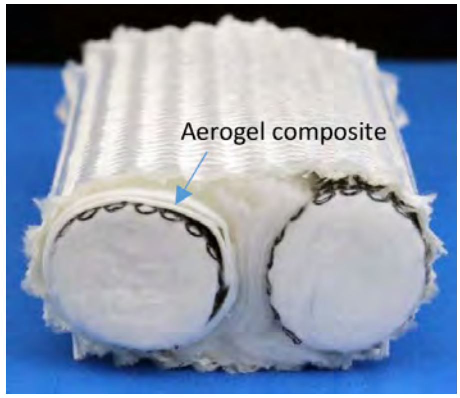


Figure 12. Aerogel composite thermal barriers. Image credit: NASA.

Polyimide aerogels are potential replacements for scrim layers in multilayer insulation (MLI), improving thermal conductivity over baseline MLI by 20% to 30% and expanding operational space to include gaseous environments. Finally, these lightweight materials have potential applications as lightweight antenna substrates.

■ US-COMP: Next Generation of Composite Materials for Crewed Space Mission
—Dr. Greg Odegard, Michigan Technological University

Dr. Greg Odegard is the Richard and Elizabeth Henes Professor of Computational Mechanics in the Department of Mechanical Engineering—Engineering Mechanics at Michigan Tech. He is the Director of the NASA Institute for Ultra-Strong Composites by Computational Design. Before joining the faculty at Michigan Tech, Greg was a researcher at NASA Langley Research Center from 2000–2004. His research is focused in computational modeling of advanced material systems.

Current state-of-the-art composite materials are not light/strong enough for crewed missions to Mars and beyond. Structural components of deep space vehicles require lighter and stronger materials for maximum fuel efficiency. The NASA Space Technologies Research Institute (STRI) for Ultra-Strong Composites by Computational Design (US- COMP) is focused on developing a new generation of composites for this purpose. US-COMP is using computational simulation to drive the material design in an efficient manner. By developing new simulation tools, experimental methods, and databases of material information, US-COMP is playing a central role in the national Materials Genome Initiative (MGI). The ultimate goals of US-COMP are to design, fabricate, and test composite panels that meet NASA's requirements and to train students to enter the advanced composite materials workforce.

NASA's future exploration missions will require advancements in composite properties and a paradigm shift in modeling and testing. 'Exploration composites' are expected to require a three-fold increase in tensile properties (quasi-isotropic specific tensile strength and modulus), a 50% increase in fracture toughness, panel level testing, and an MGI (Materials Genome Initiative) based approach for multiscale material optimization. US-COMP is part of the first generation of NASA STRIs and has the objective to: develop and test novel composite materials (TRL-1 to TRL-4), establish new computationally-driven material design paradigms for rapid material development and deployment, and develop modeling and testing tools. US-COMP consists of 11 universities and 23 faculty (Michigan Tech, Florida State University, University of Utah, MIT, Florida A&M, University of Minnesota, Johns Hopkins University, UC Boulder, GA Tech, Penn State, and Virginia Commonwealth University). Industry/government lab participants include Nanocomp, Solvay, and the Air Force Research Laboratory. The technical advisory board consists of NASA, Boeing, Lockheed Martin, U.S. Air Force, and Northrup Grumman. The institute includes efforts on next-generation workforce training to support a new cadre of technicians and engineers skilled in advanced composite fabrication. The institute is closely aligned with the work of MGI and uses a three-fold approach to materials modeling: (1) Computational tools enable multiscale simulation and topology optimization, (2) experimental tools are used for multiscale characterization and panel-level mechanical tests, and (3) digital data for design is used to derive process/property relationships and create a mechanical property database to inform structural modeling efforts. Research teams are divided into four groups:

(1) Simulation and Design team: Force field development, atomistic/molecular modeling, meso-scale modeling, and continuum modeling.

(2) Testing and Characterization Team: Materials characterization, mechanical testing, and thermal and electrical testing.

(3) Materials Synthesis Team: Ultra-dense carbon nanotube structures, CNT/polymer interfaces.
(4) Material Manufacturing Team: Manufacturing scale-up and materials characterization.

The work of these teams is highly integrated. US-COMP is approaching the end of year 2 of 5 years of initial institute funding. One overarching project objective is to develop a composite material with a specific tensile strength 3 GPa/g/cc and 150 GPa/g/cc specific modulus. Currently, US-COMP is measuring material performance at the level of 1 GPa/g/cc for tensile strength and 80 GPa/g/cc for specific modulus (which is already well beyond the identified state-of-the-art material with ~0.5 GPa/g/cc specific modulus and ~35 GPa/g/cc tensile strength. Figure 13 shows the US-COMP progress to date.

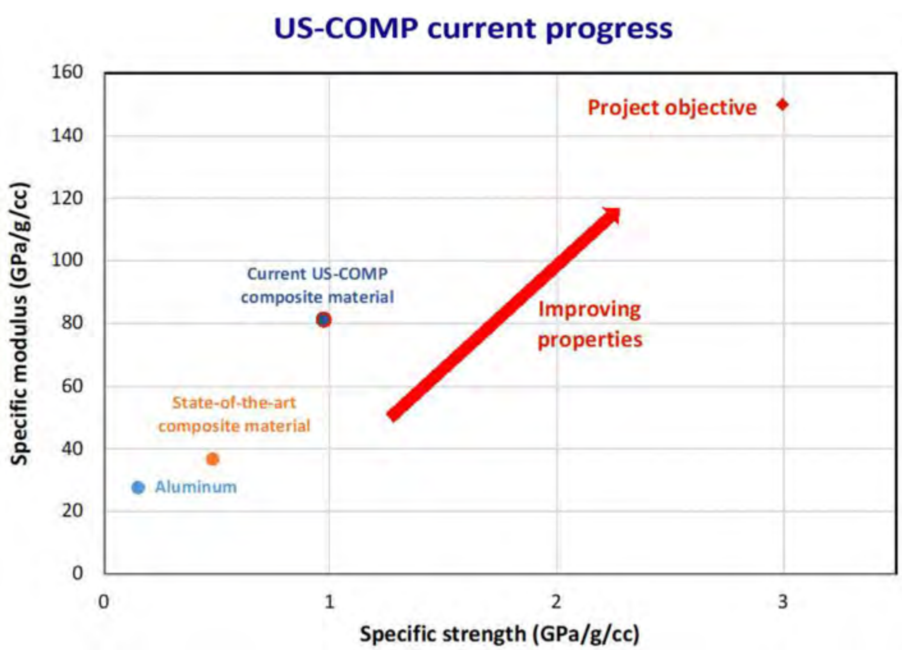


Figure 13. US-COMP progress to date in advancing material properties for composites. Image credit: US-COMP.

Another project under US-COMP seeks to develop machine learning algorithms to accelerate the design of composite materials. An initial proof of concept of this work was development of a predictive model of process/property relationships CNT/epoxy composites. Current molecular simulations for composites have long run times and high complexity. Machine learning techniques present an alternative and more efficient method to explore the design space for some materials.

Results of the machine learning algorithm for predicting pullout force were in strong agreement with the molecular simulation results. The next 3 years of US-COMP will continue to advance the state-of-the-art in composites fabrication and modeling efforts. Materials development derived from this work will open the door for new composite applications in the space industry with the goal of reducing system weight, enhancing system performance, and increasing payload mass for future exploration missions.

BREAKOUT SESSION 3—COMPUTATIONAL MATERIALS

Session 3 on computational materials highlighted advancements in process modeling for composites and metals. There was a specific focus on leveraging computational tools to support development and certification of additively manufactured metallic materials.

■ Enhanced Manufacturing Through Process Modeling: A NASA Advanced Composites Program (ACP) Approach—Dr. Sayata Ghose, Boeing

Dr. Sayata Ghose is an Associate Technical Fellow at The Boeing Company working on composites fabrication and Boeing's manufacturing lead on the NASA Advanced Composites Project. Prior to joining Boeing she worked as a researcher for 7+ years at NASA Langley Research Center. She has two B.S. degrees—one in Chemistry and one in Polymer Science—and received her Ph.D. in Polymer Engineering from the University of Akron.

The advanced composites consortium (ACC) is a consortium consisting of members from government, industry, and academia. The ACC seeks to support activities which relate to three key technical challenges in composites: (1) Development of a predictive capability to assess the strength and life of components and subcomponents, sufficient for design and fabrication, (2) rapid, quantified conditional assessment, and (3) efficient manufacturing development with performance-based quality control. The ACC has developed physics- based models to improve the quality of fabricated composite structures by reliably predicting the automated fiber placement, co-cure, and laminate cure processing parameters. This advancement helps to transition the process of composites manufacturing parameter development from iterative to predictive/knowledge-based and reduces the traditionally experimentally intensive process required for production certification. This presentation provided an overview of several physics-based models for composites manufacturing developed under the helm of the ACC.

Development of the physics-based automated fiber placement (AFP) process model consisted of several activities: material tack characterization established material properties to serve as inputs for physics-based modeling efforts; layup design of experiments linked data on layup tools, materials, and tape widths to material outcomes; mechanical defects were characterized to determine the effect of laps, gaps, and puckers on performance; predictions of the AFP were validated using DOE results. The physics-based laminate cure defects process model is designed to predict location and intensity of porosity in a cured laminate. Thermal propagation and resin flow are integrated into a three-phase system of fiber, resin, and void. The model's predictions were within 20% of test data from physical parts (parts had <3% porosity). Figure 14 shows the AFP layup defect prediction.

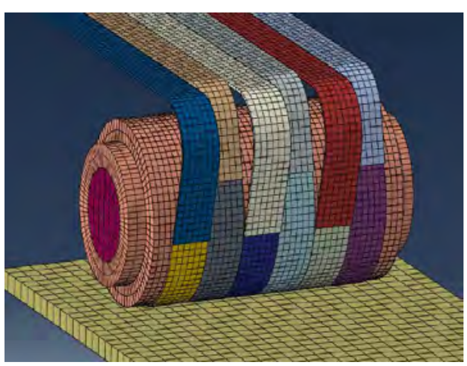


Figure 14. Image of AFP layup defect prediction. Image credit: Dr. Sayata Ghose, Boeing.

A new Design for Manufacturing (DFM) software has been created with a goal to improve structural strength as well as the surface quality of the part by predicting where defects will occur during a particular layup. The DFM software has developed a central optimizer that works with other commercial softwares (path simulations, FEA, sizing etc.) and will enable integration with commerical-off-the-shelf software products commonly used in materials and manufacturing industries. DFM represents a new software tool used to incorporate feedback from AFP manufacturing in laminate strength analysis and optimization. Members of the consortium are working to test and verify this software by comparing optimized designs with baseline designs and the prediction of models with data derived from validation builds.

SANDWICH is a physics-based process model designed to predict bond line defects that occur during fabrication of honeycomb structures. SANDWICH can also provide warnings and predictions of extreme and critical situations during a particular manufacturing procedure. The process model can predict and provide quality/defect information on the final facesheet consolidation, adhesive bond-line formation, and fillet and void growth, as well as pressure evolution. The model is provided as a standalone code for commercial and industry use. Another model is the physics-based core crush process model, capable of modeling honeycomb core crush in sandwich structures based on geometry, material, and processing factors.

In summary, all model creation and validation under ACC is based on an extensive experimental database provided by NASA and original equipment manufactures. Validation trials are typically shared only within the consortium. The desired outcomes of these activities are to reduce manufacturing process development time, reliably predict performance of composites based on inputs from the materials and processes, and accelerate the technology readiness level associated with use of composites in aerospace applications.

■ Motivation, Development, and Future Directions for Computational (Metallic) Materials at NASA—Dr. Ed Glaessgen, NASA Langley Research Center

Dr. Ed Glaessgen is NASA's Senior Technologist for Computational Materials. In this role, he plans, leads, and performs research aimed at advancing the state-of-the-art in understanding the fundamental physical phenomena that results in macroscopic material properties and behavior. Of particular interest is the development of computational and experimental methods needed to develop processing-microstructure-performance relationships for structural and multifunctional materials under representative environments and loadings.

Computational materials is a field that integrates materials science, solid mechanics, data science, and high-performance computing to develop critical tools for understanding the link between process, structures, and property/performance. Computational materials may provide enabling capabilities that are needed to address key problems in the NASA's mission portfolio. Among the several NASA investments in this growingly influential field is the development of next-generation computational materials-based capabilities to support development and certification of advanced metallic materials, including:

- Development of relationships between in situ thermographic data and defects in as-produced additively manufactured materials.
- Development of processing-to-microstructure relationships, including high-fidelity in situ process characterization, in situ strain measurement, development of thermal process models, and part-scale residual stress predictions.
- Development of microstructure-to-performance relationships, including computational and experimental studies of the effects of defects on crack initiation and growth and development of a microstructurally-informed durability and damage tolerance work flow.

Further, NASA is working to ensure relevance of the effort and planning to transition the developed capabilities from its research foundation to engineering practice. This aspect includes collaboration among several NASA research and flight centers, other government agencies, and several aerospace corporations.

This presentation provided the specific motivation for the work and discussed current developments and future directions. Among the various motivations discussed, perhaps the most significant is related to long-duration spaceflight. While ISS can be reached in 2 days and is readily accessed with commercial launch vehicles, transit times beyond the Earth-Moon system range from weeks to months. As a result, the current paradigm of resupply, repair by replacement, redundant hardware, and retreat to Earth is insufficient to meet mission demands; computational materials will be an enabling factor in achieving the unprecedented durability and extreme reliability required for these missions.

Recent ongoing and future work toward computational materials capability development includes the following:

- Ultra-Thin Composite Overwrapped Pressure Vessel (COPV) Liners: With liner thicknesses approaching 0.005 in, classical engineering mechanics and corresponding similitude assumptions begin to break down (cracks are large relative to liner thicknesses and material microstructures).

- Crack Nucleation in High-Strength Aluminum Alloys. 7075-T651 Aluminum and some other precipitation strengthened alloys can fail due to a process that begins with cracking of second phase (e.g., Al-Fe-Cu) particles. Crystal plasticity and slip accumulation models can be used to understand and predict microstructures that are prone to crack initiation by this mechanism.

- Materials Design: Computational materials models suggest that a combination of nano-grained and coarse-grain regions in a structurally-graded material may result in a significant increase in yield stress while maintaining ductility and toughness.

- Qualification of Additive Manufacturing (AM) Components and Processes: Computational materials methods can improve confidence in AM processes (e.g., selective laser melting, SLM) used to manufacture engine components and accelerate certification of parts for propulsion applications. Computational materials-based simulation may reduce manufacturing process development times and serve as an important supplement to in-process build data and test data from witness coupons (Figure 15). In SLM, the HIP process is used to consolidate the material and remove defects from the AM process (such as porosity). Computational materials can be used to predict the resulting microstructure (including precipitate volume fraction and residual stress), void closure, and remnant (post-HIP) porosity of an AM part as a function of HIP temperature and pressure. Additionally, the effects of the resulting microstructure and porosity on fatigue life can be estimated. Computational materials methods in this application provide a critical tool for reducing the iterative process development associated with HIP parameter development.

- Validation of experimental post-HIP pore data will guide refinement of these simulations and further improve their predictive capability. In situ monitoring of AM is an increasingly important capability for qualifying processes and is becoming another source of model validation data.

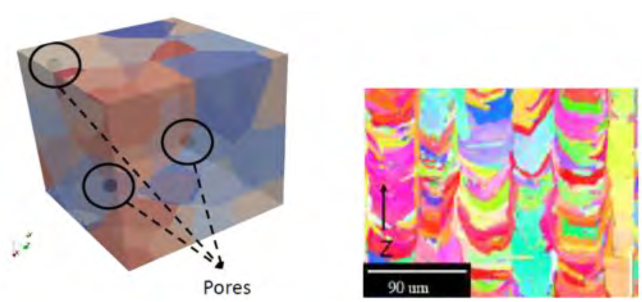


Figure 15. (left) Incorporation of defects from SLM (porosity) in 3D simulations. (right) Image of predicted microstructure. Image credit: NASA.

Other, lower TRL, thrusts of computational materials research focus on the development of simulation techniques needed to predict material behavior at atomic and dislocation scales and bridge the gap between simulation length scales (e.g., concurrent multiscale modeling wherein atomistic simulation is embedded within a continuum finite element simulation to provide more appropriate boundary conditions, sequential multiscale modeling wherein response quantities are taken from atomistic simulation for later use in dislocation scale simulation). Other computational materials modeling focuses on simulation of the fundamental physics governing materials processing and characterization of material evolution (e.g., transient heat diffusion with phase change).

In 2018, NASA published the document "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems" as NASA/CR—2018–219771, which lays out a future path toward full integration of computational modeling in the design, development, and testing process for materials and processes. Through a series of surveys, workshops, and validation exercises, Vision 2040 called upon the combined expertise of over 450 contributors throughout the materials science and engineering supply chain who worked collectively to determine the criticality and priority of numerous identified gaps and actions and then voted unanimously to endorse the findings of this study.

■ Computational Materials for Qualification of Advanced Manufacturing Metals
—Dr. Theron Rodgers, Sandia National Laboratories

Dr. Theron Rodgers is a Senior Staff Member in the Computational Materials Science Department at Sandia National Laboratories in New Mexico. He received a B.S. in Physics from the University of Missouri and a Ph.D. in Engineering Physics from the University of Virginia. His doctoral research focused on simulating vapor deposition of turbine blade coatings. Since joining Sandia, Theron's work has focused on developing computational process-structure-property-performance analyses for applications including welding, additive manufacturing, and thermal spray.

Many advanced manufacturing methods produce materials with nonequilibrium and heterogeneous microstructures that result in different properties than the same material created by traditional processing methods. Processes such as additive manufacturing (AM) may result in materials with nontraditional microstructures, significant defect populations, and residual stresses. These manufacturing methods often have many degrees of freedom (e.g., the scan pattern used in laser powder bed additive manufacturing, weld speed, and power schedules) that influence the as-processed microstructure. Additionally, these methods often create material and component simultaneously, thus preventing the use of independent material and component qualification approaches. This presentation discussed the use of mesoscale computational materials science methods to study the connections between processing methods and resulting performance.

Small changes in laser welding parameters can vastly affect grain structure in weld. Spline-based weld pool shapes allow rapid simulation of 3D weld microstructures and grain coarsening in the heat-affected zone. Results show geometric variability (e.g., porosity, weld root geometry) is the primary driver for global structural variability observed among laser welds in tension. For this study, simulation curves aligned closely with load displacement curves generated in experiments.

Thermofluid powder bed simulations for AM are highly detailed level-set simulations with extensive physics. Molten metal and gas flow, and vapor recoil pressure, can be simulated. Evolution of microstructure is highly sensitive to process parameters. Synthetic AM microstructures (generated via SPPARKS, a Sandia-developed software tool for simulating microstructure) can be used as input microstructures for crystal plasticity simulations and generate resulting stress-strain response (with CP-FEM). A 'lumped laser' model can capture spatial dependence on thermal gradients; in some cases, larger laser spot sizes can be used to reduce simulation times without compromising the model's predictive capability (Figure 16).

In thermal spray processes, coatings are formed by the successive impact of molten particles. Resulting microstructures are stochastic and include pores, unmelted particles, cracks, and anisotropic microstructures. Grain sizes are typically on the order of 1 µm. The rules-based thermal spray microstructure model predicts the diameter of melted particles and porosity. Results indicate that increasing the molten spreading of particles during manufacturing reduces porosity in the resulting coating.

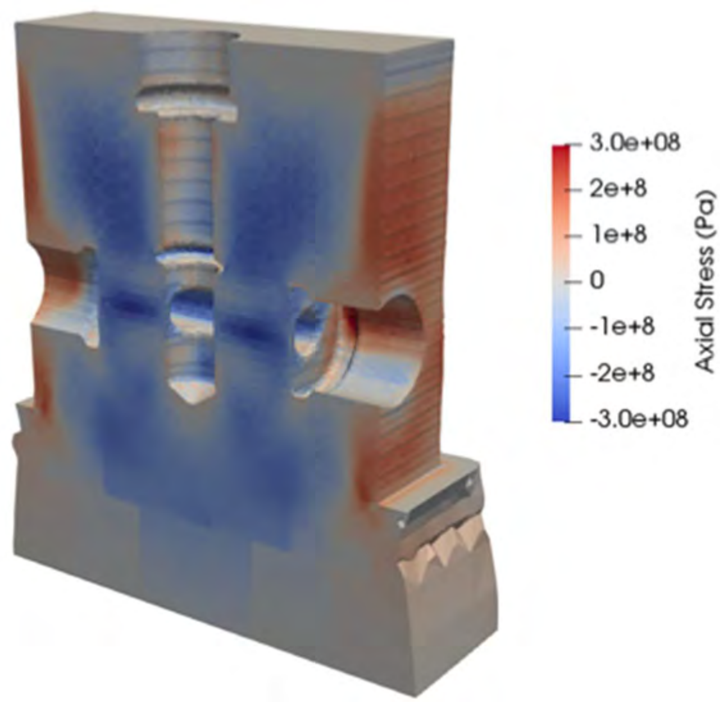


Figure 16. Macroscopic residual stress predicted with 'lumped laser' model.
Image credit: Kyle Johnson, Sandia National Laboratories.

Enabling technologies and methods developed by Sandia for computational modeling include the following:

- SPARRKS, a framework to simulate mesoscale microstructure.
- STITCH, a library capable of simulating overlapping subvolumes across a large domain (used in the laser welding simulation profiled in this presentation).
- SCULPT, a part of CUBIT, which enables meshing of complex models.

In summary, computational methods are evolving to address material heterogeneities introduced by new and advanced manufacturing processes. Computational materials is key to incorporating the effects of microstructure, residual stresses, and porosity in classical continuum materials models. Models should move toward including manufacturing effects on material properties rather than assuming bulk properties are present. Future work can improve the understanding of multiphase materials, grain-scale residual stress, and dislocation densities.

■ Modeling of Polymer Matrix Composites Within the Air Force Research Laboratory Materials and Manufacturing Directorate—Dr. David Mollenhauer, Air Force Research Laboratory

Dr. David Mollenhauer is a Principal Materials Engineer at the U.S. Air Force Research Laboratory (AFRL) in Dayton, Ohio. He received his Ph.D. in Engineering Mechanics from Virginia Tech in 1997. His AFRL career has focused on the mechanics of failure in polymer matrix composites (PMCs), developing experimental data for discovery of phenomena and advanced numerical techniques and codes to simulate PMC failure processes.

United States Air Force (USAF) certification criteria focuses on damage tolerance, slow damage growth, fail safe structural designs, multiple load path designs, and damage arrestment. Barriers to certification of polymer matrix composites include manufacturing variability, limitations of nondestructive evaluation to detect defects in these materials, and damage growth. Based on a study from the National Institute for Aviation Research (NIAR), activities for certification of a PMC component require approximately $9 million in materials, $25 million for testing, and a timeframe of 8 to 14 years.

Certification is a lifecycle process. Structures must be designed to gracefully degrade. It is also assumed that structures contain both manufacturing and service-induced defects. Damage tolerance requires an understanding of slow damage growth and fail-safe structural designs. Fail-safe designs include multiple load path designs and damage arrest. Safe-life is a certification alternative. (Structures can operate below the endurance limit and retire before the fatigue life is reached.)

PMC manufacturing is highly variable. Ply stacking order can affect the measured strength, even with the same number of stacks and orientations. Matrix damage can accumulate in the laminate, but may not transfer between plies. The zero-degree ply often, but not always, governs the resulting strength of the laminate. BSAM is a discrete damage modeling code which models individual ply cracks to understand and predict how they interact with other cracks and defects. BSAM can simulate the initiation of cracks, the resulting damage to the matrix with crack propagation, and the initiation/propagation path which results in fiber damage (Figure 17). Dr. Mollenhauer presented some select examples of BSAM modeling code in applications. These included: overheight compact tension (notched composites loaded in tension), crack migration and fiber bridging (oscillating cracks at 90/90 interface), and a two-cell stiffened panel with a hole. Future work is in higher computational models, as processed initial statistics, stochasticity and variability, environmental effects, model-based material optimization, and advanced experiments to correlate with model data.

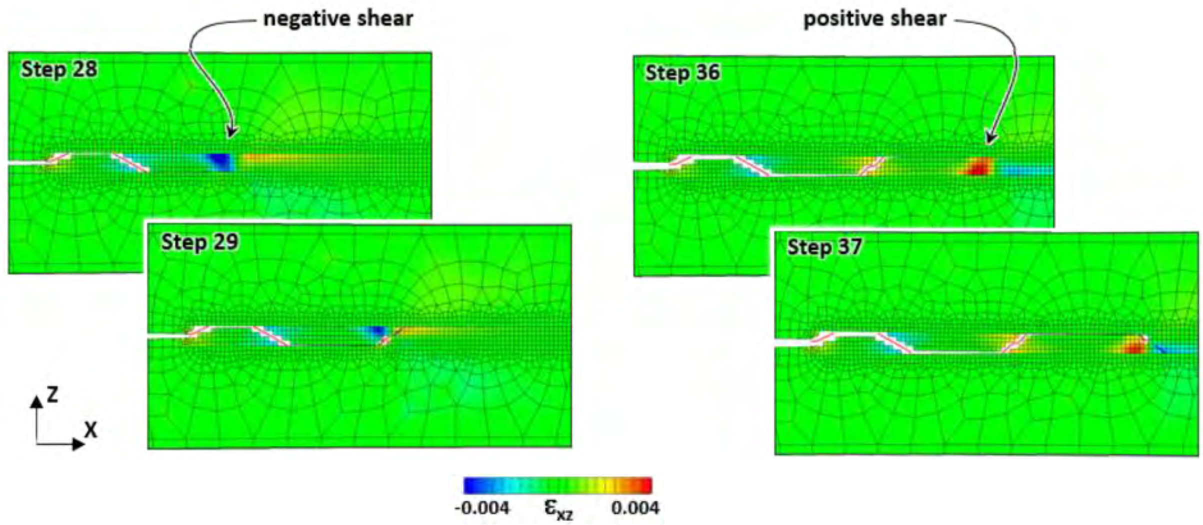


Figure 17. Simulation of crack migration and fiber bridging created with BSAM.
Image credit: Air Force Research Laboratory.

BREAKOUT SESSION 4—TESTING AND CHARACTERIZATION

Session 4 on materials characterization highlighted novel and new approaches to materials testing for nanomaterials, high-performance and high-temperature materials, and additively manufactured materials. Several presentations considered perspectives on approaches to testing and characterization to support use of materials specifically in aerospace applications.

■ Nanocalorimetry: Faster, Smaller Chip-Based Thermal Analysis—Dr. David A. LaVan, National Institute of Standards and Technology

David LaVan is a Project Leader in the Materials Measurement Science Division in the Material Measurement Laboratory at the National Institute of Standards and Technology (NIST). His work has focused on materials science challenges at small scales, with a focus on microelectromechanical systems (MEMS), machine design, and instrument development. He has a Ph.D. in Mechanical Engineering from The Johns Hopkins University and a B.S. in Materials Science and Engineering from the University of Florida. His post-doctoral training was at Sandia National Labs and then a joint Harvard-MIT program.

Nanocalorimetry is a method for thermal analysis of materials at high rates and capable of measuring very small samples. It is useful for measurements on advanced materials including thin films and nanomaterials, where samples are limited, or the behavior is expected to change at larger volumes. An overview of the nanocalorimetry method was presented, along with specific examples of materials measured and examples of the integration of nanocalorimetry with other analysis techniques.

The nanocalorimeter device consists of a microfabricated silicon nitride and platinum chip, approximately 13 mm in length, connected to precision resistors, voltmeters, and power supplies. The chips are individually fabricated and calibrated. The device provides the capability to measure heat capacity, transition temperatures, and energies, with heating rates from 100 K/s to 1,000,000 K/s and sensitivities better than 1 nJ/K. The devices are suitable for a range of temperatures from room temperature up to 1,570 K, limited only by the capabilities of the component materials. Sample sizes are small, ranging from 1,000 ng down to approximately 1 ng. The devices are easily integrated into other instruments due to their small size and low power requirements and are highly programmable using LabView[*] (commercially available programmable control software). The programmable capability allows for the application of arbitrary heating cycles to the test specimens, with cycle times as low as 5 ms (with data sampled every 5 μs).

The unique capabilities of the nanocalorimeter device enable measurements that would be challenging or impossible for traditional methods[i]. The small sample size requirements enable the devices to be used to characterize energetic materials that are dangerous in larger quantities, novel materials that are only available in small quantities, or materials that have properties that vary based on length scales. The high heating rates allow for investigations into the response of materials at these extreme conditions, and the rapid heating cycle and quick response time of the instrument allows for measurements of properties that are time-dependent in μs scales.

[*]Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.

Several examples of measurements that were obtained using the nanocalorimeter devices were presented. These included:

- Measuring heat capacity of lipids that are susceptible to thermal changes caused by hydration. The rapid heating cycle and quick response time of the instrument allowed for the characterization of properties for both the hydrated and dehydrated states, which were difficult to measure due to rapid rehydration of the specimens.
- Measurement of transition temperatures for aluminum thin films, which demonstrated recalescence.
- Measurement of the reaction energies associated with the decomposition of copper oxide nanoparticles on rapid heating.
- Characterization of energetic materials, such as trimethylenetrinitramine (RDX) or trinitrotoluene (TNT), using ≈100 ng quantities to avoid critical mass, as shown in Figure 18.
- Integration into a Dynamic Transmission Electron Microscope (DTEM) for the measurement of thermal properties concurrent with microstructural measurements obtained from the DTEM.
- Integration into a time-of-flight mass spectrometer for trace gas detection identification during heating.

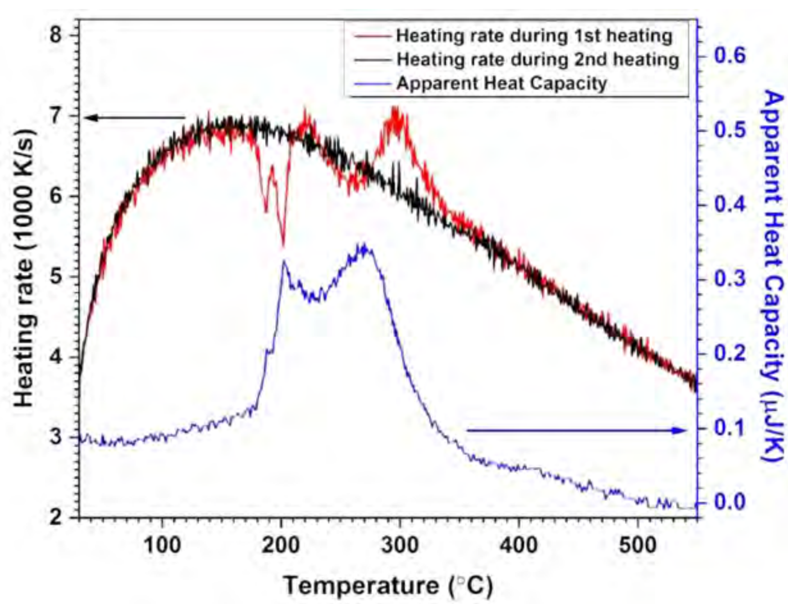


Figure 18. Heating rate and heat capacity measurements in an energetic material[ii] heated at ≈6,500 K/s. Image credit: NIST

The presentation demonstrated the unique capabilities of a novel material characterization device and provided some example applications. The device may prove valuable for characterization or detection efforts in future aerospace applications.

[i] Feng Yi and David A. LaVan, "Nanocalorimetry: Exploring materials faster and smaller" *Applied Physics Reviews* 6, 031302 (2019); https://doi.org/10.1063/1.5098297.
[ii] Feng Yi, Greg Gillen, Jeffrey Lawrence, Thomas P. Forbes, Matthew Staymates, David A. LaVan, "Nanocalorimetry of Explosives Prepared by Inkjet Printing" *submitted to Thermochimica Acta 2019.*

■ Advancing NASA's Materials Development Needs Through Nanoscale Analytical Microscopy —Dr. Gregory Thompson, The University of Alabama

Dr. Gregory B. Thompson joined the faculty in the Department of Metallurgical & Materials Engineering at The University of Alabama (UA) as an Assistant Professor in 2003. He was tenured and promoted to Associate Professor in 2008 and promoted to Professor in 2012. In 2018, the UA Board of Trustees designated him as a Distinguished University Research Professor. He currently serves as the Director for UA's Central Analytical Facility, which houses over $10M of analytical microscopy equipment (www.caf.ua.edu), and Director of the Materials Science Ph.D. program on the UA campus. Professor Thompson has published over 180 peer-reviewed articles in his research areas of analytical microscopy and phase transformations. He received his Ph.D. (2003) and M.S. (1998) from The Ohio State University in Materials Science & Engineering and a B.S. (1996) in Physics from Brigham Young University.

Materials characterization sits at the nexus of linking structure-properties-processing relationships. As NASA develops next-generation materials to meet various space exploration requirements, the ability to understand these connections become ever more apparent and necessary. The focus of this presentation was the use of advanced atomic to nanoscale characterization techniques which assist in linking structure-processing-properties relationships. Specific NASA programs highlighted included strengthening mechanisms in advanced ball bearings for the International Space Station, shape memory alloys for solid-state actuators, coatings for nuclear thermal propulsion, and chemical partitioning in nanocomposite magnetic alloys for electric motors.

The presentation focused on the role of characterization for the development of understanding structure-processing-properties materials relationships. However, many mechanisms driving properties occur at atomic or nanometer length scales, and methodologies for examining and characterizing these mechanisms at these length scales are required to fully characterize such materials. Dr. Thompson's work focuses on the use of precise analytical techniques for materials characterizations, such as chemistry, morphology, and structure, on nano- or atomic length scales.

The talk highlighted several efforts relevant to NASA interests that have employed nanoscale analytical methods:

- Shape memory alloys (SMAs), such as nickel-titanium alloys, have the potential for use as solid-state actuators, but need to operate over a larger temperature range. Alloying nickel-titanium with precious metals such as palladium by creating nanometer-sized precipitates; examination of the precipitates using nanoscale microscopy reveals chemistry changes occurring after aging that increases the transition temperature. Once the underlying mechanism is understood, the material can be tailored, specifically, to replace the expensive palladium with an alternative element, such as hafnium.

- Advanced bearings benefit from high hardness, but also moderate elastic modulus and large recoverable strain. Nitinol alloys are common for such applications. Nonequilibrium phases examined using nano-scale microscopy likely explain the high hardness of such alloys, leading to the potential for future tailoring of bearing alloys to improve properties.

• Amorphous magnetic materials have potential for applications in electric motors for commercial aircraft, where high magnetic permeability and large resistivity can lead to reduced component sizes and higher efficiencies. Nanoscale analytical techniques were used to map chemistry variations in castings of a cobalt-based amorphous alloy, leading to understandings of the effect of element clustering on the magnetic properties of the material (Figure 19).

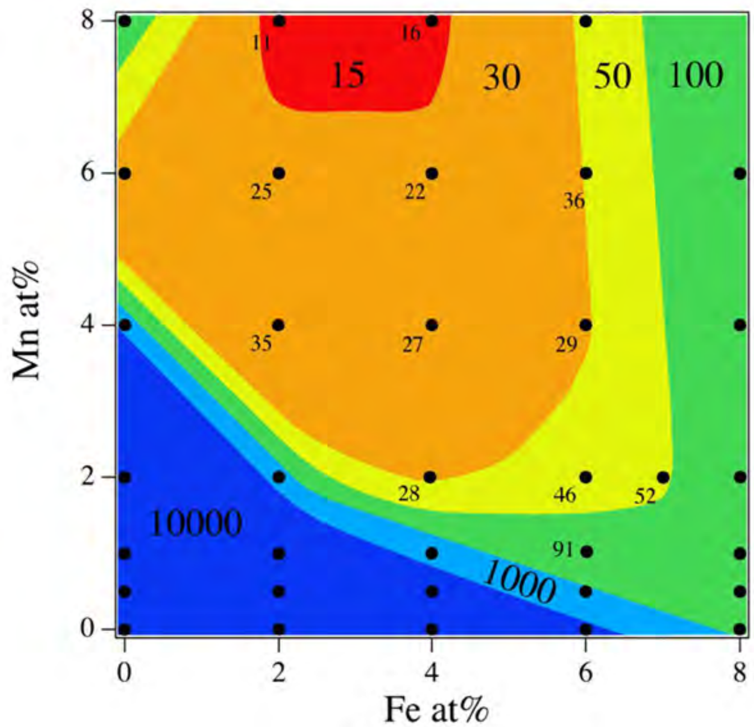


Figure 19. Iso-permeability (micro) surfaces as a function of Fe/Mn content. Material is 200 MPa, 520 ºC stress annealed. Image credit: The University of Alabama.

• Nuclear thermal propulsion (NTP) technologies require cladding fuel pellets with a refractory alloy in order to protect the fuel from reactions with the propellant. High-quality coatings are required. Nanoscale microscopy methods allow for the characterization of grain sizes and textures on micrometer-scale coatings.

Nanoscale analytical techniques show promise for increasing understanding of material structure-process-property relationships. This work demonstrated several applications for which desirable properties have been improved based on increased understanding of the underlying mechanisms enabled by the analytical techniques.

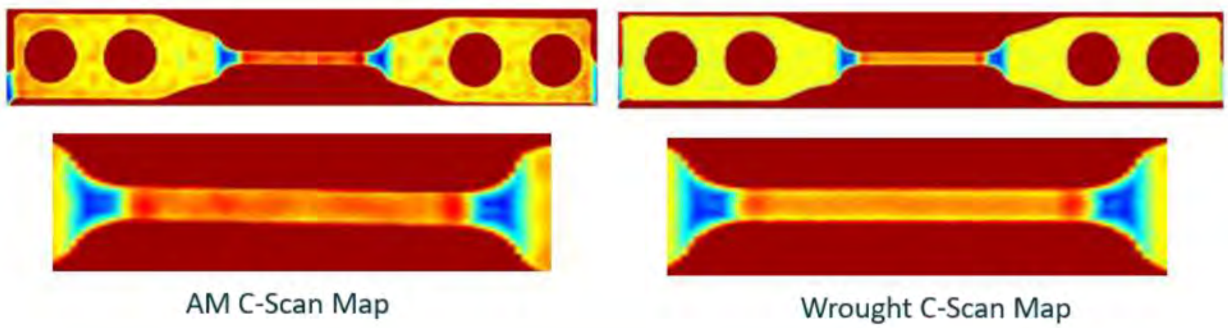
■ Characterization and Testing Facilities for Next Generation Materials—Mr. Bhavesh Patel, Southern Research Institute

Mr. Bhavesh Patel is the Associate Director of the Space and Propulsion Systems department and Thermal Lab Advisor at Southern Research. He has also served as a project manager on many NASA and the Department of Defense- (DoD-) sponsored programs to characterize various materials for use in extreme thermos-structural environments for the past 16 years. Materials include ablatives, ceramic, PMCs, CMCs, refractory metals, and TPS in support of Mars entry and Earth reentry. He has also played a critical role in developing testing facilities for evaluation of materials in extreme environments. He has a B.S. in Biology from The University of Alabama—Birmingham (UAB) and an M.S. and B.S. in Materials Engineering, also from UAB.

In the past 60 years, Southern Research (SR) has worked with NASA and the DoD to push the boundaries of space and propulsion system materials' performance in extreme environments via testing and analysis at a wide range of temperatures and conditions. Southern Research takes great care in working with NASA to ensure material properties are adequately used in analytical models and to develop test techniques to aid NASA's analysts in obtaining the data required for specific models. This is critical in the future as breakthrough material technology expands given the fruits of conducting research at extreme environments. Standard and unique thermo-mechanical facilities for evaluating breakthrough materials (i.e, TPS, C/C, CMCs, and refractory metals) were discussed. Unique environments include temperatures up to 4,000 °F at 1 atm air, low pressure air, and vacuum (10^{-5} Torr). Standard environments include cryogenic (–450 °F) to 5,000 °F. Rapid heating conditions were also presented.

This presentation focused on the capabilities of the Engineering Research division of SR. Southern Research developed mechanical testing frames based on spherical gas bearings that enable highly precise alignments for testing brittle materials such as ceramics and composites. The frames are also equipped with furnaces capable of reaching temperatures over 5,000 ºF. Southern Research regularly performs mechanical test for tension, compression, shear, torsion, fracture toughness, creep, and fatigue, and thermal property tests for thermal conductivity, thermal expansion, thermal diffusivity, specific heat, emissivity, and electrical resistivity. Southern Research also has extensive physical property and nondestructive characterization capabilities, including X-ray, computed tomography, ultrasonic, and eddy current inspection (Figure 20).

Southern Research specializes in characterization of materials in extreme environments. Mr. Patel described a device for measuring permeability under a variety of loading conditions at a range of temperatures and pressures. The device is capable of a wide range of flow rates and many common gasses used in aerospace applications. Mr. Patel has developed a high-temperature, controlled pressure thermogravimetric analysis (TGA) device for measurements in extreme environments or mission profile simulation. Additionally, SR has a mechanical test frame capable of testing at elevated temperature under near-vacuum conditions. This facility has successfully been used with digital image correlation systems for in situ strain monitoring at elevated temperatures. Many other specialized facilities are in operation, including a facility for radiant heat testing, devices for thermal strain measurement for rapid heating rates, and a chamber for thermal gradient testing in controlled environments.



Material	Velocity (in/µsec)	Resonant Frequency (MHz)	Resonance Behavior (15 – 25 MHz)
AM (A-HT-3)	0.19	2.2	Varied Across Gage Section
Wrought (C-HT-2)	0.21	2.3	Consistent Across Gage Section

Figure 20. Ultrasonic inspection results of additively manufactured and wrought material. Image credit: Southern Research.

Southern Research has developed many techniques and facilities for evaluating materials in extreme conditions. Aerospace applications often push materials to their limits, requiring a thorough understanding of the material properties in the environments to which the materials are subjected. Southern Research's capabilities allow for these properties to be evaluated and understood.

■ Characterization, Testing, and Infusion of Additively Manufactured GRCop-84 Into Hardware Programs—Mr. Robert Carter, NASA Glenn Research Center

Mr. Robert Carter is Chief of the High Temperature and Smart Alloys Branch at NASA Glenn Research Center (GRC). He manages 20 Civil Servants and 12 contractors who are performing research and development of metallic materials for aerospace applications. Robert holds a B.S. in Welding Engineering from The Ohio State University and an M.S. in Materials Engineering from Auburn University. He spent the first 15 years of his career at NASA Marshall Space Flight Center (MSFC) where he earned four patents for his work on development of the Friction Stir Welding process. At MSFC, Robert served as the Team Lead for Welding and Manufacturing and later as the Space Launch System Core Stage Element Discipline Lead Engineer for Production. Robert transferred to GRC in January 2013. There he has instigated and led several additive manufacturing (AM) projects, and has become recognized as one of the Agency's leaders in the field.

Over the last 5 years NASA has undertaken several projects to develop AM technologies to produce major structural elements of rocket engines. These elements include channel wall combustion chambers using copper alloy GRCop-84 produced using the Selective Laser Melting (SLM) technique. GRC has performed much of the materials characterization for these projects and has used state-of- the-art characterization techniques to interrogate microstructure and mechanical properties. Testing includes tensile, fatigue, creep, fracture toughness, and crack growth in relevant temperature environments. The goal has been to develop relationships between build parameters, microstructure, and mechanical performance that can be used to inform future manufacturing and design decisions. MSFC performed much of the detailed design, process development, and hot-fire testing of these combustion chambers. The rapid development and infusion of this technology from low Technology Readiness Level (TRL) fundamental research to high TRL engine integration and hot-fire testing was presented.

This presentation was a case study on the development of additively manufactured GRCop-84 alloy into hardware programs for aerospace applications (Figure 21). Such alloys are commonly used as liners for channel-cooled combustion chambers due to their high thermal conductivity.

They are often paired with a second material that provides structural support; the copper and supporting material must be brazed or welded together. Additive manufacturing techniques open the possibility for directly printing the cooling channel configuration without the subsequent joining operations.

GRCop was developed as an alternative to alloy NARloy-Z, which was used for combustion chamber liners in the Space Shuttle Main Engines (SSME). NARloy-Z showed limited life capability in the extreme environment of the SSME combustion chamber. GRCop attempts to increase the stability of the alloy by dispersion of Cr2Nb phases, which have a high melting temperature. Traditionally, the stabilization phase was formed during powder atomization, but SLM, an additive manufacturing technique, allows for refinement of these particles during production, resulting in properties that are improved relative to the original powder metallurgy processes.

While GRCop alloys have been under development since the late 1980s, advancements are continuing to be made. Recently, a GRCop combustion chamber for the Low Cost Upper Stage Propulsion (LCUSP) program was produced by SLM techniques and then over- deposited with a nickel superalloy structural jacket using electron beam free-form fabrication. This required careful control of the input powder, development of appropriate machine parameters for the additive manufacturing techniques, and investigation of effective heat treatments in order to generate the desired mechanical properties in the final component. Extensive material characterization was conducted, including tensile, creep, and fatigue evaluations at application-relevant temperatures.

Parts fabricated using GRCop have undergone ground testing, demonstrating the potential for successful implementation of GRCop alloys in spaceflight applications. While more development needs to be done, including further investigations on the interface between the GRCop material and materials commonly used for structural jackets, the alloys shows promise for future applications and provides a pathfinder for the use of additively manufactured material in aerospace components.

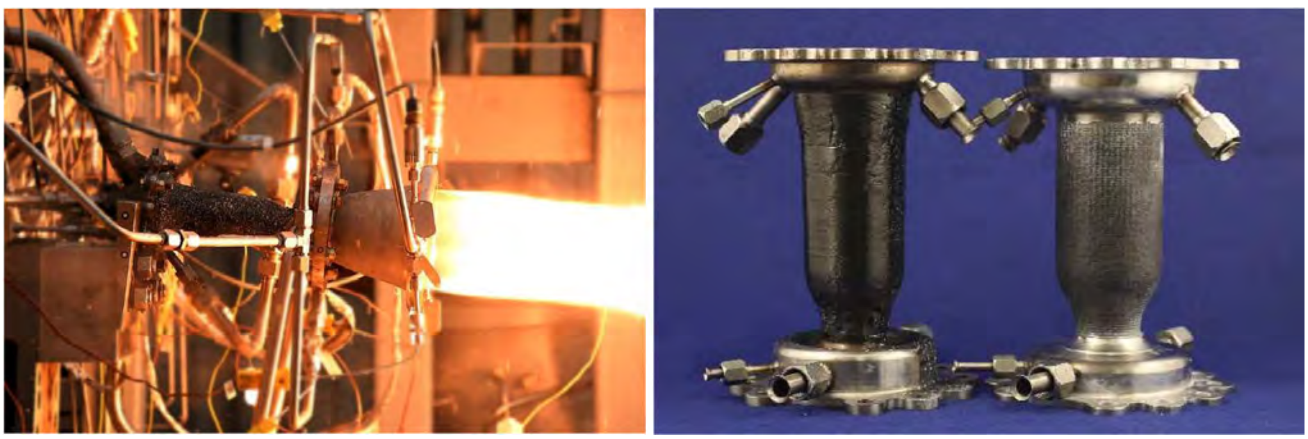


Figure 21. (Left) Image from hot-fire testing of GRCop alloy in engine (combustion chamber) application. (Right) 3D Printed GRCop chambers with composite overwrap. Image credit: NASA.

KEYNOTE SESSION II—APRIL 24, 2019

Keynote session B showcased the work of two NASA field centers (NASA Glenn Research Center and NASA Langley Research Center) in advancing the state of the art for materials in both space and aviation. Another presentation from the NASA engineering safety center highlighted the challenges faced by the Agency in certification of new materials and manufacturing processes for crewed spaceflight, including parts made for propulsion systems using additive manufacturing.

■ Recent Advances in Materials and Methods for Aerospace Applications at NASA Langley Research Center—Dr. Jonathan Ransom, NASA Langley Research Center

Dr. Jonathan Ransom is the Deputy Director for Structures and Materials in the Research Directorate at NASA Langley Research Center, Hampton, Virginia. In this role, he advocates for and directs workforce, computational and experimental facilities, and research and development in support of NASA's programs and projects. In addition, he ensures national leadership in materials, structures, mechanisms and manipulators, advanced manufacturing technology, and advanced nondestructive evaluation and structural health monitoring technologies.

NASA Langley Research Center (LaRC) is developing new materials, methods, and structural concepts that enable future aviation and space exploration. Materials technologies encompass:

- Development of advanced materials through synthesis, processing or combining of stock materials into new forms via new fabrication techniques.
- Determination of material microstructure and performance using new and standard characterization, nondestructive evaluation, and mechanical testing capabilities.
- Development of computational materials methods to predict processing-microstructure-property-performance relationships that guide material development and enable new certification capabilities.

Further, a recent NASA-hosted workshop on Rapid Manufacturing has focused many of these technologies toward enabling new high-performance vehicle designs and dramatically increased production rates.

This presentation provided an overview of NASA's recent Rapid Manufacturing workshop and highlighted the broad range of Langley's materials and methods developments for aerospace applications. The key technology areas at LaRC for materials and processes include: structures, mechanisms and manipulators, advanced manufacturing technology, flight-qualified structures, advanced NDE, and structural health monitoring technology.

In the area of materials development, LaRC has conducted research on aligned electro-spun fabric, metal decorated nanotubes, and Boron Nitride nanotubes. Holey graphene materials are being developed for high-performance energy storage and conversion applications. Holey graphene has a unique combination of properties (conductivity, porosity, surface area, chemistry, ability to be processed) that make it a top electrode platform choice for a variety of next-generation energy applications. LaRC has used the MISSE platform to investigate the effect of the space environment on radiation shielding materials, radiation resistant materials, atomic oxygen resistant materials, Mars regolith simulant materials, bulk metallic glasses, and advanced composites. Space durable hardware experiments on the Shields-1 Cubesat provide measurements of the total ionizing dose and monitor the performance of system electronics in the space environment.

In process development, LaRC is maturing integrally-stiffened cylinder fabrication techniques for launch vehicles. This technique in Al-Li 2195 has produced a 10-foot-diameter cryogenic tank dome. LaRC is also using the electron beam freeform fabrication (EBFF) process, a wire-fed metal AM process, to build next-generation rocket components (structural jackets for nozzles and manifolds). This technology can reduce injector manufacture time and increase performance through improved cooling. Large-scale nozzle development work with EBFF is part of the Rapid Analysis and Manufacturing

Propulsion Technology (RAMPT) project. The combustion chamber and nozzle for this assembly are made with selective laser melting (SLM). The assembly is shown in Figure 22.

Figure 22. Structural Inconel 625 jacket EBF3 deposited on to SLM Cu liner. Image credit: NASA.

Characterization work at LaRC includes the advanced composites project (ACP), which seeks to develop high-fidelity analysis tools to reliably predict the strength and life of composite structures with damage or defects (as-manufactured or service-induced) and the failure of structures due to high-impact energy events. This work includes development of in situ quality control systems and rapid NDE techniques. Another technical objective of the ACP is a multiphysics-based model of automated fiber placement (AFP), which predicts the effect of defects on the laminate. In situ NDE for AFP has also been demonstrated. The overarching goal of this work is real-time inspection with immediate defect reporting, enabling real-time control of the manufacturing process. LaRC has a suite of state-of-the-art materials characterization capabilities and can conduct microscopy, spectroscopy, mechanical testing, thermal analysis, multiscale characterization of damage progression, and delamination/migration characterization.

LaRC also has extensive expertise in modeling and simulation of materials and processes. Certification of AM parts is a current challenge and depends on process and material modeling. Computational models can be used to identify process parameters for ideal melt pool size to inform development of machine parameters for the XLINE system (a Concept Laser SLM system at NASA MSFC used for builds of propulsion hardware). Computational methods were also used to guide the development of process parameters for fabrication of high-strength carbon nanotube composites. Computational techniques can simulate physical processes at relevant length scales, characterize the physics of damage to a material, simulate the fundament physics governing processing, and characterize material evolution.

On November 14–15, 2018, LaRC hosted the Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop. The objective of this event was to assess the state of the technology rapid/advanced manufacturing, identify technology gaps, develop a whitepaper/roadmap identifying industry needs and insertion points, and recommend proposed investment priorities for NASA. The workshop had 122 participants from government, industry, and academia. A high level summary of the workshop and outcomes was presented. Future aircraft will be heterogeneous, representing a combination of metals and composites manufactured using a myriad of approaches. Rate improvement from current advanced tools while using current materials is limited to 2X. New materials and processes required to meet 5X current production rate goals set by industry. Future production rates require improvements and streamlined relationships in aircraft design, materials, certification, and manufacturing methodologies. The commercial and urban aviation markets have similar challenges. While rates of production and manufacturing approaches are different, neither market can sacrifice structural performance for faster production rates. Discussions at the workshop informed identification of NASA investment areas in design, materials and processes, certification efforts, and cross-cutting technologies.

■ Advanced Materials Research at NASA Glenn Research Center—Dr. James Zakrajsek, NASA Glenn Research Center

James Zakrajsek is Chief of the Materials and Structures Division at the NASA Glenn Research Center (GRC). He manages 10 technical branches with over 180 Civil Servants conducting a wide range of technology development activities from basic materials research to flight hardware design, analysis, and testing. Mr. Zakrajsek' s over 39 years of experience includes managing branch and division groups that span numerous technology areas, teaching mechanical engineering courses, and leading and serving on cross-Agency technical teams. Mr. Zakrajsek earned his B.S. and M.S, degrees in mechanical engineering from Cleveland State University. and has authored 36 publications, one book chapter, and six NASA Tech Brief articles in gear dynamics and rotorcraft health management. He has received numerous awards for his technical accomplishments and leadership including NASA Outstanding Leadership Medal, NASA Exceptional Service Medal, and NASA Group Achievement Honor Award as lead of the GRC Shuttle Actuator Investigation Team.

The Materials and Structures Division at GRC encompasses a broad range of technology areas from basic materials research to flight hardware design, analysis, and testing. This unique arrangement—the integration of science and engineering disciplines—has enabled results from basic materials research to be more effectively applied to aerospace flight systems. Fundamental research focused on advanced materials for extreme aero propulsion environments has led to the development of breakthrough materials for aeronautics as well as space applications. This presentation provided several examples of aero-based materials research which have been successfully transitioned to space applications. Space environments are particularly extreme. On the lunar surface, temperatures vary from –280 °F to 260 °F, with the craters at the poles in permanent shadow. Regolith has sharp abrasive edges which quickly wear materials it comes in contact with. For Mars, reentry temperatures experienced by a material may exceed 4,800 °F. In deep space, temperatures may dip as low as 2.7K and materials will also experience high levels of radiation and micrometeor impacts. GRC's work in advanced materials for aeronautics may also be a key enabler for missions beyond low Earth orbit.

Examples of historical achievements in materials development at GRC include the following:

- GRC developed a Nickel Titanium alloy to enable shape memory alloy (SMA) actuation systems and super elastic corrosion resistant bearings. These alloys exhibit a strong resistance to corrosion and flight loads. Applications to date include a highly wear-resistant spring tire for planetary rover wheels (Figure 23) and noncorrosive, highly shock-tolerant bearings for the International Space Station urine processor.

- GRC developed high-temperature braided rope seals for variable geometry engine and vehicle seal locations. While developed for aeronautics applications, this material was transitioned to space; the braided carbon fiber thermal barrier rope seal was used in the interface between the Orion heat shield and its back shell. A heritage use of this material is the Space Shuttle solid rocket motor joints.

Figure 23. Nickel Titanium alloy spring for rover wheels. Image credit: NASA.

In recent years, GRC has continued work on composites and advanced materials processing for aviation:

- GRC is developing advanced electric propulsion systems for future aircraft. As part of this work, GRC has developed highly efficient nanocomposite soft magnetic alloys, which have been successfully integrated into prototype electric power components in partnership with the Department of Energy.

- A ceramic Matric Composite/environmental barrier-coated material system was developed for turbine engine components with the goal of significant weight reduction and higher operational temperature over conventional metal alloy materials. This material was successfully tested over 300 hours at a 2,950 °F surface temperature.

- Additive manufacturing processes were used to fabricate components to increase power density and enable efficient cooling of a high-power-density electric motor.

- GRC developed a 5,000 HP hybrid gear using polymer matrix composite of variable thickness. The PMC had improved fatigue in a no-oil test and reduced the weight of the component 30% relative to conventional materials (steel). This gear also reduced vibration transmission between bearings and gears. The variable thickness web design survived 240,000 in-lbf torsion test without fracture.

- GRC developed high-temperature RTM resins used in a triaxial braided RTM 370 composite. This material demonstrated outstanding impact resistance at 550 °F. Current GRIC is developing a 3D processing method to selectively melt cross sections in powdered polymers using laser sintering.

■ Material Design for Deep Space Reliability: Looking to the Future While Learning From the Past—Mr. Richard Russell, NASA Engineering Safety Center

Mr. Richard Russell began his career in 1986 at the Naval Aviation Depot in Pensacola, Florida. In 1989, he joined NASA's Kennedy Space Center (KSC) as a Quality Engineer. In 1992, he moved to the Shuttle Engineering Project Office serving as a Materials and Processes (M&P) Engineering expert. In 1996, Mr. Russell left NASA and worked in aircraft manufacturing and design at The Aerostructures Corporation in Nashville, Tennessee, and Bell Helicopter in Ft. Worth, Texas. In 2001, Mr. Russell rejoined the Shuttle program working for the United Space Alliance at KSC, serving as lead of the ground operations M&P Engineering Group. In 2009, Mr. Russell became a member of the Materials Science Division at KSC. In 2016, Mr. Russell joined the NASA Engineering Safety Center (NESC) as the NASA Technical Fellow for Materials. Mr. Russell has a B.S. degree in Metallurgical Engineering from the University of Illinois and an M.S. degree from the University of Florida in Materials and Science and Engineering.

The NESC was formed after the Columbia accident and serves to provide independent technical expertise to NASA programs and projects. This presentation provided a historical critical review of the Agency's revealed issues associated with current Durability and Damage Tolerance (D&DT) standard practices, as described in the associated report "Re-Tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance" (published as a NASA Technical Memorandum in 2017). At NASA, failures are understood with the framework of understanding design margins, anchoring margins and assumptions to test data, and evaluating performance at the boundary conditions. Within the Agency, D&DT understanding is critical to reliability and becomes even more important as the human space travel paradigm is shifted away from low Earth orbit. Deep space reliability is based on: (a) a 50- to 100-year design life and (b) limited replacement (spare) parts with virtually no opportunity for resupply.

With reduced emphasis on testing and increased emphasis on computational D&DT methods as the standard practice, it is paramount that capabilities of these methods are understood, the methods are used within their technical limits, and validation by well-designed tests confirms understanding. This presentation discussed growing vulnerabilities of D&DT methods in terms of three important local parameters:

(1) Local length scales (structural and material) within the micromechanics regime. Many are still using continuum-based linear elastic fracture mechanics (LEFM) in a noncontinuum regime. Computational methods can characterize and predict behavior at the micron and nanometer scale and current engineering practice allows for understanding of material performance at the macro level. However, there exists a gap region of micromechanics, complex structures, and complex microstructures which represents a shortfall in analysis and test. This gap is visually depicted in figure 24.

(2) Local environments and local properties that influence D&DT behavior.

(3) Local material behavior (i.e., anisotropy, properties, damage mechanisms, etc.), that are not thoroughly considered.

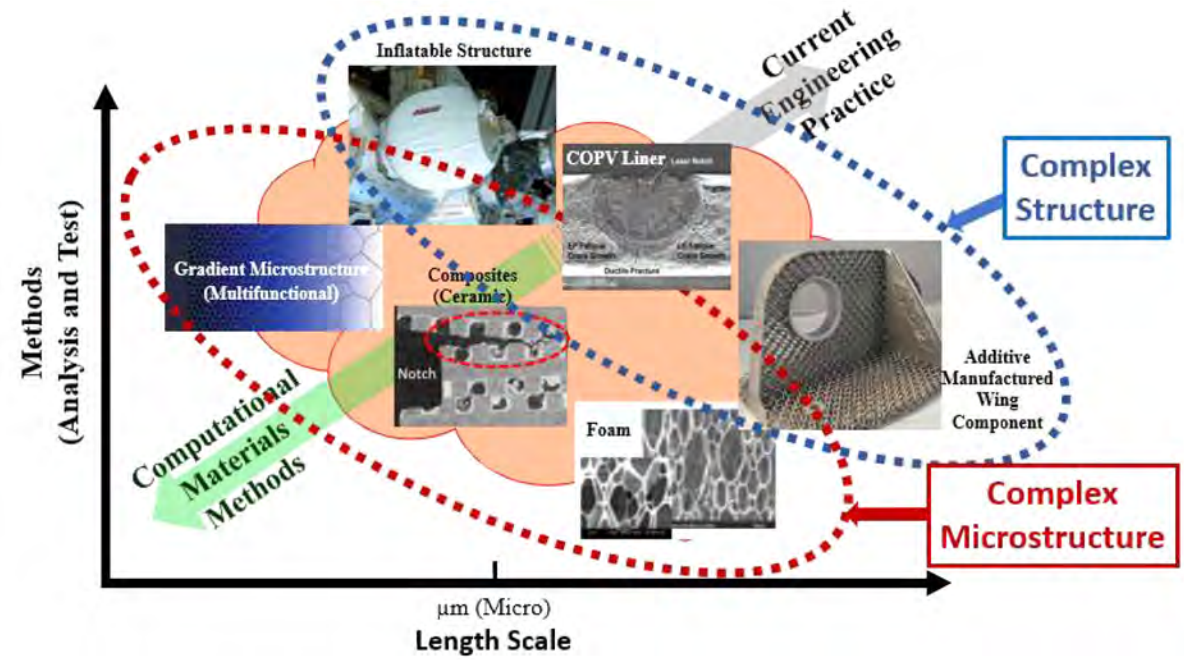


Figure 24. Visual depiction of the regions of the micro and nano scale (red circle) and the micro and macro scale (blue circle). The overlap of the circles indicates the complex region of micromechanics, where traditional D&DT methods may not accurately characterize material behavior. Image credit: NASA.

Recently, the lack of understanding of any of the local parameters listed above have led to incomplete and erroneous estimates of D&DT performance. Discussions included several vulnerable engineering practices related to estimating the D&DT of fracture-critical components and why D&DT method vulnerabilities will rapidly increase with new weight-saving designs, advanced materials, and unique fabrication processes. Scenarios which present challenges to traditional D&DT methods include: COPV liners, additively manufactured (AM) components, and inflatable structures. Thin-walled COPVs are a fracture control concern, as LEFM assumptions become violated as the liner thickness is reduced. The current theories that define the LEFM limitations relative to thickness may not be valid in this thin-wall regime. Better guidelines must be developed to quantify when the use of LEFM is invalidated by decreasing thickness (influenced by rapid stress, yield stress, and microstructure).

An example of the development of microstructurally-informed D&DT was also provided. A characterization of the microstructure using quantitative measurements can inform localized FEA models and analyses. With this technique, a microstructurally small crack growth model and analysis were used to understand local parameters. D&DT analysis tools were then used to construct global FEA models and analyses which predict behavior inservice environments. Creating a bridge between the microstructure and macrostructure of the material accounts for local length scales, environments, and material properties and produces distributions of behavior by relying more heavily on modeling and simulation.

A specific focus was placed on the critical need for future development of NASA's knowledge and understanding of the materials, processes, analysis, inspection, and validation methods for additively manufactured parts. Additive manufacturing is finding more frequent use in aerospace hardware. Therefore, there is a critical need to increase NASA's knowledge and understanding of the materials, processes, analysis, inspection, and validation methods for AM parts. This includes standardization, property validation, specification development, computational materials, NDE, and in situ process monitoring. NASA is currently developing NASA standards based on the principles of the Marshall standard and specification for AM parts (MSFC-STD-3716 and MSFC-SPEC-3717).

BREAKOUT SESSION 5—EMERGING MATERIALS

Session 5 on emerging materials included a diversity of topics. Graphene is perennially cited as a 'material of the future' for aerospace and the first talk examined the remarkable properties of graphene and how it can be used to enhance existing materials. The session highlighted work on high entropy alloys, another class of materials viewed as having immense potential for extreme environment applications. Atomic layer deposition (ALD) is a coating process which can potentially be used to protect nuclear fuel material from undesirable reactions with propellants. Emerging efforts in additive manufacturing (AM) were also highlighted, including the ability of AM techniques to produce thin-walled lattice structures not possible with conventional manufacturing and the use of computational software to enable material design specifically for AM processes. Another presentation offered perspectives on approaches to in situ resource utilization for construction of precursor infrastructure on the lunar surface and plume/material interaction for landing pads.

■ Graphene in Aerospace Applications—Dr. Ahmed Al-Ostaz, University of Mississippi

Dr. Ahmed Al-Ostaz is a Professor and the Brevard Family Chair in the Department of Civil Engineering at the University of Mississippi, where he also serves as Director of the Center for Graphene Research and Innovation. During the last 10 years, Al-Ostaz has focused his research activities on advanced materials by design for protecting infrastructures against natural (extreme hydrometeorological events, earthquake, etc.), human-made (industrial, accidental or malevolent), or environmental (climate change and drought) disasters.

The University of Mississippi has established a new center to advance translational science and engineering of graphene-based technologies. The Center for Graphene Research and Innovation was officially established on October 19, 2017, with approval from the Board of Trustees of State Institutions of Higher Learning. The center focuses on bridging the gap between university-based science and discovery and industry-led innovations and applications for graphene.

Graphene can be utilized in composite materials to enhance multifunctionality. By developing a material that has an optimal response to varying and perhaps competing demands, the user gains optimal value as measured in performance per unit cost. Recent advances in designing new materials show this optimal multifunctionality is achieved when graphene is incorporated into materials with several constituents, such as composite materials. By changing the amount of these constituents, an optimal material response to different, perhaps competing, demands can be obtained, thus achieving the desired multifunctionality.

This presentation focused on utilizing graphene as a multifunctional material in aerospace applications. Graphene, a single layer of carbon atoms bonded together in a repeating hexagon pattern, is one million times thinner than a single piece of paper. It is so thin it can be considered as a two-dimensional material. Graphene has exceptional characteristics, including excellent electrical conductivity, heat conductivity, and mechanical strength properties. It is 200-fold stronger than structural steel with less than one-third the density. Graphene also has a very high surface area. One gram of graphene theoretically has about the area of a half football field. Graphene presents many potential applications: reinforcements in composites, energy conversion/storage, thermal conductors, electronics, anti-corrosion coatings/paints, and medical devices.

Dr. Al-Ostaz spoke on developments and applications of graphene to aeronautics and space applications. Graphene sheets have a thousand times the electrical current capacity of copper wire, are two hundred times stronger than steel, and can sustain 20% flexibility without damage. Applications include more efficient solar cells, faster semiconductors, and lighter aircraft. First isolated in 2004, graphene is beginning to move towards commercial adoption with significant investments in research and development across the globe.

To meet the demanding material requirements for spaceflight applications, constituent materials with different properties can be combined, forming a multifunctional material. A multifunctional approach allows for optimization in material design, enabling the designer to meet varying and sometimes competing material property needs. This approach has the potential to result in materials with higher performance per cost ratios.

Graphene can help facilitate a multifunctional material design approach. For polymer materials, properties such as stiffness, toughness, and strength can be obtained by mixing graphene nanoparticles with the base material. Additions of graphene can improve the electrical or thermal properties of a material (example plot in fig. 25), as well as improve the reflection and transmission properties. Graphene is also being investigated as shielding for hypervelocity impacts, potentially caused by collision of a spacecraft with space debris in low Earth orbit. Graphene has been successfully used to shield materials against these impacts in a test environment (a sheet of graphene material is adhered to the susceptible material). Additional attractive properties of graphene include its ability to modify glass transition temperatures, nonmetallic protect against lightning strikes, and lightweight core material for structural composite structures.

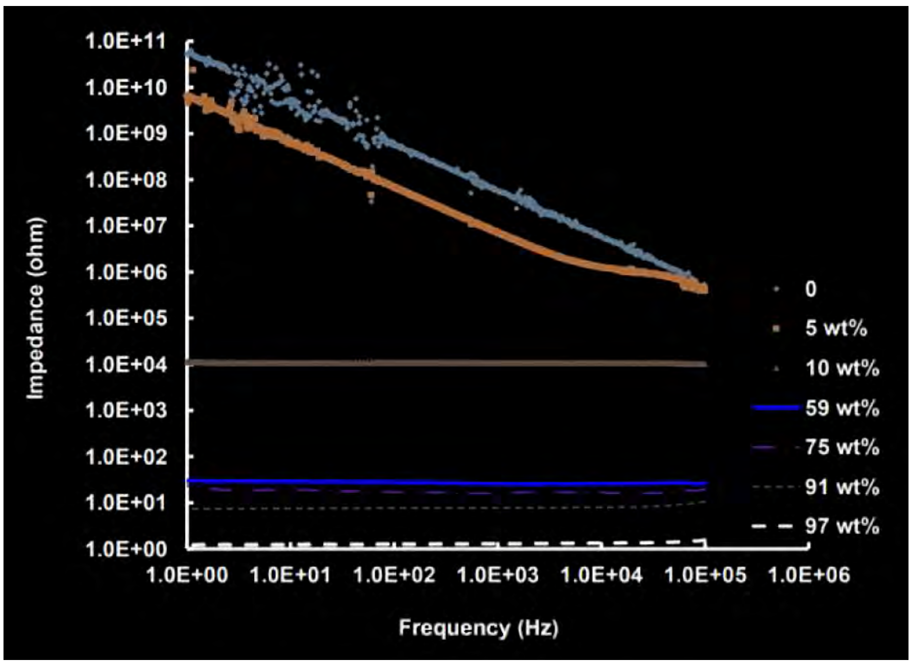


Figure 25. Impedance response for material containing zero to 97% graphene loading by weight. Image credit: University of Mississippi.

■ On the Properties and Design of Complex Solid-Solution Alloys—Dr. Duane Johnson, Ames Laboratory, U.S. Department of Energy

Dr. Duane D. Johnson is the F. Wendell Miller Professor of Materials Science & Engineering at Iowa State University. He has over 250+ publications and is a leading expert in materials theory and computational materials science. His research expertise is in electronic structure-based methods for quantitative prediction of stability, properties, thermodynamics, and transformations in alloys (e.g., high entropy) and energy-conversion materials. He has multiple patent applications and patents, as well as open-source codes. He served over 6 years as Chief Research Officer of Ames Laboratory, overseeing the full research and development portfolio during this time.

High-entropy alloys, a subset of near-equiatomic complex solid-solution alloys (CSAs), exhibit remarkable high-temperature mechanical strength, toughness, and oxidation resistance in harsh environments. From an alloy design perspective, CSAs offer a much larger and fertile design space to control/tune stability and properties, especially in extreme environments. The presentation showcased theory as a direct quantitative guide to combinatorial synthesis experiment and characterization, offering an integrated validation and design approach to high entropy alloys. CSAs are particularly well-suited for applications that require high-temperature mechanical behavior, oxidation resistance (with co-design, self-healing coatings), high-temperature thermoelectric properties, radiation resistance, hydrogen-embrittlement resistance, or cryogenic-enhanced strength. These are all areas relevant to NASA's intended use applications for breakthrough materials.

CSAs are combinations of four or more constituent elements. CSAs offer a large and fertile design space to control and tune stability and properties, especially in various extreme environments. Exploration in this design space is enabled by software tools to calculate and predict electronic-structure characteristics for different combinations of the constituent elements at an atomic level. When combined with data from experimentalists, these tools can point to potential new alloys with combinations of desirable properties.

A subset of CSAs, high-entropy alloys (HEAs), exhibit good high-temperature mechanical strength, toughness, and oxidation resistance, and are of particular interest for use in challenging material environments. Using computational modelling, Ames Laboratory identified a promising refractory HEA with predicted stiffness over twice as high at elevated temperature as typical commercial alloys. Experimental synthesis and characterization work has verified the predicted property improvements. HEAs also have applications as thermoelectrics for waste-heat recovery, where the addition of doping elements can increase the temperature range (i.e., 500–1,500 K) over which recovery is effective. Some HEAs exhibit low sensitivity to radiation and resistance to hydrogen embrittlement, which are attractive properties for aerospace applications and easily controlled due to the operative mechanism dictating this behavior.

Ames is developing new CSAs using a suite of equipment for rapid development and characterization of new alloys. Rapid experimental work is enabled using additive manufacturing techniques coupled with high throughput characterization equipment, such as XRDs, XRFs, and DSCs. This approach allows for the exploration of a material design space in a reduced timeframe, feeding information back to the material structure models to improve predictions and help identify alternative compositions. This combination of analysis and experiment allows Ames to accelerate materials design and discovery, potentially developing new materials with applications to spaceflight (Figure 26).

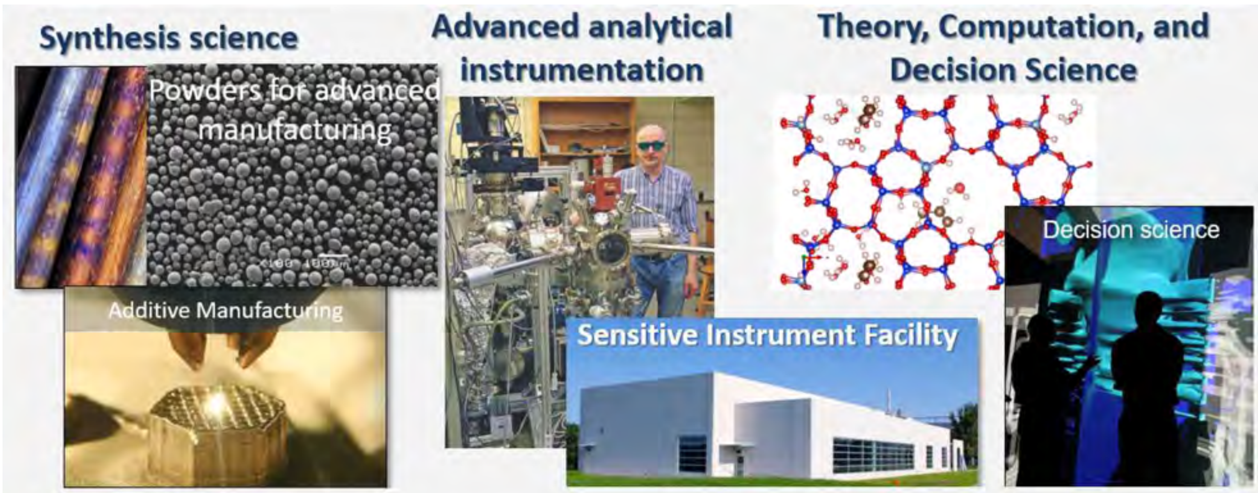


Figure 26. Ames Laboratory accelerates materials design, discovery, and deployment by transitioning basic science to applied science to technology commercialization. Image credit: Ames Laboratory.

■ Ultra-Thin Conformal Inorganic Films on Particles and High Aspect Ratio Inner Surfaces by Atomic Layer Deposition—Dr. Alan Weimer, University of Colorado at Boulder

Alan (Al) W. Weimer is the Melvin E. and Virginia M. Clark Professor of Chemical and Biological Engineering at the University of Colorado (CU), joining the faculty in 1996 after a 16-year career with the Dow Chemical Company (Dow). He has received six major research awards from the American Institute of Chemical Engineers (AIChE) including the 2017 AIChE Lifetime Achievement Award for Particle Technology. He is the recipient of the Dow Chemical Company 1995 Excellence in Science Award for the invention and commercialization of advanced nonoxide materials. He was recently inducted into the National Hall of Inventors.

Dr. Weimer spoke on his research into Atomic Layer Deposition (ALD) technology for the application of precisely controlled coatings to substrate materials, such as particles or inner surfaces of high-aspect-ratio channels. The ALD process developed by Dr. Weimer consists of a binary reaction that results in an atomically thin layer of the coating bonded to the substrate. Dr. Weimer described processes producing coatings of aluminum oxide, boron nitride, and silicon dioxide, with a variety of substrate materials.

ALD coatings have advantages over processes using chemical vapor deposition (CVD). The ALD coatings are smooth, defect free, and can be very tightly controlled. Coating thickness is dependent on the number of binary reactions allowed to occur, with each reaction contributing an additional atomic layer to the coating. Additionally, the gas phase reaction in CVD is not necessary with ALD and input material requirements are subsequently reduced. As a result, expensive precursors can be used for ALD with minimal waste and overall reduced cost.

ALD has potential applications in several aerospace fields, including nuclear thermal propulsion (NTP). In NTP applications, coatings are required to protect the nuclear fuel material from reactions with the propellant (Figure 27). ALD has been demonstrated for both fuel particle coatings and high aspect ratio flow channel coatings. ALD also has applications in solid oxide fuel cells, where electrolyte conductivity can be improved with aluminum oxide coatings, and as surge protectors for quantum tunneling devices.

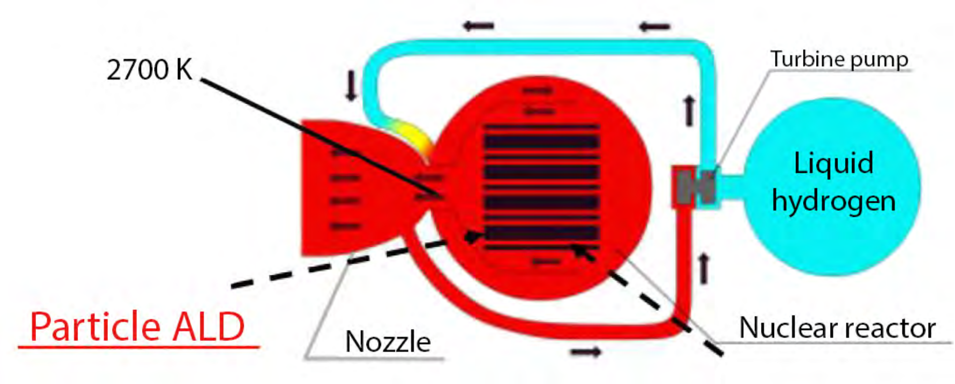


Figure 27. Particle ALD in a nuclear thermal propulsion application.
Image credit: University of Colorado at Boulder.

■ Moon Base: 35 Years of Study and Ideas—Mr. Rob Kelso, Kelso Aerospace Consulting, LLC

Rob Kelso is originally from Houston, Texas. He graduated college with a degree in physics and then an MBA. He worked at NASA as a Space Shuttle Flight Director for 25 Shuttle missions. Rob then worked at NASA preparing missions for returning to the Moon. Later, Rob spent 3½ years as the Executive Director of Hawaii's planetary robotics test site on the Big Island of Hawaii. Recently, Rob has been consulting with two South Korean government agencies on lunar missions and lunar construction.

There were many lunar construction studies conducted by NASA in the 1980s and 1990s. Interest in lunar construction is reemerging within the private section, NASA, and international space agencies. Recently, Vice President Pence called for a return to the Moon by humans by 2024, followed by a sustainable presence. However, there has yet to be any consensus on architecture, building standards/codes, and construction methodologies. In fact, many aspects of construction for the Moon and Mars remain unknown and untried.

When most people refer to In Situ Resource Utilization (ISRU), the reference in most cases is toward extraction of volatiles and water/ice. Another critical aspect of ISRU is in using the indigenous resources for construction. This presentation discussed the need for a technology development program in ISRU construction technologies and the need for commonality of standards for construction/architecture for the Moon.

Mr. Kelso spoke on the importance of infrastructure development in order to maintain a stable presence on the Moon. Moon base plans and concepts have been around since before the Moon landings, with little agreement on the best way to proceed. Many studies have been undertaken, identifying materials, tools, and equipment to help maintain a Moon base, but no overall direction has been clarified as far as overall architecture, approach, and standardization. For lunar structures, studies have focused on inflatable structures, rigid structures, or some hybrid of the two, with much recent interest on using 3D printing techniques to construct structures with in situ resources (Figure 28). However, these approaches remain largely untried and unproven beyond nascent technology development efforts.

Figure 28. Example of sintered basalt for a paver application. Image credit: Rob Kelso.

With the renewed emphasis at NASA for a return to the Moon, Mr. Kelso proposes that the role of government space agencies should be to open new frontiers and enable subsequent exploration efforts by public and private users. For example, the goal of NASA should not be to mine resources from the Moon, but to establish that mining on the Moon is possible. Development of a lunar infrastructure program would align with this goal. A three-phase approach to a lunar development program would establish the fundamental knowledge and infrastructure necessary to support a Moon base. Phase I would consist of lunar resource prospecting, identifying sources, and means of extracting in situ resources such as lunar ice for propellants and life support or metallics for construction or development materials. Phase II involves construction and site preparation by robotic rovers. Mr. Kelso cautions that there is currently little emphasis on aspects related to this phase, such as means of constructing roads or landing pads, means for site survey, and even building codes. Phase III would be habitation by Moon base crew.

The Apollo landers produced a significant amount of particle ejecta during landing and takeoff. This ejecta presents a maintenance issue for lunar infrastructure, which may not be able to withstand such debris. Mr. Kelso was involved in a project to use a rover to place sintered blocks of basalt sand to form a landing pad. The pad was constructed by the rover and tested with a solid rocket motor with 940 pounds of thrust, with positive results.

Mr. Kelso emphasizes the need for an in-flight technology development program to test mid Technology Review Level technologies for future use in future exploration efforts. Basic civil engineering problems remain unsolved when applied to extra-terrestrial outposts, such as means of drilling and anchoring structures, production of building materials from in situ resources, and material transport equipment. Mr. Kelso encouraged development of an integrated, strategic approach toward preparing technologies to enable a sustainable presence on the Moon.

■ Materials Design for Advanced Manufacturing—Dr. Scott McCall, Lawrence Livermore National Laboratory

Scott McCall earned his Ph.D. in condensed matter physics from Florida State University where he worked at the National High Magnetic Field Laboratory under Prof. Jack Crow. He joined Lawrence Livermore National Laboratory (LLNL) in 2004 and is currently the Actinide and Lanthanide Science Group Leader for the Materials Science Division and the Magnet Thrust Lead for the Critical Materials Institute (CMI), an Energy Innovation Hub. Scott is an author of more than 90 papers and several patents. His interests include advanced materials, energy security, and magnetism.

Within that mission, LLNL is investigating new technologies enabled by advancements in modeling and design, materials, and manufacturing techniques. Integrations of these new technologies enable new, high-performance materials and components.

An example is the development of stable combination of four or more metallic elements, known as high entropy alloys (HEAs). HEAs were identified and developed with assistance from computer models that predicted atomic stability. These HEAs show superior strength-to-elongation ratios relative to more commonly used metals, and exhibit good resistance to corrosion and resistance to radiation. LLNL has developed a Materials Design simulator, a software package to accelerate searches for appropriate HEA alloy systems. The tool uses solidification models and thermodynamic databases to identify candidate alloy systems given optimization targets and constraints. The tool is also useful for identifying alloy systems that may have properties desirable for advanced manufacturing techniques, such as an aluminum-cerium alloy developed by the CMI which is well-suited to additive manufacturing. The alloy retains secondary phases which remain stable up to high temperatures and leads to an alloy that may be additively manufactured without a need for post-build heat treatments. The advancements in materials modelling can guide in the design of future materials, leading potentially to a wide variety of bespoke materials for a particular application.

LLNL is involved in several other areas of advanced materials research. LLNL is developing advancements to feedstock materials for additive manufacturing, including manufacturing nanocubes and nanowires as alternatives to the powder agglomerates commonly used in metallic additive manufacturing. Projection micro-stereolithography (PmSL) techniques are being developed to form metallic hierarchical lattice structures with improved stiffness-to-weight ratios. These lattice structures can form lightweight, hard cermet composites that are suitable for applications such as body armor. Custom structures can be formed by producing the base lattice using PmSL techniques, then infiltrating the structure with the ceramic material. After firing, the base lattice can be dissolved or burned away and the material filled with molten metal for reinforcement. LLNL is also investigating additive manufacturing techniques with carbon fiber that allow for control of the placement fiber orientation, resulting in lower cost due to less expensive precursor materials. Techniques have been developed to simulate and model the printing process so that fibers can be aligned in the most beneficial orientation, yielding structures that are optimized for the particular application. Finally, LLNL is investigating composites of graphene aerogels and oxides to make electrodes with high energy densities and developing in situ monitoring systems to help qualify and certify laser-based additive manufacturing techniques.

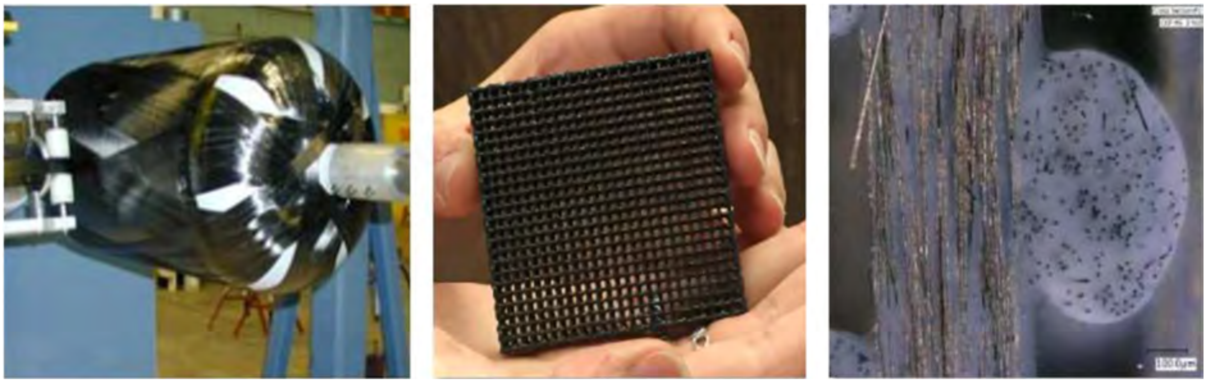


Figure 29. Printing to control carbon fiber alignment in three dimensions improves material properties and allows for fabrication of strong materials from cheaper chopped fiber precursors. Image credit: Lawrence Livermore National Laboratory.

BREAKOUT SESSION 6—INTERNATIONAL SPACE STATION AND TRANSLATIONAL MATERIALS RESEARCH

The International Space Station (ISS) session highlighted Space Station as a unique research platform for exploring the behavior of materials in a microgravity environment. Researchers use the long microgravity time constant of ISS to explore materials and manufacturing processes in ways that are not possible with parabolic flights or suborbital flight research opportunities. An overview presentation highlighted the portfolio of NASA's Space Life and Physical Sciences Research and Applications (SLPSRA) division, which includes work in metals, nonmetals, semiconductors, biomaterials, granular materials, and glasses and ceramics.

Historically ZBLAN has been regarded as a material with great economic potential. The high market value for 'pure' ZBLAN fiber, whose production is perhaps uniquely enabled by fiber drawing in a microgravity environment, makes it an attractive material for processing in space. ISS can also be used to characterize gravity-dependent properties of materials; levitation facilities on ISS are commonly used for this purpose. The higher fidelity thermophysical property measurements possible in a microgravity environment represent high value translational research to improve the predictive capability of material models on Earth.

Applications for bulk metallic glasses (BMGs) and an ISS experiment to investigate formation of BMGs in microgravity were also discussed during this session.

■ NASA Microgravity Materials Science Overview—Dr. Jan Rogers, NASA Marshall Space Flight Center

Dr. Jan Rogers earned a Ph.D. in Chemical Engineering from the University of Colorado, Boulder in 1990. She has extensive experience in materials science and characterization and Program/Project management. She has been the Project Science Lead for the Microgravity Program for several years and has supported Program Management for NASA's Space Technology Mission Directorate. She has served as the lead scientist on numerous funded proposals in materials science. She has led the efforts of the Electrostatic Levitation (ESL) Facility at NASA Marshall Space Flight Center since its inception in 1997.

Platforms for microgravity research include the International Space Station (ISS), parabolic flight aircraft and suborbital rockets. The Space Life and Physical Sciences Research and Applications (SLPSRA) Division is a part of NASA's Human Exploration and Operations Mission Directorate. The vision of the program is to lead the space life and physical sciences research community to enable space exploration technology development and benefit life on Earth. Implementation principles include maximizing open science and cultivating government, industry, and academic partnerships. Research areas for SLPSRA include: biophysics, combustion science, fluid physics, materials science, fundamental physics, complex fluids, and materials science. The SLPSRA Microgravity Materials Science program conducts experiments on the ISS designed to improve our understanding of materials processing and properties. Focus areas include metals, semiconductors, polymers, glasses and ceramics, granular materials, composites, and organics. The scientific understanding gained from experimentation in the long microgravity time constant of ISS can be applied to Earth-based industrial processes in order to achieve better and/or less expensive materials. The Space Station provides a simplified environment to study materials since there is nearly negligible sedimentation- and buoyancy-driven convection affecting the observations. Microgravity platforms can enable research establishing quantitative and predictive relationships between the way a material is produced (processing), its structure (atomic arrangement), and properties and provide insights that cannot be accessed in an Earth-based lab. The program supports a diverse portfolio of projects. Applications of the research to date include improved turbine blades, higher quality steel, new materials for medical lasers, improved semiconductor devices, and new pharmaceuticals.

The presentation highlighted several on-orbit investigations for materials. The Penn State University Microgravity Investigation of Cement Solidification (MICS) benchmark experimental study of cement hydration in reduced gravity. This work informs NASA extraterrestrial infrastructure development utilizing in situ materials and advances our knowledge of Earth-based cement processing. An example of an ISS-processed sample is shown in figure 30. The study of cement hydration and microstructure in microgravity on ISS sheds light on crystal hydration kinetics, phase formations, pore distribution, and material properties, and helps to understand crystal growth kinetics and morphology. Burst-Seal bags were used to mix the reactants and initiate a reaction in the maintenance workbench area (MWA) on the ISS.

To execute its research activities, the microgravity materials science program makes use of several facilities on the ISS, including the Microgravity Materials Science Research Rack (MSRR), Microgravity Science Glovebox (MSG), Pore Formation and Mobility (PFMI), Solidification

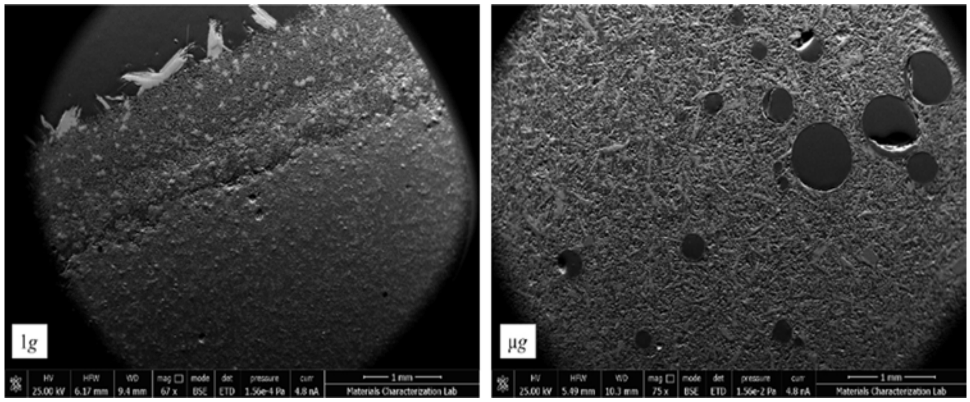


Figure 30. Polished surface of C_3S pastes hydrated at 1*g* (left) and µg (right). The 1*g* sample shows a porosity gradient and the cross section of large portlandite crystals at the surface as a result of buoyancy. The µ*g* sample shows the presence of large air bubbles and uniform porosity. Image credit: NASA.

Using a Baffle in Sealed Ampoules (SUBSA), and the Light Microscopy Module (LMM). Payloads can interface with the Expedite the Processing of Experiments to Space Station (EXPRESS) rack. Facilities and payloads enable:

- The study of solidification microstructures.
- Crystal formation and growth. Some proteins—and other complex structures—grown on orbit are larger and have fewer defects than those grown on Earth. High-quality crystals can be used to help develop new pharmaceuticals. The improved data from the space-grown crystals significantly enhance scientists' understanding of the protein's structure and this information can be used to support structure-based drug design.
- Infrastructure materials and processes in microgravity (soldering, brazing, cement formation) thermophysical properties research (uses the ESA electromagnetic levitation facility and the JAXA Electrostatic Levitation Furnace). Containerless processing capabilities facilitate precise measurement of thermophysical properties not possible on Earth in the presence of gravity effects on material behavior.

Potential future NRA topics and research priorities flow from workshops which engage the exploration pull community. One such workshop was held at the ISS R&D conference in Atlanta July 2019. The workshop was co-sponsored by the ISS National Lab and NASA SLPSRA. Topics included advanced manufacturing for in-space fabrication and repairs, joining of materials, metallic alloys for high-temperature and cryogenic applications, lunar habitat and infrastructure materials, and techniques for thermophysical measurements in microgravity. A biophysics workshop, sponsored by NASA Space Biology and ECLSS, was held in Bozeman, Montana, at the Center for Biofilm Engineering annual conference in July 2019.

The physical science informatics (PSI) program is focused on open science. The platform (psi.nasa.gov/index.html) provides global access to cutting-edge research data, including data from ISS experiments or other carriers. The intent of this platform is to leverage research data to advance fundamental research and accelerate materials development and commercialization activities.

■ Electrostatic Levitation of ZBLAN and Chalcogenide—Dr. Dennis Tucker, NASA Marshall Space Flight Center

Dr. Dennis Tucker received his Ph.D. in Materials Science from the University of Florida in 1983. He subsequently worked at ARCO Research Labs, Los Alamos National Laboratory, and was on faculty at Georgia Tech. He has been at NASA Marshall Space Flight Center for almost 31 years. His research interests lie in the areas of microgravity processing of exotic glasses, Nuclear Thermal Propulsion, SHM sensors, and solid state supercapacitors.

Heavy metal Fluoride glasses have been studied for 35 years. ZBLAN and chalcogenide glasses are nonoxide materials which transmit well into the infrared. Both show immense promise as optical fibers with applications in fiber amplifiers, fiber lasers, and nuclear radiation resistant inks. The theoretical transmission loss coefficient for these materials is 0.001 dB/km. However, this loss coefficient has not been achieved to date in terrestrial processing due to intrinsic issues (band gap absorption, Rayleigh scatter, multiphonon absorption) and extrinsic issues (impurities such as rare Earth ions and multiphonon absorption). In both cases, processing in unit gravity can lead to small crystallites which can scatter light and increase the optical attenuation coefficient.

In a parabolic flight experiment, ZBLAN fibers were obtained from Focal Systems, Inc. and Bell Laboratories. Fibers were stripped of coatings and placed in evacuated quartz ampoules. In 200 distinct experiments lasting approximately 30 seconds each, fibers were heated to the crystallization temperature in reduced gravity and compared to fibers processed in gravity. Other fibers were flown on a suborbital rocket which provided 6.5 minutes of reduced gravity for processing experiments. High-G fibers produce white crystals, scatter light, and have reduced mechanical integrity relative to fibers processed in zero-G or reduced-G. The zero-G and 1-G fibers processed in these experiments are shown in Figure 31.

The precise mechanism which suppresses nucleation is not well understood at this time. One hypothesis uses shear thinning and accompanying changes in viscosity to explain the phenomenon. Nucleation and growth rates are inversely proportional to viscosity. Viscosity decreases with increasing shear rate. Shear thinning present in unit gravity (1G) may be absent in reduced gravity. Low gravity processing is known to reduce convection, which also reduces shear. Thus crystallization will be reduced in low gravity, as the viscosity curve is flattened relative to the 1G curve.

To confirm this hypothesis, it is proposed to use electrostatic levitation (ESL) to conduct viscosity and crystallization studies of pure ZBLAN and selected chalcogenide glasses. Data from these experiments can be used to generate viscosity versus time curves. Viscosity is inversely proportional to nucleation and growth and represents the only measurable quantity in the equations governing fiber processing. To date, chalcogenide samples have been investigated in the MSFC ESL facility, which can levitate 2–3 mm spheres of ZBLAN in the 500 ºC temperature regime. The field is created between six electrodes and charge is maintained by irradiating the sample with UV light. Samples are heated and melted with a laser and temperature is measured with a pyrometer.

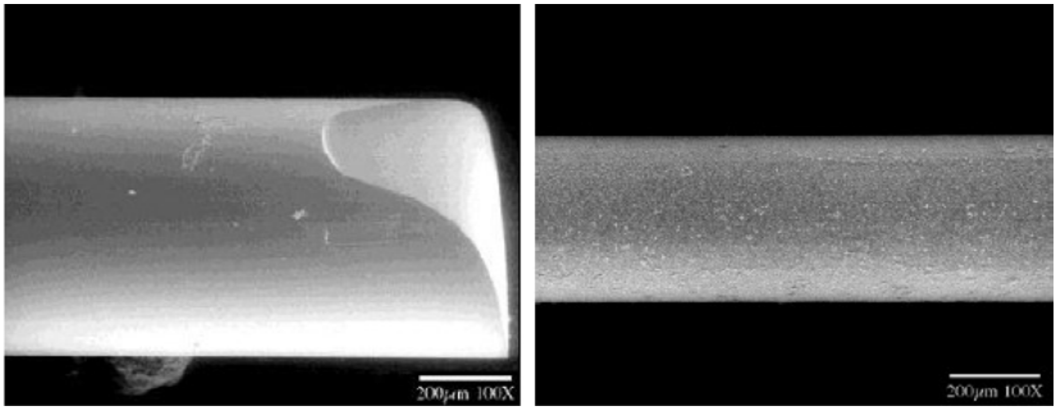


Figure 31. ZBLAN fibers processed in 0G (top) and 1G (bottom). Image credit: NASA.

Viscosity measurements are obtained via the oscillating drop methods, where surface oscillations are induced in the molten sample by modulating the electrostatic field near the resonant frequency. Surface tension is calculated from natural frequency and the viscosity is calculated from the damping coefficient. It is hypothesized that the nonlinear viscosity behavior of these materials in unit gravity becomes more linear in microgravity.

■ Materials Development Using Levitation Techniques on Ground and in Microgravity —Mr. Michael SanSoucie, NASA Marshall Space Flight Center

Mr. Michael SanSoucie leads the MSFC electrostatic levitation (ESL) laboratory, which provides advanced materials experimentation approaches to obtain materials science/property data on high-temperature materials. The ESL lab provides support to numerous programs including ISS, Orion, J2X, and academic, and commercial customers. Its capabilities include thermophysical properties measurement, triggered nucleation, creep strength measurement, rapid quench, and oxygen partial pressure control.

Using the levitators on the International Space Station (ISS), investigators are studying a wide range of NASA exploration-relevant materials. Levitation experiments enable exploration in many ways. For example, high-quality thermophysical properties of high-temperature materials are critical to develop accurate models of casting, joining, and metal additive manufacturing, which could lead to more efficient and more reliable production of hardware for exploration, commercial, and industrial applications. High-quality thermophysical properties could also lead to the development of novel functional oxide glass and optical materials. In many cases, the accuracy of available property data is the limiting factor in the predictive capabilities of the models.

There are several levitation techniques for materials science experiments and thermophysical property measurements: aerodynamic, acoustic, electrostatic, and electromagnetic. Electrostatic and electromagnetic levitation have an advantage in that they provide a containerless method for the study of undercooled melts and metastable states. Since samples do not come in contact with a container, they will not be contaminated by the container or react with it. The atmosphere in the levitator apparatus can be high-vacuum, inert gas, or even pressurized. MSFC has an ESL laboratory with two electrostatic levitation chambers—a main unit and a portable unit. These chambers typically run in high vacuum (~10^{-7} torr) and have fiber optic (1,064 nm) and CO_2 lasers (10.6 micrometer) to facilitate heating of the sample. A pyrometer provides temperature measurement and a high-speed camera measures thermophysical properties of the specimens (density, surface tension, and viscosity). The sample size is typically 2–3 mm in diameter. The portable chamber has been used in the high-energy beamline at Argonne National Laboratory for determination of equilibrium and nonequilibrium phase diagrams, and it has been used for structure and phase determination of quasicrystals. Figure 32 shows a thermal profile for a 2-mm sample that was used to measure viscosity (determined by how fast the motion dampens out), surface tension (determined by motion frequency), and density (by edge detection). Density is derived from the temperature measurement during the rapid cooling of the sample at the end of the experiment.

In addition to these ground-based facilities, there are also two levitation facilities currently in use on the ISS. They are the European Space Agency's Electromagnetic Levitator (ISS-EML) and the Japan Aerospace Exploration Agency's Electrostatic Levitation Furnace (ELF). The ISS-EML has been used to study conductive materials, including steel analogues, bulk metallic glasses, and nickel-based superalloys. The ELF has been used mainly in the study of metal oxides. ISS facilities eliminate the convective contamination which may contribute to the formation of intermediate phases in ground-based processing. Precise nucleation and viscosity measurements are uniquely enabled by the microgravity environment. Metal oxides in particular are very difficult to study

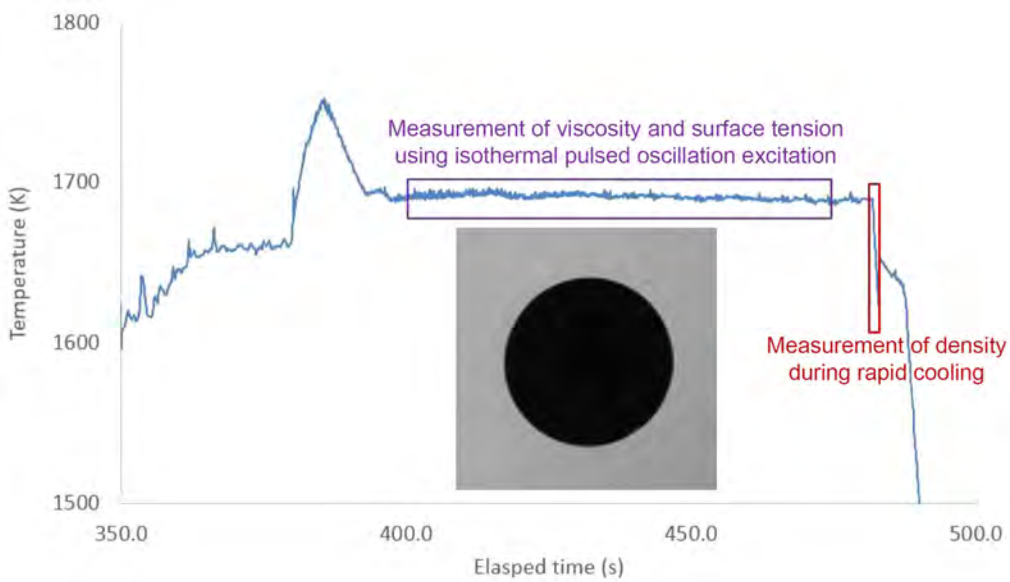


Figure 32. An example of a temperature profile of a 2-mm-diameter material specimen that was used for thermophysical property measurements. Image credit: NASA.

using ground-based levitation. High-fidelity thermophysical properties derived from microgravity measurements are critical for developing accurate models of material behavior during casting, welding, and additive manufacturing.

Highlights of recent work with ISS-EML include magentohydrodynamic (MHD) modeling support of macroconvection in various materials (Robert Hyers, University of Massachusetts), correlating nucleation kinetics with the local structure of liquids (Keneth Kelton, Washington University in St. Louis), and investigating the effect of fluid flow on the solidification path of peritectic structural alloys (Douglas Matson, Tufts University). Current and planned ELF investigations include modeling and simulation of electrostatically levitated multiphase liquid drops (Robert Hyers, University of Massachusetts), round-robin study of thermophysical property measurement (Douglas Matson, Tufts University), novel measurements of interfacial tension (Ranga Narayanan, University of Florida), and thermophysical properties of supercooled molten metal oxides (Richard Weber, Materials Development, Inc.) Understanding interfacial phenomena,which is possible with the EML and ELF facilities, is particularly important in steel production and the production of higher purity steels. The ESA THERMOLAB (Thermophysical Properties of Liquid Metallic Alloys – Modeling of Industrial Solidification Processes and Development of Advanced Products) project is measuring thermophysical properties and solidification of Zirconium alloys used in nuclear reactors with the goal of improving manufacturing of reactor components (work is also relevant to NASA's nuclear thermal propulsion research). Ground-based electrostatic levitation investigations at MSFC also enabled the development of bulk metallic glass (BMG) Vitralloy 106a, which was used for one of the collector materials in the Genesis spacecraft, a sample return probe which sampled solar wind particles.

NASA Space Life and Physics Sciences Research and Applications (SLPSRA) supports experiments using the ISS-EML and ELF facilities on board the ISS.

■ Bulk Metallic Glass Research on the International Space Station—Dr. Scott Roberts, NASA Jet Propulsion Laboratory

Dr. Scott Roberts earned his Ph.D. from the California Institute of Technology in Materials Science for his thesis on Developing and Characterizing Bulk Metallic Glasses for Extreme Environments. He is now a member of Jet Propulsion Laboratory's (JPL's) Materials & Manufacturing group whose research is focused on applying new materials and manufacturing techniques to solving NASA's spaceflight problems. His primary projects include additively manufacturing porous structures with controllable gradients, using advanced manufacturing methods to improve thermal control technologies, and attempting to one day make metallic glasses a success story. He is an author on more than 20 peer-reviewed publications and 10 patents.

Bulk Metallic Glasses (BMGs), also known as amorphous metals, are characterized by high strength, high elastic limits, low melting point, low modulus, and good wear resistance relative to other metallic alloys, such as zinc, aluminum, titanium, and steel. BMGs can also be injection-molded or die-cast into complex parts at low cost. This talk outlined the unique processing routes available to BMGs, some of their applications identified within NASA, and a retrospective on microgravity experiments with BMG which have enabled maturation of the material for spaceflight applications. Processing for BMGs is critical—temperature and time windows tend to be narrow. Heating and cooling determine the atomic structure of the material and the resulting properties; high temperature and rapid cooling are necessary to avoid crystalline formation. Methods to process BMGs include direct casting (Figure 33), semisolid processing, rapid discharge forming, and thermoplastic forming.

Figure 33. Images of BMG gears made with direct casting. BMG gears have excellent performance at cryogenic temperatures. Image credit: NASA JPL.

Thanks in part to support from NASA, recent innovations in bulk metallic glass processing technology, and the emergence of large manufacturing capabilities within industry, this material class is finally ready to come to market. Additionally, JPL is using and developing several metal 3D printing technologies for fabricating BMGs: powder bed fusion, thermal spray additive manufacturing (AM), ultrasonic AM, laser foil printing, capacitive weld printing, and hybrid AM/casting.

Microgravity materials science research with BMGs dates back to 1997, when the TEMPUS facility was flown as part of MSL-1. A U.S./German collaboration resulted in 10 different studies on undercooled liquids, including Vitreloy 106. Electrostatic levitation of small BMG samples can measure undercoolings, viscosity, and surface tension. ESL experiments to characterize the BMG Vitreloy 106 enabled its use in panels of the solar wind particle collector Genesis. When the Genesis probe crash-landed, the BMG sample was one of the only targets that survived. Several high-profile papers resulted from the science that was gathered on the BMG panels. In 2005, BMG foams were fabricated on the ISS using a soldering gun (Pd-based BMG). This experiment was an early demonstration of manufacturing of materials in the space (microgravity, IVA) environment. Amorphous metal foils are now baselined for JPL's Starshade mission concept. (A Starshade flown between a space telescope and a star could precisely block out a star's light and reveal the presence of planets orbiting the star.)

Currently JPL is pursuing manufacture of BMGs on-orbit. Vitreloy 106 is safe for use in an IVA environment, but there is difficulty in vitrifying BMG samples on orbit. (Vitrifying refers to conversion of a molten liquid to a glass.) The proposed flight project seeks to perform mechanical tests (e.g., wear test) on samples produced in space. Nanocrystalline BMGs (with 30% Tungsten reinforcement) have reduced wear loss significantly relative to amorphous Vitreloy 106 and crystalline Vitreloy 106. The mass loss observed in wear testing for the 30% W-reinforced alloy is 5% of the crystalline material under the same test conditions. Nanocrystalline BMGs with Tungsten are an alternative to BMGs containing Beryllium. (Beryllium violates toxicity requirements for material use in the habitable volume of the ISS.) The ISS project FAMIS intends to process W-heavy BMG alloys on orbit without sedimentation and additionally demonstrate fabrication of MMC cylinders on orbit. The wear resistance and toughness of devitrified specimens made in space will be compared with parts made on the ground. This work is supported by NASA STMD's Game-Changing Development Program, NASA Marshall Space Flight Center, and the JPL Office of Space Technology.

PANEL DISCUSSION WITH SESSION CHAIRS

At the conclusion of the breakout session on the second day, the session chairs participated in a panel discussion. Panelists included Dr. Sandeep Shah, MSFC; Michael Frazier, MSFC; Ed Glaessgen, LaRC; Erin Richardson, MSFC; Dr. Mark Hilburger, LaRC; and Dr. Jan Rogers, MSFC. The panel was moderated by James Zakrajsek from NASA GRC and Dr. Jonathan Ransom from LaRC. Panelists offered their thoughts on highlights and high potential research areas in their session.

METALS

Sandeep Shah (session chair, metals) joined NASA in the Metallic Materials Branch of Materials, Manufacturing, and Processes Laboratory in 1999. Prior to this he worked as principal engineer with Lockheed Martin. Since joining NASA, he has held positions of increasing responsibility. He is currently the Division Chief of Metallic Materials and Processes Division, where he is responsible for advancement of state of art and product deliverables in areas such as Alloy and Process development, International Space Station Materials Science research, Diagnostics and Failure Analysis, Project Support, Nuclear Thermal Propulsion, Corrosion, Forming Processes, and Welding and Joining processes. He received his Ph.D. and M.S. in Materials Engineering from Vanderbilt University. He has co-authored 27 publications and holds one patent. He is the recipient of NASA's Exceptional Service Medal, NASA's Silver Snoopy Award, NASA Space Act Award, NASA Manned Space Flight Launch Honoree, Lockheed Martin's Technology Disclosure and Achievement awards, and several group achievement awards.

Key Points:

- Additive manufacturing (AM) is a focus area for metals research. NASA and industry see the potential of AM to enable engine reuse and reduce the cost, weight, and time to manufacture engine systems.
- Engines require unique approaches to thermal protection and coatings.
- Friction stir welding is a versatile method for joining commonly used in the aerospace industry. The MELD technique is derived from friction stir welding and can build large-scale metal parts with high deposition rates. As a solid-state process, MELD is not dependent on buoyancy-driven convection for material solidification.

NONMETALS

Michael Frazier (session chair, nonmetals) has served as the Division Chief of Marshall Space Flight Center's Nonmetallic Materials and Advanced Manufacturing Division since 2017.

Michael graduated from the University of Mississippi with a B.S. in Mechanical Engineering in 1998 and an M.S. in Material Science and Engineering in 2000. He came to NASA in July 2000 and has been involved with various material- and process-related accomplishments including managing development of new environmentally compliant thermal protection systems for NASA launch vehicles; design development, procurement, assembly, and activation of MSFC's Thermal Protection System Development Facility; and material and process development for the Shuttle-Reinforced Carbon-Carbon On-Orbit Crack Repair (ROCR) system during Return to Flight.

Key Points:

- Properties of thermoplastics can be modified for a specific application. These materials have been used for 3D printing on the ISS and also demonstrated in a NASA competition for large-scale printing of habitats (NASA's Centennial Challenge: 3D Printed Habitat).
- Aerogels are multifunctional and low-weight materials. Their applications include insulation and communication systems.
- High-strength ceramics and accompanying fabrication methods are an emerging research area. Development of computational modeling capabilities for these materials are needed to support their use in flight systems.
- Approaches to certification of additively manufactured materials remains an overarching concern across material classes.

COMPUTATIONAL MATERIALS

Dr. Ed Glassgaen (session chair, computational materials) is NASA's Senior Technologist for Computational Materials. In this role, he plans, leads, and performs research aimed at advancing the state-of-the-art in understanding the fundamental physical phenomena that result in macroscopic material properties and behavior. Of particular interest is the development of analytical and experimental methods needed to develop processing-microstructure-performance relationships for structural and multifunctional materials under representative environments and loadings.

Key Points

- There are numerous barriers to certification of materials (particularly PMCs and additively manufactured materials) which computational modeling approaches can help address. These include manufacturing variability, limitations of NDE, and damage growth.
- There is a need to develop computational materials capabilities to address the following:
  - Reduction of test matrices
  - Effort in materials design/processing
  - Modeling of processes at small length scales
  - Robust certification, especially for additive manufacturing.
- There is continued work on development of processing-microstructure-property-performance relationships for multiple length scales and multiple physical processes. This work seeks to link different models (and scales of models) together.

- There was discussion on advantages and disadvantages of commercial and in-house codes:
  - High-impact capabilities are at DoE, DoD, and NASA, but these tools have a somewhat limited user base.
  - Commercial codes have broad capabilities and a commercial user base.
- There is a need to transition from research outcomes to engineering capabilities (the vernacular technology readiness level 'valley of death'). We need to gain confidence in the use of simulation to perform verification and validation activities. The ultimate goal is to design and certify materials in a paradigm that is similar to design and certification of structures.

TESTING AND CHARACTERIZATION

Erin Richardson (session chair, testing and characterization) is the Chief for the Materials Test, Chemistry, and Contamination Control Branch at NASA Marshall Space Flight Center. She has served in this position since August 2015. Ms. Richardson began her career in 1988 as a cooperative education student in the Materials and Processes Laboratory. She worked for Plasma Processes, Inc developing vacuum plasma-sprayed functionally gradient materials in support of the Department of Energy's International Thermonuclear Experimental Reactor (ITER). Ms. Richardson retuned to the Materials and Processes Laboratory as a support contractor with Native American Services, Inc in the Materials Combustion Research Facility (MCRF) where she was a test engineer and served as lead data engineer for the MAPTIS database. In 1999, Ms. Richardson joined M&P as a civil servant. She served as lead engineer for oxygen compatibility testing and oxygen hazards assessments. She then served in various positions including MSFC Engineering Lead for the Ares I First Stage Deceleration Subsystem, Assistant Manager for Stage Operations in the Upper Stage Element Office, and most recently as the Sub-Discipline Lead Engineer for Debris Environments and Abort Environments for the Space Launch System. Ms. Richardson earned a B.M. Engineering from Auburn University in 1992 and an M.S. in Management of Technology from the University of Alabama—Huntsville in 2001.

Key Points:

- Focus of session was how to assess and characterize materials and how test results can inform and validate modeling efforts.
- New and unique approaches to testing were presented. Nanocalorimetry enables rapid thermal measurements at small length scales that were not previously possible.
- There is a need to link the macroscale to the microscale (testing and characterization across length scales). GRCop-84 parts produced through SLM can create better properties than in analogous wrought material. The development of GRCop-84 and its infusion into engine applications represents an important case study for development of AM for flight hardware.

EMERGING MATERIALS

Dr. Mark W. Hilburger (session chair, emerging materials) is a Senior Research Engineer in the Space Technology Exploration Directorate at NASA Langley Research Center in Hampton

VA. He was recently appointed Space Technology Mission Directorate (STMD) Principal Technologist (PT) for Structures, Materials, and Nanotechnology at NASA. His roles and responsibilities include developing technology investment plans across his assigned areas in coordination with NASA Exploration Programs. Previous to his STMD PT appointment, he was the Principal Investigator and Manager of the NASA Engineering and Safety Center's Shell Buckling Knockdown Factor Project from 2007 to 2018. The goal of the project was to develop and validate new design, analysis, and testing methods for buckling-critical launch vehicle structures. His responsibilities included defining and managing the integration of analysis, design, manufacturing, and test teams to develop an efficient, multidisciplinary approach to optimal structural design, verification, and validation. He also coordinated Space Act Agreements with Boeing, Northrop-Grumman, the German Research Laboratory (DLR), and the European Space Agency (ESA). Dr. Hilburger specializes in High-Fidelity Analysis and Design Technology Development and Experimental Methods for Aerospace Structures. He has been presented with numerous awards including the 2018 Middle Career Stellar Award presented by The Rotary National Award for Space Achievement; the NASA Exceptional Engineering Achievement Medal, 2010; the NASA Engineering and Safety Center Engineering Excellence Award, 2009; selected as 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 Ph.D. and M.S.E. in Aerospace Engineering from the University of Michigan in Ann Arbor, Michigan, in 1998 and 1995, respectively, and his B.S. in Mechanical Engineering from Rutgers University in New Brunswick, New Jersey in 1993.

Key Points:

- Graphene research has high potential for aerospace applications. Researchers seek to alter properties of existing materials using graphene.
- Many emerging materials will require development of standards governing their manufacturing and use before they can gain acceptance in the aerospace community.
- Analysis tools and high-performance computing can increasingly be leveraged to smartly design materials.
- In-space manufacturing of materials and in situ manufacturing (on a planetary surface) will be important for ensuring the sustainability of crewed exploration.

INTERNATIONAL SPACE STATION TRANSLATIONAL RESEARCH

Dr. Jan Rogers (session chair, ISS Translational Research) earned a Ph.D. in Chemical Engineering from the University of Colorado, Boulder in 1990. She has extensive experience in materials science and characterization and Program/Project management. She has been the Project Science Lead for the Microgravity Program at MSFC for several years and has supported Program Management for NASA's Space Technology Mission Directorate. She has served as the lead scientist on numerous funded proposals in materials science. She has led the efforts of the Electrostatic Levitation (ESL) Facility at MSFC since its inception in 1997.

Key Points:

- NASA has a long history of conducting and facilitating microgravity research. This research has led to improved models of materials and manufacturing processing.
- NASA has an increased focus on commercialization of ISS. The user community for ISS is broadening through ISS National Lab. NASA is always seeking new experiments that require the use of the microgravity environment uniquely provided by ISS.
- Materials researchers in all fields understand that gravity is a variable and many materials will behave differently in a low or microgravity environment. The dependence of materials and materials processing on the gravity vector can also lead to improved materials design and processing techniques for Earth.

CONCLUSION

Dr. Suren Singhal spoke briefly to conclude the 1½ day workshop. The first NASA Breakthrough Materials Workshop brought together a diverse array of researchers and representatives from projects and programs within NASA and the federal government. Dr. Singhal emphasized the criticality of materials to every project in the Agency's technology portfolio, from small-scale research and development projects to multi-billion-dollar assets like the James Webb Space Telescope or the Space Launch System. NASA considers materials development to be an integral part of the science and engineering approach required to meet the Agency's missions and reduce risk. NASA and the broader materials community are charged with accelerating the development of new materials and ensuring they are appropriately infused into projects where they could help address engineering challenges. The workshop demonstrated modeling and simulation approaches that have matured immensely in recent years with the advent of high-performance computing capabilities and have the potential to reduce schedule and cost. These techniques, however, represent a paradigm shift from the traditional approach of extensive and iterative testing for flight hardware.

NASA has a strong demand for high-performing materials (materials that can survive launch loads, vacuum environments, the high temperatures in propulsion systems, and multiyear missions on a planetary surface). The aerospace community must collaborate to develop and characterize materials to satisfy these demanding mission requirements. The first Breakthrough Materials Workshop will serve as a starting point for future collaboration in the high value areas identified through the event. NASA looks forward to continuing the workshop in 2021 and highlighting even greater advances made possible by the groundbreaking materials research happening across the United States in government, academia, and industry.

APPENDIX A—AGENDA

NASA BREAKTHROUGH MATERIALS WORKSHOP
April 23–24, 2019
Jackson Center, 6001 Moquin Drive NW, Huntsville, Alabama

DAY 1—APRIL 23, 2019

7:30 AM Coffee and Networking, Lobby

8:00 AM Welcome and Opening Remarks, Discovery Hall B

Dr. Suren Singhal, Director, NASA Marshall Space Flight Center (MSFC), Materials and Processes Laboratory
Dr. Lisa Watson-Morgan, NASA MSFC Deputy Director, Engineering
Mr. John Vickers, NASA Principal Technologist, Manufacturing
Mr. Randy Lycans, Vice President and General Manager, Jacobs Engineering

8:15 AM Revolutionary Composites

Dr. Keith Young, Director of Composites and Metals Management and Technology, Boeing

8:45 AM Forging a Path for Materials Revolution

Dr. Melissa K. Rhoads, Lockheed Martin Space, Advanced Technology Center

9:15 AM Nanostructured Materials for Energy Capture, Storage and Delivery in Space-Based Applications

Dr. Jud Ready, Georgia Institute of Technology, Deputy Director for the Institute for Materials

9:45 AM Break

10:00 AM High Rate Composites Manufacturing for Aerospace

Dr. Byron Pipes, Purdue University, Executive Director of the Composites Manufacturing Simulation Center

10:30 AM Advancing Technology Through Measurement Science: The Materials Genome Initiative 2.0

Dr. Eric Lin, Director of the Material Measurement Laboratory National Institute of Standards and Technology

11:00 AM Optimized Geometries Meet Optimized Materials: 3D Printing of Nanostructured Metals

Dr. Christopher Schuh, Department Head, Materials Science and Engineering Massachusetts Institute of Technology

11:30 AM Lunch

BREAKOUT SESSION 1—METALS
Discovery Hall B, 1:00 PM – 2:40 PM
Chair: Dr. Sandeep Shah, NASA MSFC

1:00 PM Additive Manufacturing of Lightweight Metal Composites

Dr. Ethan Parsons and Dr. Todd Mower, MIT Lincoln Laboratory

1:20 PM Emergence of Airware 2050 for Space Applications

Michael Niedzinski, Constellium

1:40 PM A Survey of High-Temperature Materials and Processes Developed Through NASA's Small Business Innovative Research Program at Plasma Processes

Tim McKechnie, President of Plasma Processes

2:00 PM Meld Manufacturing of Functionally Graded and Advanced Materials

Dr. Paul Allison, Assistant Professor, University of Alabama, Department of Mechanical Engineering

2:20 PM Discussion

2:45 PM Snack Break and Transition to Next Session

BREAKOUT SESSION 2—NONMETALS
Board of Directors Room, 1:00 PM – 2:40 PM
Chair: Michael Frazier, NASA MSFC

1:00 PM Design and Manufacture of High-Performance Thermoplastic Compounds for Technically Demanding Applications

Alan Franc, Product Development Manager at Techmer

1:20 PM Aerogels: Ultralightweight Materials With Multiple Applications

Jessica Cashman, Chemical Engineer, NASA Glenn Research Center and Dr. Frances Hurwitz, Materials Research Engineer, NASA Glenn Research Center

1:40 PM A High-Strength, Shape-Stable Ceramic for Challenging Thermo-Structural Environments

Dr. Brian Sullivan, Materials Research & Design

2:00 PM US-COMP: Next Generation of Composite Materials for Crewed Deep Space Missions

Dr. Greg Odegard, Professor of Computational Mechanics in the Department of Mechanical Engineering – Engineering Mechanics, Michigan Technological University

2:20 PM Discussion

2:45 PM Snack Break and Transition to Next Session

BREAKOUT SESSION 3—COMPUTATIONAL MATERIALS
Discovery Hall B, 3:00 PM – 5:00 PM
Chair: Dr. Ed Glaessgen, NASA Langley Research Center

3:00 PM Enhanced Manufacturing Through Process Modeling: A NASA Advanced Composites Program (ACP) Approach

Dr. Sayata Ghose, Associate Technical Fellow, Composites Fabrication, Boeing

3:20 PM Motivation, Development, and Future Directions for Computational (Metallics) Materials at NASA

Dr. Ed Glaessgen, NASA Senior Technologist for Computational Materials, NASA Langley Research Center

3:40 PM Computational Materials for Qualification of Advanced Manufacturing Metals

Dr. Theron Rodgers, Computational Materials Science, Sandia National Laboratories

4:00 PM Modeling of Polymer Matrix Composites Within the Air Force Research Laboratory Materials and Manufacturing Directorate

Dr. David Mollenhauer, Principal Materials Engineer, Air Force Research Laboratory

4:20 Discussion

BREAKOUT SESSION 4—TESTING AND CHARACTERIZATION

Board of Directors Room, 3:00 PM – 5:00 PM

Chair: Erin Richardson, NASA MSFC

3:00 PM Nanocalorimetry: Faster, Smaller Chip-Based Thermal Analysis

Dr. David LaVan, Material Measurement Laboratory, National Institute of Standards and Technology

3:20 PM Advancing NASA's Materials Development Needs Through Nanoscale Analytical Microsocopy

Dr. Gregory Thompson, University of Alabama

3:40 PM Characterization and Testing Facilities for Next Generation Materials

Bhavesh Patel, Southern Research Institute

4:00 PM Characterization, Testing, and Infusion of Additively Manufactured GRCop- 84 Into Hardware Programs

Robert Carter, NASA Glenn Research Center, Chief – High Temperature and Smart Alloys Branch

4:20 PM Discussion

5:00 PM End of Day 1

DAY 2—APRIL 24, 2019

7:30 AM Coffee and Networking, Lobby

7:50 AM Introduction, Discovery Hall B

Dr. Suren Singhal, Director, MSFC Materials and Processes Laboratory

Space Tech Prize Announcement

Mr. Randy Lycans, Vice President and General Manager of Jacobs Engineering

8:00 AM Recent Advances in Materials and Methods for Aerospace Applications at NASA Langley Research Center

Dr. Jonathan Ransom, Deputy Director for Structures & Materials, Research Directorate, NASA Langley Research Center

8:20 AM Advanced Materials Research at NASA Glenn Research Center

Dr. James Zakrajsek, Division Chief, Materials and Structures Division, NASA Glenn Research Center

8:40 AM Material Design for Deep Space Reliability: Looking to the Future While Learning From the Past

Richard Russell, Technical Fellow for Materials, NASA Engineering Safety Center

BREAKOUT SESSION 5—EMERGING MATERIALS

Discovery Hall B, 9:00 AM – 11:00 AM
Chair: Dr. Mark Hilburger, NASA Langley Research Center

9:00 AM Graphene in Aerospace Applications

Dr. Ahmed Al-Ostaz, Professor of Civil Engineering, University of Mississippi

9:20 AM On the Properties and Design of Complex Solid-Solution Alloys

Dr. Duane Johnson, Materials Science and Engineering, Iowa State University and Chief Scientist, Ames Laboratory, U.S. Department of Energy

9:40 AM Ultra-Thin Conformal Inorganic Films on Particles and High Aspect Ratio Inner Surfaces by Atomic Layer Deposition

Dr. Alan Weimer, University of Colorado at Boulder, Chemical and Biological Engineering

10:00 AM Moon Base: 35 Years of Study and Ideas

Rob Kelso, Founder/CEO Kelso Aerospace Consulting, LLC

10:20 AM Materials Design for Advanced Manufacturing

Dr. Scott McCall, Lawrence Livermore National Laboratory

10:40 AM Discussion

BREAKOUT SESSION 6—INTERNATIONAL SPACE STATION AND TRANSLATIONAL MATERIALS RESEARCH

Board of Directors, 9:00 AM – 11:00 AM
Chair: Dr. Jan Rogers, NASA MSFC

9:00 AM NASA Microgravity Materials Science Overview

Dr. Jan Rogers, NASA MSFC

9:20 AM Electrostatic Levitation of ZBLAN and Chalcogenide

Dr. Dennis Tucker, NASA MSFC

9:40 AM Materials Development Using Levitation Techniques on Ground and in Microgravity

Michael SanSoucie, Materials Engineer, NASA MSFC

10:00 AM Bulk Metallic Glass Research on the International Space Station

Dr. Scott Roberts, NASA Jet Propulsion Laboratory (JPL)

10:20 AM TBD

10:40 AM Discussion

11:00 AM Break

11:15 AM Panel Discussion With Session Chairs (Discovery Hall B)

12:00 PM Concluding Remarks

Dr. Suren Singhal, Director, MSFC Materials and Processes Laboratory

APPENDIX B—LIST OF ATTENDEES

Jimmy Allen	Dynetics
Ian Allen	i3-corps
Paul Allison	University of Alabama
Ahmed Al-Ostasz	University of Mississippi
Robert Amaro	Southern Research
Majid Babai	NASA Marshall Space Flight Center
Roger Bagwell	Actuated Medical, Inc.
Raj Banerjee	University of North Texas
Mark Barkey	University of Alabama
David Barry	NASA Marshall Space Flight Center
Olga Baturina	Naval Research Laboratory
Bilyar Bhat	NASA Marshall Space Flight Center
Marion Holt	NASA Marshall Space Flight Center
Robert Biggs	Lockheed Martin
John Bloyer	NASA Marshall Space Flight Center
Janice Booth	US Army Futures Command
Joel Booth	US Army Futures Command
Robert Boucher	Boeing
Mark Bray	NASA Marshall Space Flight Center
Ellis Brazeal	University of Alabama
Jeramie Broadway	NASA Marshall Space Flight Center
Steven Burlingame	NASA Marshall Space Flight Center
DeWitt Burns	NASA Marshall Space Flight Center
Chad Carl	NASA Kennedy Space Center
Robert Carter	NASA Glenn Research Center
Jessica Cashman	NASA Glenn Research Center
Allison Clark	NASA MSFC
James Cole	CFRDC
Richard Cooper	NASA Marshall Space Flight Center
Megan Le Corre	NASA Marshall Space Flight Center
Patrick Cosgrove	NASA Langley Research Center
Zachary Courtright	NASA Marshall Space Flight Center
Chase Cox	MELD Manufacturing
Narendra Dahotre	University of North Texas
Richie Delmont	Teijin Aramid
Chaitanya Deo	Georgia Institute of Technology
Joyce Dever	NASA Glenn Research Center
Claudio Di Leo	Georgia Institute of Technology

Brenna Dickinson	US Army Futures Command
James Dobbs	Boeing
David Dress	NASA Langley Research Center
Tom Drye	Techmer PM
Terrisa Duenas	DryWired
Michael Eller	Lockheed Martin
Mike Eller	Lockheed Martin
Phil Farrington	Trivector US
Catharine Fay	NASA Langley Research Center
Laura Ferris	University of Alabama Huntsville
Miria Finckenor	NASA Marshall Space Flight Center
Mike Fiske	NASA Marshall Space Flight Center
Eric Fox	NASA Marshall Space Flight Center
Alan Franc	Techmer PM
Michael Frazier	NASA Marshall Space Flight Center
Ryan Gallagher	Oak Ridge National Laboratory
Wayne Gamwell	NASA Marshall Space Flight Center
Jian Gan	Idaho National Laboratory
Sayata Ghose	Boeing
Ed Glaessgen	NASA Marshall Space Flight Center
Michael Gnau	Lockheed Martin
Justin Gorham	National Institute of Standards and Technology
Edward Gorzkowski	Naval Research Laboratory
Craig Green	Carbice
Christine Gregg	ARC
William Guin	NASA Marshall Space Flight Center
Chris Haines	US Army Futures Command
Jimmy Hannah	NASA Marshall Space Flight Center
Ian Hanson	NASA Marshall Space Flight Center
Anwarul Haque	University of Alabama
Mary Jo Harris	NASA Marshall Space Flight Center
Michael Havlorson	Auburn University
Chris Henry	NASA Marshall Space Flight Center
Mark Hilburger	NASA Langley Research Center
Curtis Hill	NASA Marshall Space Flight Center
Samuel Hocker	NASA Langley Research Center
Timothy Hokanson	Boeing
Billy Hornbuckle	US Army Futures Command
Richard Howard	Oak Ridge National Laboratory
Tracy Hudson	US Army Futures Command
Frances Hurwitz	NASA Glenn Research Center
Dale Jackson	NASA Marshall Space Flight Center
Randall Jenkins	Aerojet Rocketdyne

Brian Jensen	NASA Langley Research Center
Duane Johnson	AmesLab
Jackie Johnson	University of Tennessee Space Institute
Patrick Johnson	NASA Langley Research Center
Ron Jones	National Institute of Standards and Technology
Gregory Jones	US Army Futures Command
Josh Kacher	Georgia Institute of Technology
Rob Kelso	Kelso Aerospace Consulting, LLC
Seongsin Kim	University of Alabama
Paul Krasa	NASA Langley Research Center
Patrick Kung	University of Alabama
John Lassiter	NASA Marshall Space Flight Center
David LaVan	National Institute of Standards and Technology
Lee Leonard	University of Tennessee Space Institute
Dan Lewis	Rensselaer Polytechnic Institute
Eric Lin	National Institute of Standards and Technology
David Mandrus	University of Tennessee (Knoxville)
Ed Mathias	i3-corps
Brian Mayeux	NASA Johnson Space Center
Jason Mayeur	University of Alabama Huntsville
Scott McCall	Lawrence Livermore National Laboratory
Bryan McEnerney	NASA Jet Propulsion Laboratory
Tim McKechnie	Plasma Processes
Joseph Meany	On-Line Instrument Systems, Inc.
Tim Mewes	University of Alabama
Fredrick Michael	NASA Marshall Space Flight Center
Jason Middleton	US Army Futures Command
Scott Miller	CFDRC
Sandy Miller	NASA Glenn Research Center
Michael Minor	US Army Test and Evaluation Command,RedstoneTestCenter
Omar Mireles	NASA Marshall Space Flight Center
Rajiv Mishra	University of North Texas
Mark Mitchell	NASA Marshall Space Flight Center
David Mollenhauer	Air Force Research Laboratory
Eliza Montgomery	NASA Kennedy Space Center
Paul Montgomery	University of Tennessee (Knoxville)
Jimmy Moore	NASA Marshall Space Flight Center
Todd Mower	Massachusetts Institute of Technology Lincoln Laboratory
Zach Myers	University of Alabama Huntsville
Michael Niedzinski	Constellium
Charlie Nola	NASA Marshall Space Flight Center
Greg Odegard	Michigan Institute of Technology
Michael Ogles	Auburn

Teng Ooi	Missile Defense Agency
Allison Park	Aerojet Rocketdyne
Cheol Park	NASA Langley Research Center
Ethan Parsons	Massachusetts Institute of Technology Lincoln Laboratory
Bhavesh Patel	Southern Research
Mark Patterson	Southern Research
Zhijian Pei	Texas A&M University
Byron Pipes	Purdue University
Tracie Prater	NASA Marshall Space Flight Center
Bryan Priest	Geocent
Alison Protz	NASA Marshall Space Flight Center
Jonathan Ransom	NASA Langley Research Center
Jud Ready	Georgia Institute of Technology Research Institute
Shawn Reagan	NASA Marshall Space Flight Center
Melissa Rhoads	Lockheed Martin
Erin Richardson	NASA Marshall Space Flight Center
Scott Roberts	Jet Propulsion Laboratory
Christopher Roberts	NASA Marshall Space Flight Center
Kristina Rodgers	NASA Marshall Space Flight Center
Theron Rodgers	Sandia National Laboratories
Lynn Rodman	Nexolve
Omar Rodriguez	NASA Marshall Space Flight Center
Rogie Rodriguez	Boeing
Jan Rogers	NASA Marshall Space Flight Center
Matthew Rogers	US Army Futures Command
Jhonathon Rosales	NASA Marshall Space Flight Center
Samit Roy	University of Alabama
Richard Russell	NASA Engineering Safety Center
Paul Russo	GA Tech
Masoud Mahjouri Samani	Auburn University
Mike Sansoucie	NASA Marshall Space Flight Center
Patrick Scheuermann	Geocent
Judy Schneider	The University of Alabama—Huntsville
Christopher Schuh	Massachusetts Institute of Technology
Katie Sebeck	US Army Futures Command
Ron Sega	Colorado State University
Zach Seibers	George Institute of Technology
Subhayu Sen	GeoCent
Sandeep Shah	NASA Marshall Space Flight Center
Nima Shamsaei	Auburn University
Jeffrey Sheehy	NASA Headquarters
James Shelton	Missile Defense Agency

James Shepherd	Cornerstone Research Group
Michael Schoenfeld	NASA Marshall Space Flight Center
Meisha Shofner	Georgia Institute of Technology
Davide Simone	Air Force Research Laboratory
Suren Singhal	NASA Marshall Space Flight Center
Sameer Singhal	CFDRC
Paul Smith	Constellium
Claude Snoddy	Missile Defense Agency
Ryan Snyder	Cornerstone Research Group
Louise Strutzenberg	NASA Marshall Space Flight Center
Rani Sullivan	Mississippi State University
Alma Stephanie Tapia	NASA Johnson Space Center
Wes Tayon	NASA Langley Research Center
Stephanie TerMaath	University of Tennessee (Knoxville)
Jordan Terrell	University of Alabama Huntsville
Vinoy Thomas	University of Alabama Huntsville
Gregory Thompson	University of Alabama
Will Tilson	NASA Marshall Space Flight Center
Gary Tiscia	Materials Research and Design, Inc.
James Tucker	Southern Research
Garritt Tucker	Colorado School of Mines
Dennis Tucker	NASA Marshall Space Flight Center
Uday Vaidya	University of Tennessee (Knoxville)
John Vickers	NASA Marshall Space Flight Center
Tomar Vikas	Purdue University
Yan Wang	Georgia Institute of Technology
Lisa Watson Morgan	NASA Marshall Space Flight Center
Alan Weimer	University of Colorado
Shawn Whitehead	i3-corps
Ryan Wilkerson	NASA Marshall Space Flight Center
Dustin Winslow	Summit Technologies
Sarah Wolff	Texas A&M
James Wollmershauser	Naval Research Laboratory
Keith Young	Boeing
James Zakrajsek	NASA Glenn Research Center
Bruno Zamoranosenderos	Boeing

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14. ABSTRACT
In April 2019, NASA Marshall Space Flight Center, along with NASA Langley Research Center and NASA Glenn Research Center, organized the first 'Breakthrough Materials for Space Applications' Workshop. This two-day event brought together over 100 representatives from government, industry, and academia to present significant advances in materials in the following areas: metals, nonmetals, testing and characterization, microgravity materials research, computational materials, and emerging materials. Presentations emphasized relevance of the work to aerospace applications and potential for advancements to address identified technical gaps and challenges for the aerospace industry. This Conference Publication summarizes the workshop content and discussions.

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