2019 ISS R&D Conference
Materials Science in Space
Workshop Report

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Hyatt Regency

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Workshop conducted jointly by NASA SLPSRA and the International Space Station (ISS) U.S. National Laboratory as part of the 2019 ISS R&D Conference

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Workshop Presentations

Presentations from the 2019 ISSRDC Materials in Space Workshop are available at the ISS National Laboratory website: https://www.issnationallab.org/workshops/2019-materials-in-space/.

About the Sponsoring Organizations

ISS U.S. National Laboratory: In 2005, Congress designated the U.S. portion of the ISS as the nation's newest national laboratory to optimize its use for improving the quality of life on Earth, promoting collaboration among diverse users, and advancing science, technology, engineering, and mathematics (STEM) education. This unique laboratory environment is available for use by non-NASA U.S. government agencies, academic institutions, and the private sector. The ISS National Laboratory manages access to the permanent microgravity research environment, vantage point in low Earth orbit, and the extreme and varied conditions of space. To learn more about the ISS National Laboratory, visit www.ISSNationalLab.org.

NASA SLPSRA: The Division of Space Life and Physical Sciences Research and Applications (SLPSRA) was established as part of NASA's Human Exploration and Operations Mission Directorate in 2011. SLPSRA administers NASA's Life and Physical Sciences Research, which includes the Human Research, Space Biology, and Physical Sciences Programs, to enable human spaceflight exploration and pioneer scientific discovery in and beyond low Earth orbit. To learn more about SLPSRA, visit www.nasa.gov/content/slpsra-overview.

Table of Contents

1 Executive Summary

The 2019 ISS Research and Development Conference (ISSRDC) Materials Science in Space Workshop, conducted jointly by NASA’s Space Life and Physical Sciences Research and Applications (SLPSRA) Division and the International Space Station (ISS) U.S. National Laboratory, was held on July 29, 2019 in Atlanta. Researchers from academia, industry, and government agencies gathered to discuss future materials science research opportunities aboard the ISS that enable achievement of both NASA’s exploration goals and the ISS National Lab’s goals for research and technology development to benefit life on Earth. A total of 147 individuals registered and attended various sessions of the day-long workshop.

Workshop participants identified overarching future research themes relevant to both NASA and the ISS National Lab in four key areas: (i) Advanced manufacturing cut across all other areas and encompasses additive manufacturing and joining processes as well as manufacturing at various length scales; (ii) The persistent microgravity environment aboard the ISS provides unparalleled opportunity for thermophysical property measurements; (iii) Microgravity-focused computational materials simulation can use thermophysical and other data to potential of microgravity research; (iv) There are many high-value materials manufacturing opportunities for materials that cannot be replicated by terrestrial manufacturing. As a specific example of one of these research themes, additive manufacturing advancements will provide in-situ resource utilization (ISRU) opportunities for NASA exploration programs. Space-based research in this area can also inform the burgeoning industry of additive manufacturing on Earth by elucidating the underlying physics and isolating key heat and mass transport phenomena, providing information that could significantly enhance the properties, functions, and applications of new additively manufactured materials.

New hardware and facilities to advance ISS materials science research were proposed in the three breakout session topic areas of Functional Materials; Materials Characterization, Microstructure, and Process Modeling; and Lunar Infrastructure and Surface Operations. There was significant overlap in the needs of all areas for materials characterization and furnace availability. All breakout sessions discussed both in-situ and ex-situ characterization hardware for integration into existing facilities or as stand-alone hardware. The characterization hardware proposed includes optical spectrometers, instruments for mechanical property measurements, and high-speed cameras.

Finally, the workshop participants challenged NASA’s SLPSRA Division and the ISS National Lab to commit resources toward the establishment of materials science research in low Earth orbit (LEO). Suggestions included dedicated programs, funding opportunities, and working groups to accelerate materials science research and manufacturing. Participants also sought standardization of experiments and databases of experimental results to inform the research community about past experimental investigations. Overall, response from the workshop participants demonstrated there is a strong demand among academic, industrial, and governmental research to take advantage of the unique ISS platform for materials science research, development, and manufacturing.

2 Workshop Overview and Objectives

The 2019 ISSRDC Materials Science in Space Workshop, jointly hosted by NASA's SLPSA Division and the ISS National Lab, was held on July 29 during ISSRDC in Atlanta, Georgia. This joint workshop connected government, university, and industry researchers and engineers interested in using microgravity and the extreme environmental conditions on the ISS to conduct innovative materials research. A total of 147 individuals registered and attended various sessions of the workshop.

2.1 Workshop Objectives

The workshop was held to help define the next generation of materials research themes for the ISS that enable achievement of both NASA's exploration goals and the ISS National Lab's goals for research and technology development to benefit life on Earth. NASA's SLPSRA Division is planning research and technology development to enable human spaceflight and scientific discovery beyond Earth orbit, and investigations into materials enabling NASA's exploration goals are of particular interest. The ISS National Lab's Advanced Materials Program is focused on basic and translational science as well as applied research for terrestrial benefit, with impacts that range from fundamental discovery to enabling significant commercial opportunities.

Enacting Space Policy Directive 1—Reinvigorating America's Human Space Exploration Program—will require innovative materials in every aspect of space exploration, from Earth launch to human habitation on the Moon and Mars. Space Policy Directive 2—Streamlining Regulations on the Commercial Use of Space—is intended to stimulate American leadership in space commerce that will include the discovery, development, and manufacture of new beneficial materials in space for use on Earth.

The ISS provides researchers the ability to conduct long-duration experiments in low Earth orbit, enabling scientists, engineers, and technologists to pursue innovations and discoveries not achievable by other means. Materials science encompasses a breadth of research areas made accessible in an environment where gravity-driven phenomena such as buoyancy-driven fluid flows and sedimentation are nearly negligible, allowing scientists to clarify the role of different effects on materials processes. The ISS also supports a variety of external platforms that enable exploitation of the harsh space environment for development and testing of new materials.

This workshop focused on the identification of future materials science investigations that address the goals of both NASA and the ISS National Lab. The workshop format consisted of morning briefings on high-priority advanced materials topics and new ideas, as well as overviews of the latest facilities and instruments available for materials research on the ISS. In the afternoon, in-depth breakout sessions built on the ideas presented in the morning briefings. The three breakout sessions, which were chosen based on responses to a Request for Information (RFI) issued in advance of the workshop, were:

1. Functional Materials
2. Materials Characterization, Microstructure, and Process Modeling
3. Lunar Infrastructure and Surface Operations

Crosscutting through all three of these breakout sessions are advanced manufacturing techniques (including additive manufacturing), thermophysical properties measurements, and computational materials science enabled by machine learning and artificial intelligence. The full workshop agenda is provided in Appendix B.

This report summarizes the breakout session discussions from the workshop. The objectives were to identify potential future investigations and gaps in existing ISS research capabilities and to recommend follow-on actions. In this report, the breakout session sections (sections 3, 4, and 5) were written by the co-chairs that led each session. The concepts and ideas presented in RFI responses, as well new ideas presented by the session participants, were consolidated by the co-chairs into the key recommendations presented in each section and summarized in Appendix A.

2.2 Request for Information

In advance of the workshop, an RFI[1] was issued by NASA and the ISS National Lab requesting input for the workshop to inform the demand and facility requirements for materials research aboard the ISS. The RFI responses were used to stimulate the discussions during the breakout sessions (see Appendix C for the listing of the RFI responses received). The workshop organizing committee categorized the responses into one or more of the breakout sessions, as indicated in the table in Appendix C.

Potential topics of interest listed in the RFI included, but were not limited to, the following:

- Advanced manufacturing for in-space fabrication and repairs, including additive manufacturing techniques and freeze casting
- Joining of materials, including brazing, soldering, and welding
- Metallic alloys for high-temperature and cryogenic applications, including multiscale modeling and the use of data from the ISS directional solidification experiments
- Lunar habitat and infrastructure materials, including cementitious materials
- Functional materials for space and terrestrial uses, including semiconductors, polymers, ceramics, and glasses
- Techniques for thermophysical properties measurements and microstructure assessment
- Computational materials science, including materials discovery and development enabled by machine learning and artificial intelligence

[1] RFI number NNH19ZTT001L titled "NASA and the ISS National Lab Request for Information in Advance of the 2019 Joint NASA/ISS National Lab Materials Science for ISS Workshop" was released on June 7, 2019.

3 Breakout Session: Functional Materials

Co-chairs: Michael Holman, Lux Research
Rick Weber, Materials Development, Inc.

3.1 Purpose of Session

This breakout session focuses on use of the microgravity environment of the ISS platform to develop materials with improved or tailored properties and characteristics that are useful terrestrially or in exploration systems. The term "functional materials" typically includes classes of materials with native functional properties such as ferroelectricity, piezoelectricity, magnetism, and energy storage. Broader interpretation includes biomimetic materials, self-assembly, smart coatings and films, and interface engineering.

3.2 Summary and Recommendations

This breakout session reviewed and discussed 25 contributed RFI responses in an open session. In addition to the RFI responses, the session solicited input from the workshop participants, session chairs, and facilitators, all included in this report. Theme areas identified were: (i) Additive Manufacturing, (ii) Materials Reuse, (iii) High-Value Functional Materials, and (iv) Thermophysical Properties. There were multiple synergies and areas of overlap between these topics identified by workshop participants, and the discussions highlighted the value to NASA and other stakeholders of an integrated approach.

The RFI responses that were discussed, and their grouping into theme areas, are provided in the list in Appendix C. (Note, the Functional Materials entries are designated “F” in the table in Appendix C). Additional research areas proposed during the session include continuous flow chemistry in space, understanding distortion of honeycombs in microgravity, and the behavior of foams in microgravity.

Recommendations from the session were that NASA and the ISS National Lab should:

1. Prioritize areas for funding early-stage research to establish the value of using existing ISS National Lab capabilities for functional materials development and production. This step is viewed as a high priority in order to manage resources effectively.

2. Review existing technical capabilities (both on the ISS National Lab and NASA’s ground-based capabilities) and identify high-leverage areas that can be implemented to increase throughput while building on existing capabilities (e.g., adding additional sensors or instruments to established facilities).

3. Identify areas that would benefit from a group of independently funded investigators approaching different aspects of the same problem (e.g., additive manufacturing processes, relevant materials properties and structure, and modelling of the process dynamics).

4. Develop and issue an Announcement of Opportunity to seek proposals from qualified research groups to help implement Recommendation 1.

5. Establish a working group to identify, plan, and define specific requirements for development of additional ISS National Lab capabilities and research areas. This workshop output provides a starting point for this activity.

6. Develop a plan for handling proprietary information and intellectual property that may result from work done on the ISS National Lab. (A review of the types of agreements used by other agencies such as the DOE or NIH would be a useful).

7. Identify the perceived and real opportunities and barriers to inter-agency and international collaborations and funding. (Historically it has been difficult to arrange multi-agency or international funding agreements).

8. Develop a plan and schedule to fund and implement the above recommendations, including communicating effectively to the community about the types of research that are desired and will be funded. Allocate resources and provide access to required facilities.

3.3 Overarching Themes

Microgravity processing and characterization are beneficial in cases where it is necessary to (i) decouple diffusive and convective transport processes and/or (ii) avoid buoyancy-driven sedimentation or phase separation. As a practical matter, the advantages are typically useful for processes that involve liquids, molten, or gaseous materials as well as multiphase mixtures where stabilization of spatial distributions of phases is essential but cannot be achieved in terrestrial processing. Based on the RFI responses and discussions during the workshop session, four key themes were identified:

- ***Additive Manufacturing***, with a focus on how it can enable greater materials functionality and performance.
- ***Materials Reuse***, including planning for reuse and the ability to process waste into useful functional material.
- ***High-value Materials***, where in-space studies of production and processing can help support the creation of materials with valuable functionality and performance.
- ***Thermophysical Property Data***, for driving machine learning and modeling.

There are strong synergies between these theme areas. Ranking them in a way that could potentially eliminate one or more of them would limit the potential for exploiting the synergies. In each theme area sub-section below, high priority topics are noted in the key research areas identified. Several other topics of interest were captured from the RFI responses and workshop discussions. Each theme area sub-section briefly discusses potential facilities needed. (A discussion of existing ISS facilities can be found in the NASA resources on ISS facilities and research).

3.3.1 Additive Manufacturing

A number of RFI responses, as well as much discussion during the workshop, focused on additive manufacturing on the ISS. While 3D-printing capability exists on the ISS today, there is interest in extending the capabilities to new materials, including metals, ceramics, and high-performance polymers, as well as studying the microgravity physics of established and novel additive manufacturing technologies.

3.3.1.1 Key Research Areas

As reflected in the RFI submissions and workshop dialogue, the community sees extensive opportunities for additive manufacturing to enable space missions, not just in allowing printing of replacement parts but in being able to create certain structures in-situ to avoid the constraint of designing them to withstand launch loads. There is also a role for additive manufacturing in enabling greater material reuse.

- In-orbit additive manufacturing allows parts to be designed solely for their function, without having to also design them to withstand launch—this could lead to the development of lighter-weight parts (for example by introduction of voids or controlled porosity into a material). Launching heavy additive manufacturing machines could be worthwhile because one machine can make many parts.

- When considering materials for use in orbit, in addition to the capability of a material itself, it is also important to consider the material's cost performance. Material produced in orbit may be preferable even if it is inferior to other materials that could be launched from Earth due to the cost savings.

- Making effective use of additive manufacturing will require considering the mobility of additive manufacturing systems and the conditions they will have to endure in harsh space environments—there is a need to test additive manufacturing systems and fabricated parts/material to make sure they function correctly in space and can be maintained as needed, which the ISS can uniquely support.

- There is a need to determine if there are byproducts of in-orbit production that could lead to pollution in space and to assess and address any problems that may arise.

- Printable electronics (circuit boards, etc.)—2D and 3D as well as 4D (e.g., antennas that respond mechanically to specific thermal ranges)—would be useful for NASA missions as well as potentially in terrestrial applications.

- Although it may be more valuable to print larger, more complex shapes and parts, it may be better to start with simple shapes initially to gain a better fundamental understanding. It would be useful to evaluate the use of multiple print heads to enable faster production of large objects (i.e. parallel printing). For example, would this approach lead to reduced tolerance in parallel printed parts compared with a single head approach?

- Another important area of study is the exploration of fundamental physics of additive processes through experiments in microgravity. For instance, "1½-D printing," which is based on shooting a laser beam into a gas and extruding a solid out, enables the production of curved filaments of materials (silicon carbide, etc.) that are normally unworkable as the structure grows and follows the focus of the laser. In this process, byproduct gasses are emitted violently in the direction of the laser, making the process unstable. In space, this emission would still exist, but it would be in the direction of fiber, so there would be no perturbation. Thus, the space environment could enable production of higher-quality material with a better-controlled microstructure and provide a better understanding of how this process could be optimized on Earth.

- It is necessary to evaluate 3D printing of functional glasses and optical materials to make near net shape components. Characterization of such products is needed to determine fitness for purpose for space and Earth-based applications.

3.3.1.2 Prioritized Areas of Commercial/Applied and Basic research

Prioritized research areas related to additive manufacturing include:

1. Demonstration and development of in-space additive techniques using a greater variety of materials—including other polymers, as well as metal and ceramics.

2. Determining ways in which 3D printing in microgravity could enable the production of novel functional or high-performance materials that are difficult to produce on Earth, such as high-entropy alloys.

3. Examining how research in microgravity could elucidate fundamental physics and the role of gravity versus other factors in various additive manufacturing processes in order to facilitate better technology development for both terrestrial and space applications.

Research area (1) is largely applied for space exploration uses, though techniques developed may have terrestrial applications as well. Area (2) would advance basic research on these material systems as well as potentially enabling applications in space and on Earth. Area (3) would advance basic research on additive processes in ways that would benefit space and terrestrial uses as well.

3.3.1.3 Facilities Needed

Additional types of additive manufacturing capabilities should be added to the ISS, both to enable applied research as well as to support basic research on more types of techniques and material systems. Determining which types of manufacturing equipment should be prioritized would require more input both from the perspective of NASA as well as the broader additive manufacturing research community—though initial submissions (i.e., the RFI responses) and the breakout session discussions suggest a high priority for metal systems.

3.3.2 Materials Reuse

While fewer RFI responses focused specifically on materials reuse, discussion from the workshop attendees highlighted this topic as important for functional materials research to consider. As techniques such as additive manufacturing for in-space production become more successful, designing a limited palette of materials that can be used to produce parts for a variety of applications while delivering necessary performance will be important. Notably this includes the ability for materials scrap, and in some cases used parts, to be reprocessed for use in new parts. The ability to reuse waste from materials and components brought into space (such as food packaging), rather than simply disposing of it, can also be beneficial and will become even more so for longer missions further from ready resupply.

3.3.2.1 Key Research Areas

Research should focus on how materials likely to be brought into space and end up as waste product—potentially even including space debris that could be collected from orbit or otherwise—can be reprocessed into feedstock or useful material products that can offer adequate performance and functionality to enable beneficial use for applications in space.

- In choosing materials for use in orbit, it is important to make selections based on not only how well the materials function but also how they can be recycled for another use. Materials should be designed for their entire life cycle (i.e. life cycle engineering).

- Ideally, ISS research would help identify a limited set of materials that can be used as the building blocks for all in-orbit production to maximize utilization and recycling of the materials, potentially incorporating such materials into packaging for launch and then having the capabilities to recycle them in orbit.

- Space debris could be captured, melted down, and reused—this would provide both the benefit of cost savings in launching material as well as the added value of removing debris. There may be opportunities to partner with companies collecting large space debris. Even if the materials in the debris are inferior to other materials, it may be preferable to reuse them rather than launch new materials.

- How does degradation from exposure to the harsh conditions of space affect materials and the ability to recycle them?
    - What if metal oxidizes? If polymer degrades, can it be reused? Are there other defects from degradation that could affect materials?
    - There is a need for the ability to characterize the composition of materials exposed to the harsh conditions of space (spectroscopy) to understand the degree of degradation.
    - Are there a limited number of times that a material can be reused before it is exhausted?
- How much energy (input and waste heat), water, or other materials are needed for materials recycling—how clean is that process?

3.3.2.2 Prioritize Areas of Commercial/Applied and Basic Research

Prioritized research areas related to materials reuse include:

1. Research on designing for reuse, such as studies to elucidate what types of material properties and attributes will help facilitate subsequent reuse, and how to enable those attributes without compromising for the initial product during use.

2. Research on how various materials (notably metals and plastics) can be processed under microgravity conditions to enable reuse will also be important.

Both of these research areas, as well as most others that might arise under this theme, will be heavily applied, with an eye toward space applications. Some areas, such as techniques for the processing of waste materials, may yield insight into basis research on materials attributes that may provide useful insights for terrestrial applications as well.

3.3.2.3 Facilities Needed

New facilities needed will depend on the specific research avenues chosen but could potentially include furnaces, reactors, or mechanical devices for converting various types of wastes into forms that can be reused.

3.3.3 High-Value Materials

Another topic arising from workshop discussions centered on materials that can uniquely benefit from studying their production in microgravity. Generally, this includes systems that can exploit the separation of convection and diffusion transport and/or avoidance of sedimentation that are possible in extended microgravity. Potential materials include immiscible liquid systems, porous materials from freeze casting, and high-entropy alloys. This also includes materials made using recycled or locally available feedstocks (e.g., regolith or reused parts).

3.3.3.1 Key Research Areas

Research should include synthesis of materials in microgravity and the investigation of process-property relationships in liquids and gases used to synthesize materials (e.g., the effects of sedimentation, fluid motion, gas convection, and heat and mass transport), including the production of benchmark and reference materials.

- The materials science community needs to understand the needs and challenges of the space program to be able to determine how to address those needs and challenges from a materials science standpoint.

- Space-based materials research should not be limited to applications focused solely on future space exploration—the market for astronauts is limited. It is important to also think about what materials can be produced in space that are of value to humans on Earth.
    - There is a need to understand how materials work in space, how space could improve materials, and what materials research/production could be done in space that is difficult or not possible on Earth.
    - There is a need to determine what could be produced in space that cannot be produced on Earth or how space could improve the production of certain materials (e.g., ZBLAN glass).
    - If one understands why microgravity improves/enables production of the materials and the variables affected by the space environment, these insights could be applied to production processes back on Earth.

- The fabrication of lightweight composite structures (e.g., honeycomb structures) would be useful—but there is a need to understand the damage tolerance of such lightweight materials.

- The fabrication of glasses and optics using conventional and additive methods is an area ripe for investigation while also benchmarking the manufacturing ability for near net shape glass optics production.

- Understanding materials in microgravity at a fundamental level is crucial. It is important to understand the microstructure of materials in microgravity—different morphologies affect material properties, and a lack of understanding could lead to high risks.

- There is a need to understand how a material's properties (such as corrosion resistance of 3D-printed materials) are different in space than on Earth.

- Research should examine whether there are ways to use the harsh environment of space (e.g., ultraviolet (UV) radiation, atomic oxygen) to process materials or further advance the production of new materials and composites.
    - The Materials International Space Station Experiment Flight Facility (MISSE-FF) is currently being used to see whether foams can be cured using UV exposure.

- There is a need to further examine the fundamental aspects of microgravity's effects on production (e.g., migration of bubbles in liquids, flow through nozzles, heat transfer effects, etc.).

- It may be of interest to examine what effect controlling the freeze rate (slow or flash) in microgravity has on the porosity of materials (e.g., to determine whether the material becomes more uniform throughout).

3.3.3.2 Prioritize Areas of Commercial/Applied and Basic Research

The development of high-value materials can benefit from: (i) processing in microgravity in order to be able to produce them, and (ii) performing reference experiments and making benchmark materials in order to inform improved (potentially commercially valuable) methods for terrestrial manufacturing. The first area has potential for commercial production of material in space, provided the value add is sufficient, and the second area can improve manufacturing and increase the efficiency of materials usage in a range of terrestrial manufacturing applications.

3.3.3.3 Facilities Needed

There is a need for melting and characterizing materials as a function of process variables, the ability to make in-situ measurements, and the ability to recover materials for ground-based characterization and analysis. There is also a need for the ability to transport feedstock and processed materials round trip from the ground to the ISS.

3.3.4 Thermophysical Property Data Driving Machine Learning

Computational modelling and the availability of high-reliability thermophysical property data are often coupled because models need to be validated using reference data. This research can include measurements of properties of materials made in microgravity in order to determine fitness for purpose and to compare them with similar materials made on the ground.

3.3.4.1 Key Research Areas

Machine learning from thermophysical property data is most relevant to measurements on liquids and molten phases. Key areas include measurement of selected properties in pristine conditions achieved in space, measurements on supercooled liquids, and wetting of surfaces for bonding in low gravity and on the ground.

- There is a need to determine what can be done with machine learning and materials informatics to accelerate materials development. It is now possible to merge experimental data and results from computational modeling and to apply machine learning to accelerate understanding of materials and suggest potential new material compositions or formulations.

- Can data collected in space enhance machine learning for materials discovery?
    - Machine learning is currently based on data collected on Earth, but for space applications, using data collected from space (rather than data from Earth) could enhance capabilities.
    - Incorporating data collected in space into deep learning algorithms could enable many more predictions and could have a significant impact.

- There is a need for data curation capabilities. Although some data may not be relevant, it is important to incorporate the proper data, including an understanding of the environment in which the data was collected.

3.3.4.2 Prioritize Areas of Commercial/Applied and Basic Research

Property data on proprietary materials may have commercial value. In many cases, reference data would be desirable to publish for use in developing models and improving understanding of manufacturing processes.

3.3.4.3 Facilities Needed

There is a need for both the Electromagnetic Levitator (EML) and the Electrostatic Levitation Furnace (ELF), enhanced capabilities, furnaces, and in-situ measurement capabilities. High-speed imaging of drops in levitators is essential to enable a more accurate determination of properties and the investigation of solidification behavior.

3.4 Hot Topics and Knowledge Gaps

Other topics discussed included metamaterials, carbon and composite materials, functional glasses, additional capabilities for materials characterization on the ISS (such as Fourier Transform Infrared (FTIR) and Raman spectroscopy, nano-indentation, high-speed cameras, etc.)

- There is a need for a compiled dataset of the exact exposure conditions on MISSE-FF so researchers investing in a MISSE-FF experiment know they will get the data that they need.
  - Identify required exposure conditions and document them in a consistent way.
  - Consider setting performance standards for materials sets that can be used for in-space testing (similar to some ASTM standards).

- Material characterization is important to understand the reliability of materials. Determining how well materials survive in the space environment directly impacts which materials might be best for in-orbit recycling and additive manufacturing.
  - Are there ways to improve in-situ characterization of degradation? Are there ways to characterize the materials before they return to Earth to understand the degradation pathways?
  - The ability to characterize MISSE-FF samples while in orbit would be useful.

- There is a need to understand how long to conduct experiments on the ISS to adequately characterize materials. Computational analysis methods could be used to reduce the time required to do in-orbit characterization.

- Additional characterization methods (e.g., Raman spectroscopy, nanoindentation, FTIR, and mechanical characterization) would be useful in orbit.

- Polymer composite carbon-based materials could benefit a variety of applications, but it is important to determine whether such materials can hold up in the harsh space environment.
  - Composite materials that survive for short periods of time on the space station could survive for much longer periods of time on Earth.

- Metamaterials (a class of materials in which the properties of the materials stem not necessarily from their composition but from the way in which they are patterned or arranged) have several applications (5G infrastructure, lidar/radar for self-driving cars, etc.) and could be useful in space applications (improving communication, etc.).
  - Metamaterials are more about design and processing/patterning than fundamental materials science—it is more about physics and optics than material properties. As a result, simple materials can provide unusual properties and could improve performance.
  - Not many metamaterials have been developed and tested. Being able to adapt fabrication techniques to develop metamaterials and scale up production is an outstanding issue.
  - MISSE-FF could be used to test and characterize metamaterials, which could provide industry with the data to develop the confidence or willingness to use metamaterials for satellites or terrestrial applications.
  - Some 3D printing techniques or techniques for making 3D circuit boards could be adapted to make metamaterials on the ISS, which could be useful.
  - The 3D printing of functional glass and optics for devices and instruments could be useful, including evaluation of the degree to which near net shape optics can be made using additive methods.
  - The ISS could be used to study the interface between materials and how materials complement each other.

- There may be ways to test metamaterials on the ISS—not just external environment exposure, but testing using ESL or EML—to understand basic principles for use in improving a material's design and performance for targeted applications.

3.5 Commercial Application/Innovation

The identified themes and priority research areas align well to topics that are of significant commercial interest and relevant on Earth.

- Additive manufacturing is a market set to reach nearly $20 billion by 2025.[2] Companies in a variety of industries are looking to see how additive manufacturing can be used to manufacture parts with greater flexibility and customization as well as lower costs or environmental impact, and advances in fundamental materials science and processing techniques to extend additive manufacturing capabilities can help support these terrestrial goals.

- Many companies are looking to advance sustainability goals and improve material use efficiency by pursuing the concept of a circular economy. For instance, 13 large consumer products companies recent joined with the Ellen MacArthur Foundation in committing to improving recycling and use of recycled content for product packaging, accounting for more than 11 million tons per year worth of plastic use. Advances in knowledge on how to reuse waste materials and design materials for reuse will help support these ambitions and provide environmental as well as commercial goals.

- Greater pressure on R&D and innovation budgets is pushing companies to invest in more modeling and simulation of materials, including machine-learning-based approaches such as materials informatics, to help develop new materials and products more rapidly at lower cost. Insight, data and benchmark materials, as well as advances in modeling and informatics algorithms pushed by ISS research would help support these initiatives.

- There is potential for production of unique materials and benchmarking performance of functional materials by initially making research quantities in low gravity. Once value is established, the potential for commercial production of selected materials in low gravity will be driven by price versus performance trade-offs. This includes materials made from locally available resources such as regolith or recycled components of flight hardware that can enable cost savings to NASA.

3.6 Recommended Partners

The primary early partner for these research areas is NASA. There is a clear need to fabricate and utilize materials in space inherent in accomplishing NASA's exploration missions. In this sense, NASA is both the customer and the vendor for some aspects of the critical early stage work.

Potential partners are large and small industrial companies in the business of developing and commercially exploiting new materials products. A key step to establish industry interest is the demonstration of a net value addition via processing or characterizing materials in low gravity. Early involvement of commercial partners will help to direct the work toward "pain points," where a breakthrough material or process can potentially justify the cost of low gravity processing.

[2] Lux Research, "3D Printing Market Forecast," 2017

Crosscutting collaborations with agencies such as the U.S. Department of Energy, the National Institute of Standards and Technology, the National Institutes of Health, and the National Science Foundation can be used to leverage the use of data, to help diffuse data to the research community (as appropriate with intellectual property considerations), and influence complementary research such as synchrotron and neutron studies of materials and development of new techniques and standards for measurements. These collaborations can be enabled through both industrial and university research partners and the agencies.

4 Breakout Session: Materials Characterization, Microstructure, and Process Modeling

Co-chairs: Edward H. Glaessgen, NASA Langley Research Center
Debbie G. Senesky, Stanford University

4.1 Purpose of Session

This breakout session focused on use of the ISS platform to conduct benchmark experiments in the microgravity environment, to examine microstructure development and to obtain critical thermophysical properties needed for development and validation of physics-based models applicable across a wide spectrum of fabrication processes. Fundamental understanding of processing-structure-property relationships provides the key to advanced materials development and insight into advantages and limitations of advanced manufacturing techniques. Examples include alloy solidification experiments and kinetic and surface energy anisotropy measurements needed to support multiscale modeling of additive manufacturing or electron beam welding on the ground and in space.

4.2 Summary and Recommendations

This breakout session discussed 31 contributed RFI responses. The RFI responses that were discussed are provided in the list in Appendix C. (Note, the Materials Characterization, Microstructure, and Process Modeling responses are designated “M” in the table in Appendix C). The topics of these RFI responses motivated division of the breakout session into two sub-groups. Depending on their interest and expertise, attendees to this breakout session self-selected participation in one of two sub-groups: ***Process Modeling*** (led by Ed Glaessgen) and ***Materials Characterization and Microstructure*** (led by Debbie Senesky).

Five key questions were posed to the attendees:

1. What overarching themes stand out in RFI responses?
2. What are the key research areas that should be pursued?
3. What are the recommendations for short-term & long-term research activities and goals?
4. Are there any missing topics/areas?
5. What are the expected hot topics/knowledge gaps?

The breakout session concluded with a brief combined discussion, wherein the two sub-groups reviewed their topic questions and presented their recommendations.

Recommendations from the Process Modeling sub-group were that NASA and the ISS National Lab should:

1. Develop an expanded material property database for advanced materials that includes both their solid (as-processed, post-processed) and liquid (in-processing) states.
2. Further develop in-situ and ex-situ measurement capabilities needed to support material processing.
3. Leverage ongoing and develop microgravity focused computational materials simulation capabilities needed to design new enabling materials and certify additive manufacturing and other relevant materials and processes.
4. Develop an ISS Materials Science Laboratory to enable rapid material development cycles in microgravity.

Recommendations from the Materials Characterization and Microstructure sub-group were that NASA and the ISS National Lab should:

1. Demonstrate manufacturing at scales of various lengths, from the atomic level (e.g., 2D sheets) to large-scale assembly (e.g., CubeSats and other types of spacecraft).
2. Deepen understanding of material solidification processes in microgravity (directional, rapid/time-defendant effects, non-equilibrium).
3. Investigate microstructure characterization methods and what instruments are needed to perform tests on-orbit (e.g., X-ray CT, indentation, tensile testing, surface analysis, thermography tools) to observe and analyze growth behavior, 3D microstructure, mechanical properties, electrical properties, thermal properties, and biocompatibility.
4. Implement data-driven manufacturing approaches (with "just-in-time" data) to enhance engineering of specific/tailored material properties in space for both ground-based and Earth-based applications.

4.3 Sub-Group 1: Process Modeling

4.3.1 Overarching Themes

The overarching themes of the discussions on process modeling were largely centered on developing an understanding of the processing-microstructure-property-performance relationships of materials developed on, and for use on, the ISS, guided by computational and experimental perspectives from attendees within the sub-group. Most of this discussion was focused on emerging capabilities for additive manufacturing. The sub-group noted that developing an understanding of the relationships is highly dependent on the accuracy of both the simulations and the input parameters themselves. Although considerable effort toward development of more accurate computational materials simulations is being funded by NASA and other agencies, little or none is specifically aimed at relevance to the ISS or other microgravity environments.

Specific interests expressed by the sub-group include:

- Determination of surface tension, surface/interfacial energies, viscosity, and flow characteristics as input for additive manufacturing processing simulations
- Characterization of microstructure of materials developed on, and for use on, the ISS; capabilities for determination of properties and performance of these materials
- Development of composition, phase, and microstructure data for a range of relevant alloys, along with their curation, archive, and retrieval in a suitable database
- Measurement of properties at relevant cooling rates for various processes of interest
- Understanding of a variety of non-equilibrium processes
- Quantifying differences of various parameters and processes in ground-based and microgravity environments
- Development of standards and reference data for microgravity materials science research; leveraging existing standards and adaptation to the ISS environment

4.3.2 Key Research Areas

Several pervasive themes regarding key research areas emerged from the sub-group's discussion, including development of:

- Materials that are enabling for various spaceflight applications
- Unique materials processed in space (a related goal is to help to develop the business case for these materials and attract the aerospace and materials manufacturing industry's investment)
- In-situ and ex-situ measurement capabilities needed to support material processing
- Simulation capabilities needed to support development and certification of materials for spaceflight applications
- High-fidelity characterization of materials at various states of processing needed to provide critical thermophysical properties, including input and validation data for computational materials simulations

- Integration of machine learning/artificial intelligence with physics-based simulations to enable validity of the data science methods beyond the extent of their training data
- More rigorous validation of simulations; data fusion to integrate simulated and measured quantities
- Understanding of dependence of damage and other processes on microstructure and composition
- Material design driven by application, environment, and performance requirements
- Understanding how the rate of processing changes the resulting material; the need for accurate measurement of material properties over a range of processing temperatures

4.3.3 Short-Term and Long-Term Goals

Several short-term and long-term goals were identified by the sub-group. Short-term goals focused on leveraging and adapting existing simulation and experimental capabilities to support development and certification of materials for spaceflight applications. Current relevant work in computational materials is supported by the NASA Aeronautics Research Mission Directorate, NASA Space Technology Mission Directorate, and the Office of the Chief Engineer through its new Engineering Research and Analysis project. Numerous investments by other government agencies, U.S. industry and private nonprofit labs could also be leveraged through appropriate Space Act Agreements. The ability to influence ISS-based research may be attractive to U.S. industry and could result in closer partnerships focused on understanding the potential advantages of materials produced in microgravity environments.

Some specific topics for early leveraging might include development of:

- An expanded material property database for these advanced materials that includes both their solid (as-processed, post-processed) and liquid (in-processing) states
- Computational materials simulation of processing, including understanding melting and solidification, microstructure and defect formation, and residual stresses and deformation
- Computational materials simulation to support next-generation durability and damage tolerance (D&DT) capabilities for additively manufactured structural components (made on Earth), including understanding the effects of defects, loads, and environments on life and performance
- Improved measurement capabilities for determination of input properties (e.g., surface tension and viscosity) needed for processing-microstructure simulations
    - A larger sample holder for the ELF
    - A high-speed camera for the ELF
- A detailed understanding of the relative advantages and applications of faceted (anisotropic) and non-faceted (isotropic) material systems

Long-term goals were focused on new capabilities with far-reaching impact, including:

- Methods for simulation of equilibrium and non-equilibrium material processing that consider the effects of microgravity
- Development of an ISS Materials Science Laboratory to enable rapid material development cycles in microgravity that are potentially enabling to NASA’s long-term exploration missions. Such capability has the potential for reducing or even eliminating the need to carry spare components on future spacecraft. Initial steps leading to this radical new capability would include:
    - Increased astronaut focus on materials, including deploying materials scientists on orbit and automation of material processing to the extent possible
    - Additive manufacturing in microgravity to understand and optimize processes such as microstructure and defect formation in both additive manufacturing and joining processes
    - Specimen preparation, metrology, and characterization
    - An enhanced materials science glovebox that includes thermal and environmental control

4.3.4 Missing Topics/Areas

Several additional topics discussed that did not rise to the level of overarching theme areas include:

- The need to convey to both the relevant funding organizations and the general public that much of the work discussed herein is not only critical for spaceflight applications but can have broader benefit to life on Earth.
- A need to understand the differences between government and industrial time horizons. The industrial time horizon tends to be very short, requiring a significantly faster rate for material design, development, and certification.
- Development of stronger relationships between the research community and the industrial (manufacturing) community that includes a demonstration of increased value of lower-Technology Readiness Level (TRL) work and a more rapid bridging of the "valley of death" at mid-TRL to increase low-TRL relevance.

4.3.5 Hot Topics and Knowledge Gaps

Several hot topics were identified by the sub-group, including:

- A need to understand the future of additive manufacturing, including its current status on the hype-cycle and managing expectations for capability development during the next 5, 10, and 20 years
- Recycling, reuse, and repurposing of materials
- Design of materials for their intended usage (i.e., materials by design)

4.4 Sub-Group 2: Materials Characterization and Microstructure Group

4.4.1 Overarching Themes

The use of microgravity to gain fundamental knowledge of additive manufacturing and metal processes was a major underlying theme of the RFI responses. Additionally, workshop participants raised discussions and ideas of how to apply technology and insights gained from fundamental ISS materials experiments to the in-space processing, manufacture, and assembly of large-scale systems.

Key overarching themes discussed included:

- Additive manufacturing in space (several examples and ideas were discussed, including the design of laser-based solidification of powder to enable synthesis of metal and ceramic materials, as well as how to scale-up demonstrations of filament-based manufacturing of polymer materials)
- How to demonstrate manufacturing at scales of various lengths, from the atomic level (e.g., 2D sheets) to large-scale assembly (e.g., CubeSats and other types of spacecraft)
- The need for a deeper understanding of material solidification processes in microgravity (directional, rapid/time-defendant effects, non-equilibrium)
- Investigations into microstructure characterization methods and what instruments are needed to perform tests on-orbit (e.g., X-ray CT, indentation, tensile testing, surface analysis, and thermography tools) to observe and analyze growth behavior, 3D microstructure, mechanical properties, electrical properties, thermal properties, and biocompatibility
- How to implement data-driven manufacturing approaches (with "just-in-time" data) to enhance engineering of specific/tailored material properties in space for both ground-based and Earth-based applications

4.4.2 Key Research Areas

Future experiments proposed for the ISS should be designed to address the following areas, which are directly based on the overarching themes:

- In-space processing of different classes of engineering materials (e.g., polymers, ceramics, composites, semiconductor, and biomaterials) such that structures, electronics, and medicines can be utilized in-orbit during missions as well as on Earth

    - Processing and manufacturing techniques should include chemical vapor deposition, sputtering, additive manufacturing, and assembly of components
- Analysis of the material properties during growth and post-growth to aid in the fundamental understanding of microgravity synthesized materials, as well as data-driven approaches
- Manufacturing and assembly from the atomic scale to the systems scale
    - Participants discussed how to progress from fundamental experiments toward building and assembly of large-scale vehicles. This involves looking beyond the fundamentals of a materials process to the systems level. Discussions highlighted the importance of gathering input from industrial processing stakeholders in the aerospace industry and from other industries such as the automotive and semiconductor industries.

4.4.3 Short-Term and Long-Term Goals

Several short-term and long-term goals were identified. Short-term goals focused on providing clearer information about ISS resources and involving the research community in research program development. The long-term goals focus on expanding and automating facilities to reach a broader range of materials research.

Short-term goals:

- Create synergy with stakeholders (inside and outside the space industry) to identify industrial needs and benefits of in-space manufacturing.
- Provide an up-to-date and easy-to-access database of the resources (tools and instruments) currently available on the ISS National Lab.
- Develop process standardization and workflows to accelerate access to and impact on research and enable commercialization.
- Hold a workshop with academic and industrial stakeholders to plan a roadmap for materials research on the ISS National Lab.
- Shorten the experiment analysis cycles by providing more ISS infrastructure for in-situ materials characterization.

Long-term goals:

- Design an efficient user model for the ISS National Lab that includes a plan for acquisition of up-to-date tools, as well as a plan for infrastructure decommission
    - Plan for the automation of tools.
    - Leverage DOE clean-room/nano facilities and synchrotron centers as a model/example.
- Broaden the materials set for ISS investigations (e.g., semiconductor, nanomaterials, polymers, and ceramics) and the assembly scale to allow for a variety of engineering systems to be manufactured.
    - Learn from the experience of other industries on the study and processing of different materials.

4.4.4 Missing Topics/Areas

Several of the topics listed in this section are directly connected to the themes and research areas. The discussion amongst the session attendees centered around the need to expand or accelerate these activities on the ISS.

- Advanced tools for synthesis and in-situ characterization: thermography, CVD of a range of thin films, synthesis of 2D materials with tailored properties, cast freezing, furnaces with a range of temperatures and pressures
- Fundamentals of melt and solidification processes of various films, crystals, and structures in microgravity environments, with a data-driven design of growth experiments (e.g., physical science informatics) and characterization

- A compelling demonstration of complete in-space manufacturing and assembly of a complex engineering system
- Identification of general facilities that are not currently on the ISS that may be strategic in the short-term
- Methodologies for recycling and reuse at a range of scales to prevent and mitigate “space junk” and decrease supply missions
- Qualification strategies for mission-driven materials and systems that have been manufactured on the ISS National Lab

4.4.5 Hot Topics and Knowledge Gaps

Several hot topics were identified by the sub-group, including:

- Development of a sample-sharing program to create synergy with multiple existing and new ISS users, in order to develop on-orbit manufacturing chains (for example, how to implement technology from fundamental crystal growth experiments in manufacturing or how to leverage knowledge from past investigations such as electron beam welding performed on the Mir space station)
- Methods for modification of existing facilities to enable more customization of future experiments and manufacturing processes
- Assembly of a stakeholder group from industry, academia, and government to create a roadmap for materials research and the near-term/long-term infrastructure on the ISS National Lab
- Qualification and recycling tools and methodologies
- Programs that focus on modeling, validation, and synthesis

4.4.6 Facilities and Operational Needs

Currently, there is a need for more tools for in-situ and post-growth characterization. Hardware that is needed includes:

- X-ray computed tomography (CT)
- Nano-indentation
- Tensile testing
- Surface analysis
- Thermography
- Chemical vapor deposition (CVD) of a range of thin films
- Synthesis of 2D materials with tailored properties
- Cast freezing
- Furnaces with a range of temperatures and pressures

In addition to new facilities, there is a need for the development of an efficient resource utilization plan and schedule for ISS users. For example, vacuum ports are currently heavily scheduled. The incorporation of flexible space or attachments of adaptable experiments (e.g., flex port) would be beneficial. Finally, the commercial sector, academia, and governmental agencies will need to work together to develop a clear near-term and long-term strategy that assesses risk. This includes plans that incorporate commercial ISS crew, as well as additional flights.

5 Breakout Session: Lunar Infrastructure and Surface Operations

Co-chairs: Eric Fox, NASA MSFC
Aleksandra Radlińska, Penn State University

5.1 Purpose of Session

This breakout session explored various materials systems and processes unique to the exploration challenges of operating in space, lunar, and Martian environments. While the theme of the session was "lunar," a variety of topics related to Mars and space environments were brought up and, as such, are included. The focus of the session was to identify potential classes of experiments using the ISS as a platform to understand the effects of microgravity or reduced gravity on materials production and repair processes needed to sustain extended-duration surface operations. Limited opportunities may also include the use of lunar landers as an alternate platform. Examples include habitat and launch/landing pad construction materials; radiation shielding materials; dust mitigation; planetary surface construction; and joining, manufacturing, and repair processes. Additionally, the potential for these experiments and techniques to provide insights into the development of advanced materials and processes for terrestrial benefits was also discussed.

5.2 Summary and Recommendations

The understanding of the effects of microgravity or reduced gravity on materials behavior is advancing but is still limited. As such, there exists a need for further exploration of materials systems and processing that will support NASA's Artemis mission of bringing man and woman back to the Moon and establishing lunar infrastructure for sustained human presence. Among various research areas discussed, advanced materials development for lunar construction and resource processing were identified as the most important under the umbrella of lunar lander experiments. Equally important, complementary experiments on the ISS were discussed, and among these, advanced materials development, advanced manufacturing, and space/lunar environment compatibility were ranked to be of highest priority.

5.3 Overarching Themes

The recommendations provided by the participants in the breakout session can be broadly categorized as falling under eight topics: advanced manufacturing, surface infrastructure, in-space assembly, resource prospecting, resource processing and handling, advanced materials development, dust mitigation, and space/lunar environmental compatibility testing. It is important to note that the order in which these topics are presented is not a representation of how important each topic was determined to be.

5.3.1 Advanced Manufacturing

Advanced manufacturing was defined as the manufacturing of small-scale parts or replacements, in contrast with the much larger-scale manufacturing of surface infrastructure or habitats. Manufacturing materials include metals, polymers, and ceramics. Studies in microgravity would provide valuable information about how the materials adhere and bond without a gravity force and would provide insights into the property differences of the component materials induced by the lack of gravity. Much of this work could be done with the 3D-printing hardware that is already onboard the ISS or is currently in development for flight on the ISS.

A subset of advanced manufacturing is the investigation of materials recycling and reuse. Such efforts include the use of printing feedstock designed to be recycled as well as the use of waste materials (e.g., polymer wrappers). The same questions regarding the effects of microgravity discussed above apply to recycled materials.

5.3.2 Surface Infrastructure

Identifying both methods to produce large-scale surface structures, such as landing pads, berms, or habitats, and the correct component materials are critically important to establishing a permanent human presence on the Moon. These structures will be critical to mitigating many of the hazards found on the Moon, such as micrometeorite impact, radiation, and wide temperature variations. The materials used on Earth are too heavy to be flown and, in some cases, are not suitable for use in a vacuum environment. The RFI responses included proposals to evaluate a range of building materials, including regolith glasses and ceramics as well as a number of water-free, space suitable binder materials. Additionally, manufacturing processes need to be developed that can ensure sufficient bonding and curing in a lunar environment.

It is important for these research efforts to be conducted in microgravity and/or lunar environments for many of the same reasons discussed in the Advanced Manufacturing sub-section above, as microgravity will potentially have similar effects on materials adhesions and bonding and the material properties. It should be noted that experiments on the ISS in microgravity and experiments under Earth's gravity will bookend the range of gravity found on both the Moon and Mars, allowing for the design of structures on both of those bodies.

5.3.3 In-Space Assembly

On-orbit assembly of large-scale structures and spacecraft has the potential to significantly reduce launch costs. These items can be assembled either from components launched from Earth or from components manufacturing on orbit. Either way, the space environment is a challenging one for assembly, given the need to automate most, if not all, of the work, along with the environmental conditions such as radiation and hard vacuum. Further, there are material handling issues, such as cold welding. The consensus of the participants was that further investigation of joining technologies for in-space use was of critical importance, as common approaches such as MIG or TIG welding are not suitable. The ISS offers an excellent platform for the small-scale assembly of structures in the near term.

5.3.4 Resource Prospecting

In-situ resource utilization (ISRU), or "living off the land," is one of the most promising ways to reduce the launch mass and thus cost of future exploration missions. Unfortunately, the processes to recover useful feedstock from planetary resources can be highly dependent on the raw materials, and there is a lack of data on this topic in the proposed landing sites at the lunar south pole. The inclusion of experiments to determine the availability of lunar resources on landers is thus of high importance. Note that this information will also be important for advanced manufacturing and surface infrastructure research, as the availability of such resources will dictate which processes and feedstocks can be used.

5.3.5 Resource Processing and Handling

Once resources are identified, the next major challenge to overcome is their collection and processing to recover and purify the resources of interest. There are a wide range of resource types to be processed, including liquids and gases from lunar cold volatiles, water ice from polar regions, and metals and oxygen from regolith. The beneficiation of these resources necessitates the development of new methods of fluid handling, liquefaction of gases, and transport of solids that can operate in a reduced gravity or microgravity environment. Developing these technologies is critically important for ISRU support of establishing a permanent human presence on the Moon in 2028, and as such, their inclusion of lunar lander platforms is highly important.

5.3.6 Advanced Materials Development

Synthesizing materials in microgravity has been shown to produce materials with properties that are significantly different from those prepared on Earth. Several RFI responses propose to continue to take advantage of this to prepare new materials in categories such as ceramics, biopolymers, advanced composites, and memory-shape alloys. All of these materials potentially have significant advantages for use on Earth and in further exploration goals.

A particular focus of these RFI responses is on making these new materials using lunar resources, which potentially offers a route to reduce the transportation costs of these materials and enables inexpensive construction and repair of lunar infrastructure. As manufacture under low-gravity conditions is an integral part of the process, the reasons for these experiments being performed on the ISS is to serve as a precursor to manufacturing on a deep-space platform such as Gateway or on the lunar surface.

5.3.7 Dust Mitigation

Lunar dust is a significant hazard both to the health of the crew and the condition of hardware. Preventing the infiltration of this dust into habitats will be a significant technical challenge, and optimum technologies capable of mitigating this hazard need to be developed. Evaluation of mitigation technologies in microgravity or reduced gravity is important, as the lack of gravity-driven settling will have a large effect on the behavior of the dust.

5.3.8 Space/Lunar Environmental Compatibility

Space and lunar environments include many environmental effects that are not found on Earth, including atomic oxygen, radiation, micrometeorite impacts, and prolonged exposure to hard vacuum. Several participants brought up the importance of continuing to take advantage of MISSE-FF and mentioned the possibility that the data from MISSE-FF may be able to be adapted to provide insight into lunar surface compatibility without the need for lander experiments. Another significant point of conversation was the need for tribological measurements, particularly with regard to seals and gaskets, over the long term.

5.4 Prioritize Areas of Commercial/Applied and Basic Research

Each research area was separately ranked on the importance and appropriateness of using the ISS or a lunar lander as a platform to perform the work. Each area was first ranked as a high, medium, or low priority for each platform, and the high priorities were subsequently ranked numerically in that category. The results are presented in Table 1 below.

Table 1: Ranking of Research Areas

	ISS Experiments	Lunar Lander Experiments
Advanced Manufacturing	High (2)	Medium
Surface Infrastructure	Low	High (4)
In-Space Assembly	Medium	Low
Resource Prospecting	Low	Medium
Resource Processing/Handling	Medium	High (2)
Advanced Materials Development	High (1)	High (1)
Dust Mitigation	Low	Medium
Space/Lunar Environmental Compatibility	High (3)	High (3)

5.5 Research Gaps

None of the submitted RFI responses addressed the development of advanced life support technologies. Development of these technologies is critical for allowing human space exploration missions to operate independently from Earth resupply. As the only permanently crewed space habitat, the ISS is an excellent platform for investigating new approaches to life support.

5.6 Equipment and Capability Needs

Several gaps in the experimental capabilities currently onboard the ISS were identified in the session. One of the primary weaknesses in space manufacturing research on the ISS is the lack of basic materials analysis equipment for on-orbit qualification of manufactured parts. Specifically, identified analysis methods that are currently unavailable include scanning electron microscopy (SEM) and atomic force microscopy (AFM). While the cost and time to return a sample from the ISS might be considered acceptable, the return of a sample from Gateway or the lunar base would be prohibitively expensive. Thus, the implementation of basic materials science tools on the ISS is a step toward the development of necessary instruments for deep-space manufacturing. Additionally, allowing for the remote operation of these instruments (as well as other experimental hardware on the ISS) will improve the research efficiency.

Other hardware needs include increasing the availability of and capabilities of ISS centrifuges. Centrifuge will allow for research to be performed under reduced gravity comparable to that found on the Moon or Mars. The utility of being able to evaluate exploration technologies under such conditions in LEO is obvious. The current onboard centrifuges are not large enough for many of the experiments that will need to be run, and the number of such centrifuges is low. Additionally, the onboard gloveboxes need to have their “plug and play” capability increased to allow for a higher throughput of experiments.

Finally, many of the proposed research activities will require appropriately designed lunar regolith simulants. There are no current sources for the commonly used JSC-1a simulant. Additionally, this simulant was designed to be mechanically similar to lunar regolith. For ISRU work, it will also be important for a chemical simulant of the regolith to be developed and available to researchers. One approach would be to provide a NASA Standard for simulant production.

5.7 Program Transition From the ISS to the Commercial Lunar Payload Services (CLPS)

As shown in Table 1, some research could benefit from ISS development, but some require experiments and demonstrations on the lunar surface. Thus, it was suggested that a program transition process from the ISS to lunar surface experiments (for example on CLPS) be developed.

Appendix A: Summary of Breakout Session Recommendations

Functional Materials

This breakout session focused on use of the microgravity environment of the ISS platform to develop materials with improved or tailored properties and characteristics that are useful terrestrially or in exploration systems. In this session, 25 RFI responses were reviewed and discussed. Theme areas identified were: (i) Additive Manufacturing, (ii) Materials Reuse, (iii) High-Value Functional Materials, and (iv) Thermophysical Properties. Multiple synergies and areas of overlap between these topics were identified by workshop participants, and the discussions highlighted the value to NASA and other stakeholders of an integrated approach.

Key recommendations from the session:

1. Establish mechanisms to fund early-stage research relevant to the identified theme areas and to establish the value of using existing ISS National Lab capabilities for functional materials development and production.
2. Ensure that technical capabilities (both on the ISS National Lab and NASA's ground-based capabilities) are well-positioned to deliver on research goals in these theme areas, prioritizing high-leverage areas that can be addressed by building on existing capabilities (e.g., additional sensors or instruments added to established facilities).
3. Develop and issue an Announcement of Opportunity to seek proposals from qualified research groups to help implement research in these prioritized areas.
4. Establish a working group to identify, plan, and define specific requirements for the development of additional ISS National Lab capabilities and research areas. This workshop output provides a starting point for this activity.
5. Develop a plan and schedule to fund and implement research, including allocating resources and providing access to required facilities, in order to advance goals in these prioritized theme areas.

Materials Characterization, Microstructure, and Process Modeling

This breakout session focused on the use of the ISS platform to examine microstructure development and to obtain critical thermophysical properties needed for development and validation of physics-based models applicable across a wide spectrum of fabrication processes. In this session, 31 contributed RFI responses were discussed, and the topics of these RFI responses motivated division into two sub-groups: (i) Process Modeling and (ii) Materials Characterization and Microstructure.

Key recommendations from the Process Modeling sub-group:

1. Develop an expanded material property database for advanced materials that includes both their solid (as-processed, post-processed) and liquid (in-processing) states.
2. Further develop in-situ and ex-situ measurement capabilities needed to support material processing.
3. Leverage ongoing and develop microgravity-focused computational materials simulation capabilities needed to design new enabling materials and certify additive manufacturing and other relevant materials and processes.
4. Develop an ISS Materials Science Laboratory to enable rapid material development cycles in microgravity.

Key recommendations from the Materials Characterization and Microstructure sub-group:

5. Demonstrate manufacturing at scales of various lengths, from the atomic level (e.g., 2D sheets) to large-scale assembly (e.g., CubeSats and other types of spacecraft).
6. Deepen understanding of material solidification processes in microgravity (directional, rapid/time-defendant effects, non-equilibrium).
7. Investigate microstructure characterization methods and what instruments are needed to perform tests on-orbit (e.g., X-ray CT, indentation, tensile testing, surface analysis, thermography tools) to observe and analyze growth behavior, 3D microstructure, mechanical properties, electrical properties, thermal properties, and biocompatibility.
8. Implement data-driven manufacturing approaches (with "just-in-time" data) to enhance engineering of specific/tailored material properties in space for both ground-based and Earth-based applications.

Lunar Infrastructure and Surface Operations

This breakout session explored various materials systems and processes unique to the exploration challenges of operating in space and in lunar and Martian environments. The focus of this session was to identify potential classes of experiments using the ISS as a platform to understand the effects of microgravity or reduced gravity on materials production and repair processes needed to sustain extended-duration surface operations. The understanding of the effects of microgravity or reduced gravity on materials behavior is advancing but is still limited. As such, there exists a need for further exploration of materials systems and processing that will support NASA's Artemis mission of bringing back humans to the Moon and establishing lunar infrastructure for sustained human presence.

Key recommendations of research areas under the umbrella of lunar lander experiments:

1. Advanced materials development for lunar construction
2. Resource processing

Key recommendations of research areas for complementary experiments on the ISS:

1. Advanced materials development
2. Advanced manufacturing
3. Space/lunar environment compatibility

Appendix B: Workshop Agenda

Presentations from the 2019 ISSRDC Materials in Space Workshop are available at the ISS National Lab website: www.issnationallab.org/workshops/2019-materials-in-space.

Time	Category	Presentation Title	Speaker
7:30 a.m.	Breakfast		
8:00 a.m.	Welcome		Etop Esen, ISS National Lab
	Workshop Objectives and Deliverables	NASA Exploration Objectives, ISS National Lab Mission, role of Materials Science and workshop objectives	Craig Kundrot, NASA; Michael Roberts, ISS National Lab
8:20 a.m.	Agenda Overview		Michael SanSoucie, NASA
	Main Session Presentations		
8:30 a.m.	Functional Materials	Corning Functional Materials Overview	Jay Sutherland, Corning
8:45 a.m.	Lunar Infrastructure and Surface Operations	Lunar Infrastructure and Surface Operations	John Vickers, NASA
9:00 a.m.	Materials Characterization, Microstructure and Process Modeling	Tiny-but-tough: Emerging Nanomaterials for Space Exploration	Debbie Senesky, Stanford
9:15 a.m.	Computational Materials Science	Machine Learning and Artificial Intelligence applications to Materials Science for customized solutions	Teodoro Laino, IBM
9:30 a.m.	Computational Materials Science	Motivation, Development and Future Directions for Computational (Metallic) Materials at NASA	Ed Glaessgen, NASA
9:45 a.m.	In-Space Manufacturing	Overview of the In-Space Manufacturing Technology Portfolio	Tracie Prater, NASA
10:00 a.m.	Additive Manufacturing	Key Trends in Additive Manufacturing	Michael Holman, Lux Research
10:15 a.m.	Break		
10:35 a.m.	ISS Materials Facilities and Research	MIS Current and Future Advanced Manufacturing Programs on the ISS	Justin Kugler, Made In Space
10:45 a.m.	ISS Materials Facilities and Research	MISSE Flight Facility on the ISS and Future ISS Programs	Mark Gittleman, Alpha Space
10:55 a.m.	ISS Materials Facilities and Research	The ISS Microgravity Science Glovebox: Experiments in Solidification, Payloads for Material Science Aboard the ISS, Pore Formation, Lyophilization	Chris Butler, TecMasters George Tipker, Techshot Kenneth Savin, ISS National Lab

Time	Category	Presentation Title	Speaker
11:25 a.m.	ISS Materials Facilities and Research	Experiments using the ISS Electrostatic Levitation Furnace (ELF) and the Solution Crystallization Observation Facility (SCOF)	Hirohisa Oda, JAXA
11:40 a.m.	ISS Materials Facilities and Research	Experiments using the ISS Electromagnetic Levitator (EML)	Michael SanSoucie, NASA
11:50 a.m.	NASEM Roundtable on LEO Materials Research	Proposed NASEM Roundtable on Advanced Materials and Manufacturing in LEO	Michael Roberts, ISS National Lab
12:00 p.m.	Breakout Session Instructions		Etop Esen, ISS National Lab
12:05 p.m.	Lunch		
12:50 p.m.	Breakout Sessions		
	Functional Materials		Co-chairs: Rick Weber, MDI; Michael Holman, Lux Research
	Lunar Infrastructure and Surface Operations		Co-chairs: Eric Fox, NASA; Aleksandra Radlińska, PSU
	Materials Characterization, Microstructure and Process Modeling		Co-Chairs: Debbie Senesky, Stanford; Ed Glaessgen, NASA
	Summary & Discussion from Breakout Sessions		
3:50 p.m.	Materials Characterization, Microstructure and Process Modeling		Session Co-Chairs
4:00 p.m.	Functional Materials		Session Co-Chairs
4:10 p.m.	Lunar Infrastructure and Surface Operations		Session Co-Chairs
4:20 p.m.	Wrap up and Close		Etop Esen, ISS National Lab

Appendix C: RFI Responses

The RFI responses received were categorized into the one or more of the breakout sessions by the workshop organizing committee. If an RFI was applicable to multiple sessions, it is listed in order of ranked relevance from high to low.

Breakout session key:

F Functional Materials
M Materials Characterization, Microstructure, and Process Modeling
L Lunar Infrastructure and Surface Operations

Note: Theme area categorizations were provided by the Functional Materials breakout session only. Thermophysical properties modeling RFI responses underpinned many of the entries for Additive Manufacturing and High-Value Materials.

RFI Number and Breakout Session	Author	RFI Title	Author Affiliation	Theme Area
N9-Mat_RFI-0001 L	Evgeny Shafirovich	Combustion Joining of Ceramic Parts in Space	The University of Texas at El Paso	
N9-Mat_RFI-0002 M	Douglas Matson	RFI on Materials Science on ISS	Tufts University	Thermophysical Properties Modeling
N9-Mat_RFI-0003 M	Ebrahim Asadi	Cyclic Rapid Solidification and Heating of Ti-6Al-4V Alloys	University of Memphis	
N9-Mat_RFI-0004 F, L	David Traore	MR (Magnetorheological) Fluid Knowledge Payload for Space Robotics	ORBIT	Other
N9-Mat_RFI-0005 L, M	Richard Weber	Fining of Glass Melts in Reduced Gravity	Materials Development Inc	High-Value Materials
N9-Mat_RFI-0006 F	Majid Minary	Additive Manufacturing and Freeze Casting	The University of Texas at Dallas	Additive Manufacturing
N9-Mat_RFI-0007 M, L	Michael Sangid	Developing an External Testbed for the Rapid Qualification of Additive Manufactured Materials in Space	Purdue University	Additive Manufacturing
N9-Mat_RFI-0008 L	Jeffrey Montes	Large-scale Additively Manufactured Surface Structures		
N9-Mat_RFI-0009 M, L, F	David Dunand	Aqueous-based Freeze-casting for the Production of Porous Materials	Northwestern University	High-Value Materials
N9-Mat_RFI-0010 L, M	Robert Hyers	In-Space Metal Additive Manufacturing	University of Massachusetts Amherst	Additive Manufacturing

N9-Mat_RFI-0011 M	Wen Chen	Response to RFI on Materials Science for ISS Workshop	University of Massachusetts Amherst	Additive Manufacturing
N9-Mat_RFI-0012 M	Ranga Narayanan	Surface Tension, Interfacial Tension, and Surface Energy measurement	University of Florida	
N9-Mat_RFI-0013 L, F, M	Kathy Lu	Creating High Performance SiOC Materials Using Mars's Abundant Natural Resources		High-Value Materials
N9-Mat_RFI-0014 M, F	Paul Faget	Sintered Inductive Metal Printer with Laser Exposure (SIMPLE)	Techshot	Additive Manufacturing
N9-Mat_RFI-0015 F, L	Gurpreet Singh	The printing Process of Clean Polymeric Parts for in-space Applications.		Additive Manufacturing
N9-Mat_RFI-0016 L, M	Ryan Snyder	Reversible Thermoset Composite Joining / Reshaping Experiment		
N9-Mat_RFI-0017 L, M	Marcus Jackson	Remanufacturing Enabled by Mechanically Generated Feedstock for Additive Manufacturing		Materials Reuse
N9-Mat_RFI-0018 F	Naidu Seetala	Synthesizing New Type of Copolymers under Zero-gravity Starting from non-mixable Monomers	Grambling State University	High-Value Materials, Other
N9-Mat_RFI-0019 F, L	Alp Sehirlioglu	Processing of Materials Through Colloidal Sciences in Space	Case Western Reserve University	High-Value Materials
N9-Mat_RFI-0020 F, L	Duane Simonson	Gravity-independent 3D Printing of Multifunctional Materials		Additive Manufacturing
N9-Mat_RFI-0021 M	Vasyl Hafiychuk	Computational Multiscale Approach to Analysis of in-Space Manufacturing of Materials and Parts	NASA ARC	Thermophysical Properties Modeling
N9-Mat_RFI-0022 M	Adarsh Krishnamurthy	Machine-Learning Accelerated Modeling of Additive Manufacturing in Zero Gravity	Iowa State University	Thermophysical Properties Modeling
N9-Mat_RFI-0023 L	Brandon Krick	Materials Tribology Experiments on the International Space Station: Characterizing the Effects of the Low Earth Orbit Environment on Materials and Coatings	Lehigh University	Other
N9-Mat_RFI-0024 F	Joseph Pegna	Material-Agnostic Additive Manufacturing: 1½-D Printing and Joining of Functional Materials and Structures in Space	Free Form Fibers	Additive Manufacturing

N9-Mat_RFI-0025 L	Pedro Cortes	The Printing Process of Clean Polymeric Parts for in-space Applications.	Youngstown State University	Additive Manufacturing
N9-Mat_RFI-0026 M, L	Fredrick Michael	Simple, Low Power, Low Cost Space Based Micro- and Low- Gravity Joining and Assembling Processes		
N9-Mat_RFI-0027 M	Kumar Ankit	Growth Competition in Weakly-anisotropic Solidification: ISS Experiments and Phase-field Modeling	Arizona State University	High-Value Materials
N9-Mat_RFI-0028 F, L	Jerome Moore	Additively Manufactured μ-linac Ion Thrusters		Additive Manufacturing
N9-Mat_RFI-0029 L	Mohammad Naraghi	Investigation of the Degradation of Carbon-based Nanomaterials and Their Composites in-space Environments, Subjected to Radiation and Thermal Cycling	Texas A&M University	Other
N9-Mat_RFI-0030 M, F, L	Ulrike G K Wegst	ICE: Directional Solidification of Water-Based Systems in Space	Dartmouth College	High-Value Materials
N9-Mat_RFI-0031 L, M	Alexsandra Radlinska	Lunar Infrastructure Materials: Cementitious Binders	Penn State University	

Appendix D: Acronyms

AFM	Atomic Force Microscopy
CLPS	Commercial Lunar Payload Services
CT	Computed Tomography
CVD	Chemical Vapor Deposition
D&DT	Durability and damage tolerance
ELF	Electrostatic Levitation Furnace
EML	Electromagnetic Levitator
ESL	Electrostatic Levitation
FTIR	Fourier Transform Infrared Spectroscopy
ISRU	In-situ Resource Utilization
ISS	International Space Station
ISSRDC	International Space Station Research and Development Conference
LEO	Low Earth orbit
MCMPM	Materials Characterization, Microstructure, and Process Modeling breakout session
MISSE-FF	Materials International Space Station Experiment Flight Facility
R&D	Research and development
RFI	Request for Information
SCOF	Solution Crystallization Observation Facility
SEM	Scanning Electron Microscopy
SLPSRA	Space Life and Physical Sciences Research and Applications, Division of NASA
TRL	Technology Readiness Level
UV	Ultraviolet