

ISMAC: Marshall Space Flight Center's In-Space Manufacturing Advancement Center

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The In-Space Manufacturing Advancement Center (ISMAC) is NASA Marshall Space Flight Center Materials and Processes Laboratory's one-stop shop for tackling the difficulties of manufacturing in space. The ISMAC mission is to facilitate in-space manufacturing development through shared resources, networking, and communication; and the vision is to overcome all barriers to development of in-space manufacturing. In this case, the definition of "in-space manufacturing" is any manufacturing activities taking place above the Earth's atmosphere. In the near term this includes Earth orbit manufacturing for use in Earth orbit as well as use on the Earth. This is expected to grow in the medium-term to include Lunar manufacturing and orbital manufacturing for Lunar use, as well as deep-space transit manufacturing for use on the way to Mars and other deep-space destinations. In the long-term, this is expected to include Martian manufacturing for Martian and deep space use, as well as begin to leverage resources found not just in planetary destinations, but also in trojan asteroids, "space junk", and other atypical sources. Capabilities and results are continually growing, but currently include robotic rover test beds, robotic arms, regolith laser powder

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bed fusion (L-PBF), microgravity simulation, laser manufacturing technologies, 3D-scanning and digital twins development, among others.

I. Nomenclature

ISMAC	=	In-Space Manufacturing Advancement Center
L-PBF	=	Laser Powder Bed Fusion
LRT	=	Lunar Regolith Terrain
CASM	=	Collaborative Architecture for Surface Mobility
ANTS	=	Autonomous Network of Telerobotic Systems
COTS	=	Consumer Off-The-Shelf
DED	=	Directed Energy Deposition
NDE	=	Non-Destructive Evaluation
AM	=	Additive Manufacturing
RoSA	=	Robotic Swing Arm
EMAT	=	Electromagnetic Acoustic Transducer
LiDAR	=	Light Detection and Ranging
FEA	=	Finite Element Analysis
EML	=	Electromagnetic Levitator
LASAR	=	Lunar Assembly and Servicing by Autonomous Robots
ECI	=	Early Career Initiative
NOM4D	=	Novel Orbital and Moon Manufacturing, Materials, and Mass-Efficient Design
ICME	=	Integrated Computational Materials Engineering
SEM-EDS	=	Scanning Electron Microscope- Energy Dispersive X-Ray Spectroscopy
ISRU	=	In-Situ Resource Utilization

II. Introduction

The In-Space Manufacturing Advancement Center (ISMAC) is a crucial part of NASA Marshall Space Flight Center's answer to the mission drive to become increasingly Earth independent [1] [2], as well as support the ever-growing space economy. Dedicated laboratory space has been upgraded to provide a unifying contact point in the Materials and Processes Laboratory organization for the laboratories and test facilities around Marshall supporting in-space manufacturing. Capabilities and results are continually growing, but currently include rovers test beds, robotic arms, regolith laser powder bed fusion (L-PBF), microgravity simulation, and laser manufacturing technologies, 3D-scanning and digital twin development, among others.

III. Technologies in Development

Several technologies pertinent to in-space manufacturing have been collected into one laboratory space, promoting communication between typically disparate working groups and sparking innovation and quick turnaround through availability and open access to a suite of tools which are constantly being tweaked, swapped, upgraded, and recombined. The current list of technologies includes but is not limited to the following:

A. Robotic Test Beds

Commercial-off-the-shelf (COTS) Husky Rovers equipped with Universal Robotics UR5e arms were procured as test beds for methods of detecting, collecting, beneficiation, and use of resources on the lunar surface. Initial tests for capability in MSFC's Lunar Regolith Test Bed (LRT) have been completed. Current efforts are underway to find synergies between such existing programs as Collaborative Autonomous Surface Mobility (CASM) and Autonomous Network of Telerobotic Systems (ANTS) [3] to combine autonomy with resource detection and collection.

This will be completed by converting typically bespoke rover solutions into modular test beds, which various payloads developed internally and externally can be integrated and tested on. To this end, an investigator can expose a nascent technology to the field faster, gaining access to mobility and robotic manipulation for simulated surface operation without deep robotics knowledge. The intention of this is to test quickly, learn, and iterate at low cost and without dedicated robotics expertise, increasing the rate of TRL advancement from a proof of concept to a prototype working in a relevant, simulated environment in a matter of weeks rather than months or years.



Fig. 1 Husky rovers on MSFC’s outdoor LRT field

B. Acoustic Levitation

Acoustic levitation is a pressure-wave driven, containerless processing method that can be leveraged to manipulate material and provide ground-based equivalents for materials processed in microgravity [4]. Applications currently being investigated include acoustic sorting of powders and particulate for pre-manufacturing beneficiation of regolith [5] or recycled metals and polymers in a “shirtsleeves” environment. The unit includes a humidity- and temperature-controlled glovebox that can also be utilized to levitate solutions and carefully control crystallization rate, supporting possible pharmaceutical and biological studies as well as material solidification and fluid diffusion experiments. Acoustic methods for dust mitigation traps and cleaning methods for habitats and fabrication areas have also been proposed.

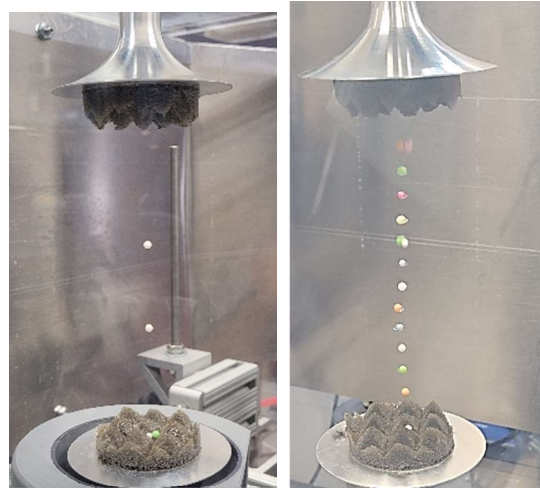


Fig. 2 Test objects trapped in different pressure nodes in the acoustic levitator

C. Powder Characterization

Powder characterization is important as a precursor to any powder-based manufacturing process (e.g. PBF, DED, etc.) as well as effectiveness of beneficiation of regolith prior to metals or oxygen extraction processes. The “GranuHeap” analyzer automatically measures angle of repose and cohesive index, providing quantitative measurement of flowability for use in additive manufacturing and construction. The “Spreadstation” measures spreadability of powders by physically spreading layers and analyzing the layer properties for spreading speed, density, and other factors to quantify performance in processing. To-date, multiple AM powders have been quantified as have various regolith simulants prior to L-PBF processes.



Fig. 3 GranuHeap and Spreadstation powder analysis

As PBF users are aware, feedstocks can have severe effects on the quality of additively manufactured parts [6]. Additive manufacturing from Lunar or Martian regolith is expected to be no different when collected for feedstocks. These resources collected from the lunar surface will likely not be uniform in size, shape, or chemistry, requiring analytical methods of measurement prior to beneficiation or direct use. Similarly, while using more uniform powders in process development, it is critical to track morphology and handling characteristics so that process limits may be discovered and set as beneficiation goals if repeatable build results are desired from raw materials.

D. Regolith Laser Powder Bed Fusion

A decommissioned, early generation laser powder bed fusion printer was modified by a commercial partner to include an upgraded laser, new in-situ thermography capture, and a complete “jailbreaking” of process parameters from those of the original equipment manufacturer. After check-out with a standard Inconel 718 capability verification print, initial trials have been made with lunar highland regolith simulant on a firebrick build plate.



Fig. 4 Left: Modified LPBF printer filled with lunar regolith simulant (inset). Right: Close-up of highland regolith simulant parameter test cubes

To date, glassy structures have been created in various states of consolidation as the processing envelope has been developed, with promising progress. Leveraging the materials diagnostic and mechanical test capabilities at MSFC, process iterations could be made quickly. As operating parameters for consolidated were selected, sample prints could be made, sectioned, polished and imaged for feedback regarding material segregation, porosity, and fracture. Hardness tests were also conducted to begin correlating the noted layered segregation to mechanical properties. Crush and bend tests are planned to tighten understanding of the process-structure-properties relationship.

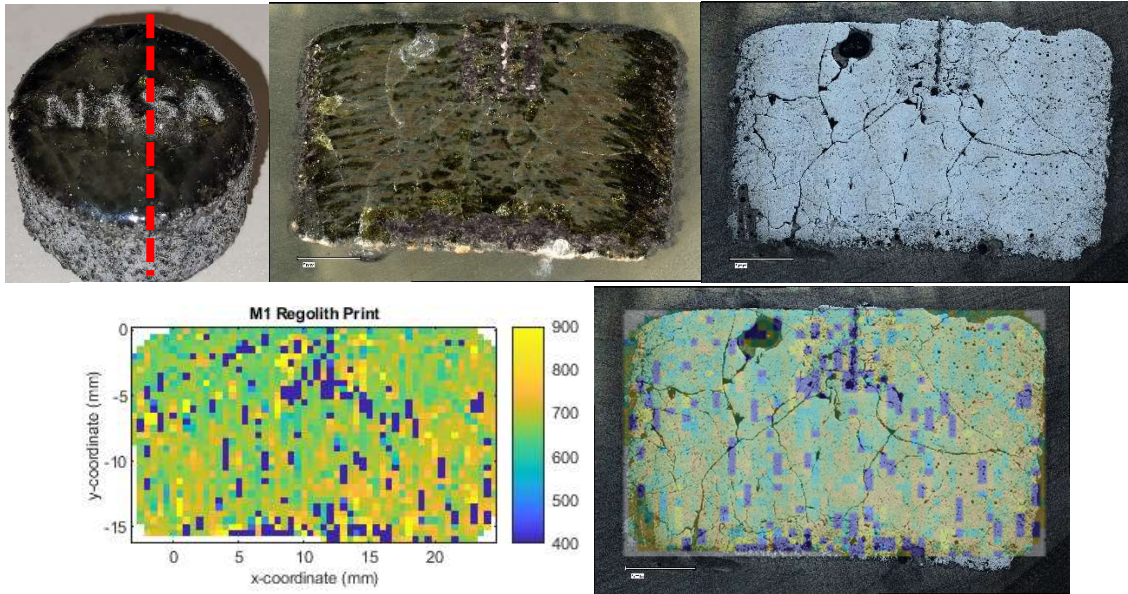


Fig. 5 Samples were printed, sectioned, polished, and imaged for general morphology and porosity investigation, including microhardness mapping

SEM-EDS analysis was also completed to investigate chemical segregation in the printed samples. It was noted that the layering and flow of the molten material likely impacted this segregation at particular areas, especially towards the edges where cooling rates were expected to be significantly higher. This appears to confirm that at least laser path, melt pool surface tension, and constituent species of regolith will all need to be considered in addition to standard laser power density, spacing, and speed factors typical in additive manufacturing. Additionally, these findings appear to indicate that altering beneficiation and process parameters may open the door to intentionally varied material properties in builds.

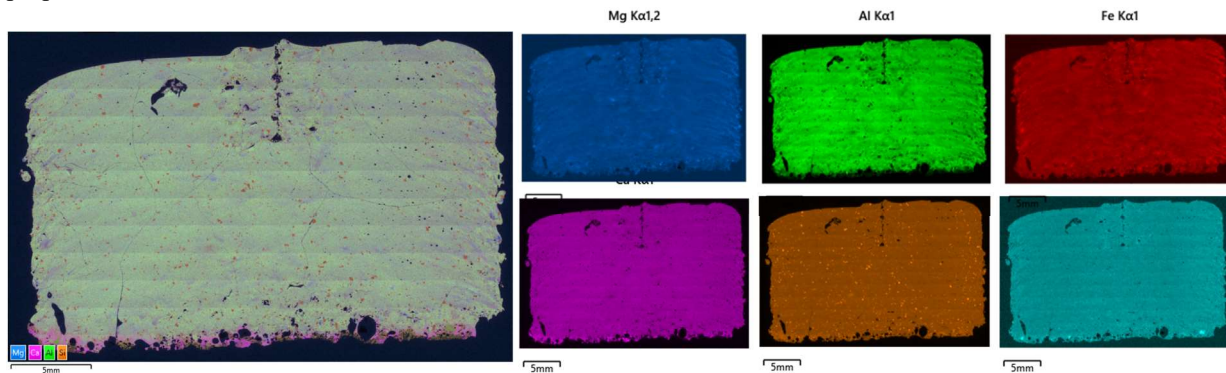


Fig. 6 SEM-EDS was performed on the sample section illustrating constituent content and segregation

Next steps include in-depth material characterization of build samples and commissioning of the thermography system, which is expected to inform in-situ process monitoring, non-destructive evaluation (NDE), and modeling efforts, which will prove critical to future ability to qualify in-space manufacturing processes and certify remotely manufactured products.

E. Microgravity Simulation

The Robotic Swing Arm (RoSA) is a short-duration microgravity simulator. Initial development trials have resulted in successful melting of an Inconel 625 foil sample heated with a diode laser in a “single toss” run mode. Accelerometer measurements confirmed around 0.5 seconds of “microgravity” conditions. Future work includes further investigating and developing “spot weld” of folded foil sheet and development of a cyclic testing mode by which multiple microgravity melting and solidification tests could be run in quick succession.



Fig. 7 From left to right, the “RoSA” microgravity simulator, a solidification-test payload, and an Inconel 625 foil tested multiple times

Standard 1g samples demonstrated a tighter dendritic spacing and branching, which indicates the effects of convective flow as the alloy density changes at the solidification front. Meanwhile, the microgravity solidification samples display a much wider dendritic spacing with a much straighter growth pattern, indicating that differences in density did not have as much affect. This would be expected based on historic solidification work [7] performed on-orbit and examined on the ground. These primary dendrites will in part determine grain size and alloy distribution in the final product, which in turn affects material properties. Gathering data such as this to feed into and verify Integrated Computation Materials Engineering (ICME) models is the first step to generating first-order digital twins, with the ultimate goal of certification on process control alone.



Fig. 8 Microstructure comparison of Inconel 625 solidification test foils

F. Laser Manufacturing

Beginning with inclusion of a handheld IPG Photonics “LightWELD” laser welding unit intended for work inside a regolith-containing glovebox to simulate Lunar surface, laser manufacturing work quickly expanded to include laser forming and robotic integration. ISMAC efforts have dovetailed well with existing projects at MSFC, including the “LASAR” Early Career Initiative (ECI) project [8] demonstrating laser beam welding in thermal vacuum environments and a partnership with the DARPA NOM4D program demonstrating laser forming of sheet metal [9] which builds on work originally performed by the University of Florida. ISMAC laboratory space and equipment is leveraged by such projects and is fully integrated into the “In-Space Laser Manufacturing Ecosystem” at MSFC. [10] Such equipment includes laser-safe enclosures, robotic arms, laser generators, and more. These efforts lead directly to large-scale construction capability in space and on planetary bodies.

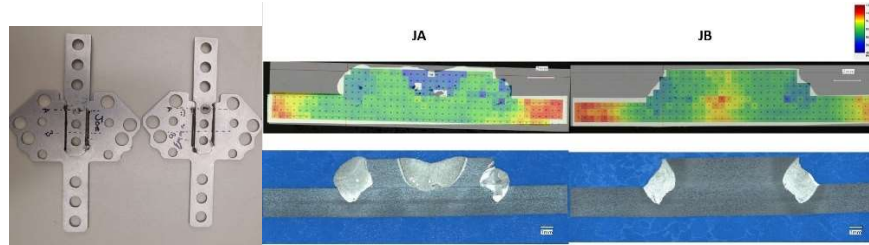


Fig. 9 Laser welding tests and parameter development specimens

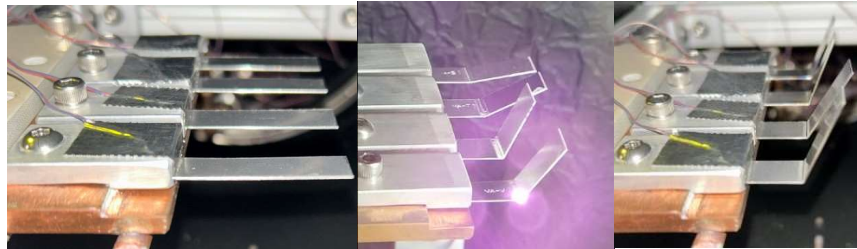


Fig. 10 Laser forming tests and parameter development specimens

Faster turnaround for laser welding and laser bending samples has been realized with a new 10' x 10' x 10' work cell dedicated to laser manufacturing. Including safety interlocks and fume collection, this addition to ISMAC will allow for both increased output and safety. Use has led to accelerated laser forming operations and is an area to safely integrate laser welding, cutting, and forming heads onto cobot arms to quickly incorporate laser processes into potential flight test platforms and exercise these systems safely.



Fig. 11 Laser manufacturing cell for fast, safe development of laser processes and parameters, including integration into robotic systems.

G. NDE Integration

The NDE team has integrated an Electromagnetic Acoustic Transducer (EMAT) head onto an ISMAC Universal Robotics UR10e arm for automatic nondestructive evaluation of as-build parts and structures. Nondestructive testing of manufactured products will be even more important in-space than it is on Earth due to the costs that destructive testing would carry. EMAT is ideal for in-space use because it is a volumetric test (a variant of ultrasonic testing) that does not require direct contact or a couplant, which would cause obvious issues in vacuum. Applications range from part manufacture to welded assemblies, to repair on large structures which require volumetric integrity. This work is key to verification, validation, certification, and monitoring systems, as well as informing digital models and digital twin development. Lessons learned will inform both NDE methodology and hardware integration, as well as future efforts to design for inspection

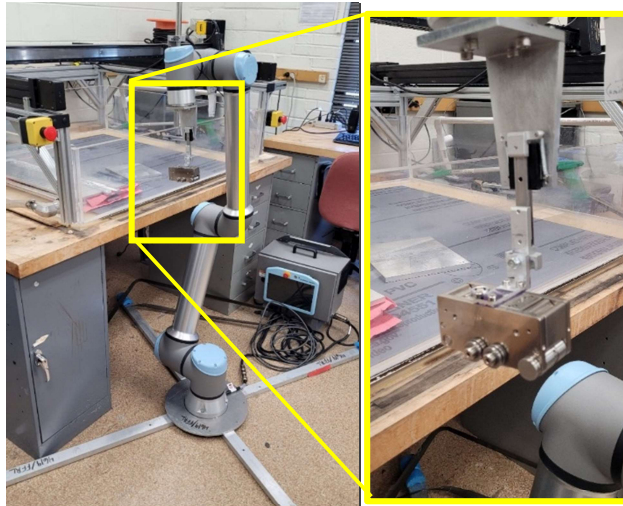


Fig. 12 EMAT head integrated into UR10e cobot arm

H. 3D Scanning and Digital Twins

Led by the Materials and Process Laboratory’s 3D Scanning Lab, the ability to precisely and accurately detect the “actual” status of as-built and existing structures is critical to validation, verification, and certification for use. Digital Twins can be generated, updated, and fed back into engineering systems for further autonomous development, NDE, and structural health monitoring even after initial release for use [11]. Work to-date in relation to ISMAC has been focused on LiDAR and large-scale structures on the order of habitats, however, the 3D Scanning Lab has additional capability, including structured light scanning to reverse-engineer components, parts, structures, and assemblies, complete with detailed FEA meshes and digital twin creation to establish the “digital thread” connecting requirements and design through repair and end-of-life activities.

Moving forward, planning and development for digital twins will be applied to as many applications as can benefit. The operating definition for digital twins to be embraced by ISMAC, being centered around physical assets, will require three major components for successful implementation: [12] 1) a physical system, 2) a simulated twin, and 3) useful communication between the two in which the state of the physical system is analyzed to inform the simulation and the simulation makes predictive decisions for the physical system. This is a stark contrast to a simple control or feedback loop in that actions will be based on leading indicators rather than trailing ones.

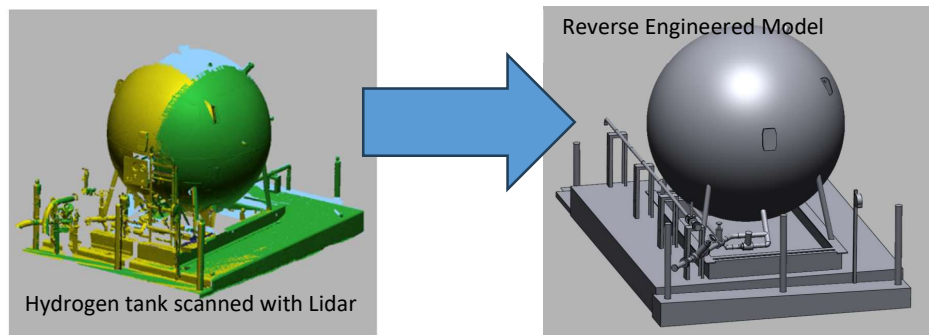


Fig 13. Engineering model generated by 3D scanning methods

IV. Future Work

Several additional projects and processes are in development and expected to come to fruition, ready for reporting before the end of fiscal year 2025:

A. Electromagnetic Levitation

Containerless thermal processing of regolith material, including regolith “slag” from oxygen and metals generation is required to characterize and understand their thermophysical properties for manufacturing utilization. This is planned to be completed through laser-aided electrostatic and electromagnetic levitation processing

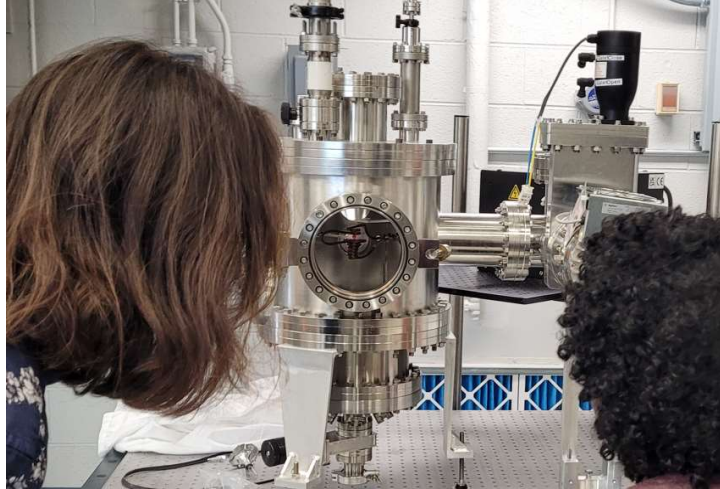


Fig. 14 Startup and levitation of a metallic test sphere

Electromagnetic Levitation (EML) in particular has been targeted for implementation into ISMAC, allowing a containerless method of interrogating the physical properties of conductive and semiconductive materials. This will help gain insight into properties to better inform computational models for ICME as well as develop better control and manipulation methods for ISRU materials during beneficiation and processing. Also, it could serve as an additional ground-analog to units already in space, such as DLR’s EML [13] aboard the ISS, to better isolate the effects of microgravity on materials.

B. In-Space Recycling Development Lab

An important factor for living and thriving in space, methods must be developed for reusing and recycling the various materials (both polymer and metal) brought to space with the crew or as retired hardware in lower Earth orbit. Initial efforts will focus on using polymer packaging materials similar to those delivered to ISS and examples of aluminums found as orbital debris as feedstocks for new product forms and additive manufacturing applications.

C. Aluminum Liquid Drop Printer

ElemX 3D Printing uses an aluminum liquid droplet formed from wire to build desired shapes and forms without the need for powder handling and spreading, while offering finer detail resolution than other wire deposition processes. This process could be potentially modified to remove gravity conditions from the jetting stream for in-space applications and higher temperature materials. Near term work includes baseline aluminum material and process characterization, study of recycled aluminum feedstocks, and studying process modifications required for adaptation for potential use in microgravity.

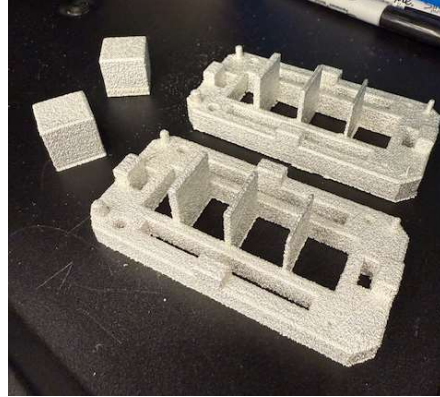


Fig. 15 Aluminum calibration prints made during commissioning of ElemX printer

V. Conclusion

Work has begun in ISMAC, Marshall Space Flight Center's hub for in-space manufacturing advancement. With a myriad of capabilities and a collaborative environment, an invigorated culture of innovation is forming in which ideas can be developed quickly, grown into larger partnerships and projects, and then integrated into in-space manufacturing use-cases. Partnerships with academia, industry, and other government organizations are heartily encouraged and technology transfer is celebrated as much as internal development. The authors of this paper look forward an ever-quickening pace of advancement and partnership as we build out our manufacturing capabilities from the isolation of a finite Earth to the vast, infinite reaches (and riches) of space.

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