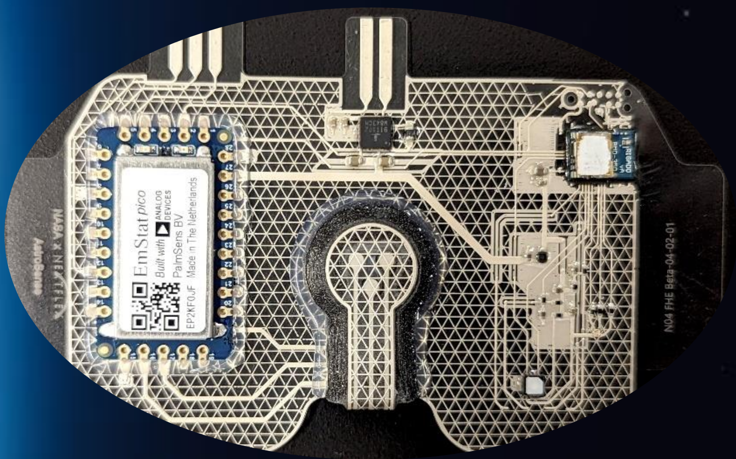
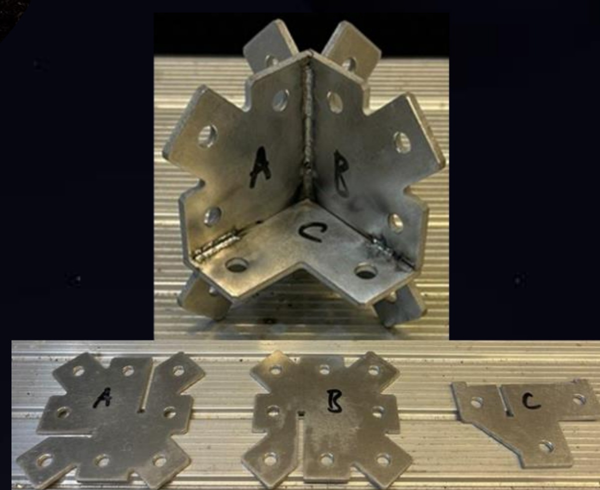
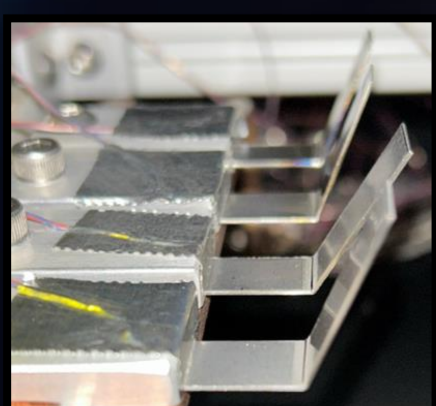
In-Space Manufacturing Portfolio Plan







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Z. S. Courtright, J. M. Jones, A. J. Blanchard, J. M. Bonebrake, T. C. Bryan, W. C. Evans, A. T. Fox, C. J. Francis, C. W. Hill, E. K. Jaynes, B. A. Kimbrel, F. E. Ledbetter, I. K. Lu, A. O'Connor, S. R. Peeples, C. S. Protz, C. E. Roberts, B. L. Rupp, P. D. Shake, J. W. Sowards, R. Subedi, J. E. Koehne, M. Seol
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LIST OF ACRONYMS AND SYMBOLS

AES - Advanced Exploration Systems
AMF - Additive Manufacturing Facility
BMD - Bound Metal Deposition
BPS - Biological and Physical Sciences
CAD - Computer Aided Design
CCsC-2 - Commercial Space Capabilities
CDR - Critical Design Review
CRM - Continuous Risk Management
DARPA - Defense Advanced Research Projects Agency
DED - Directed Energy Deposition
DISCMAN - Disk-Shaped Configurable and Modular vAcuum uNit
DT - Digital Twin
DTr - Digital Transformation
EBW - Electron Beam Welding
ECB - Engineering Control Board
ECI - Early Career Initiative
EDU - Engineering Demonstration Unit
EMAT - Electromagnetic Acoustic Transducer
FDM - Fused Deposition Modeling
FOD - Foreign Object Debris
GCD - Game Changing Development Program
ICME - Integrated Computational Materials Engineering
IDR - Interim Design Review
IMQCAM - Institute for Model-based Qualification and Certification of Additive Manufacturing
InSPA - In Space Production Applications
IRaD - Internal Research and Development
ISM - In-Space Manufacturing
ISMAC - In-Space Manufacturing Advancement Center
ISS - International Space Station
KPP - Key Performance Parameter
LaRC - Langley Research Center
LASAR - Lunar Assembly and Servicing by Autonomous Robotics
LBW - Laser Beam Welding
LEO - Low-Earth Orbit
LWIR - Long Wave Infrared
ManD - Manufacturing Device
MOU - Memorandum of Understanding
MSFC - Marshall Space Flight Center
NDE - Nondestructive Evaluation
NOM4D - Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design
ODME - On-Demand Manufacturing of Electronics
ODMM - On-Demand Manufacturing of Metals/Multi-materials
ORU - Orbital Replacement Units
PCB - Project Control Board
PDR - Preliminary Design Review

PI - Principal Investigator
PSP - Process-Structure-Property
PSRP - Payload Safety Review Panel
R&R - Recycle and Reuse
RMB - Risk Management Board
RSO - Resident Space Objects
S&MA - Safety and Mission Assurance
SAA - Space Act Agreement
SEMP - Systems Engineering Management Plan
STMD - Space Technology Mission Directorate
SwRI - Southwest Research Institute
TMP - Technology Maturation Plan
TRL - Technology Readiness Level
TVAC - Thermal Vacuum
WAAM - Wire-Arc Additive Manufacturing

1. In-Space Manufacturing

1.1. Portfolio Overview

The In-Space Manufacturing (ISM) portfolio includes projects that develop, test, and implement the materials, technologies, and capabilities needed for on-demand and infrastructure manufacturing in space and on non-terrestrial surfaces. The current International Space Station (ISS) logistics model is heavily dependent upon Orbital Replacement Units (ORU) for system-based repair and maintenance. Logistics support is a significant challenge for extended human operations in space, especially for missions beyond Low-Earth Orbit (LEO) where timely resupply or abort in the event of emergency will not be possible. In addition, some structures are too large, bulky, or fragile to launch when fully assembled. As a result, ISM is a promising technology portfolio that could reduce deep space logistics requirements, mitigate risks, and augment operational capabilities, enabling Earth-independent human spaceflight and an economically sustainable lunar presence.

The capabilities under pursuit align with technology shortfalls identified by the Space Technology Mission Directorate (STMD) such as 1) “In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks” (ID 1485), 2) “In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction” (ID 1486), 3) “In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction” (ID 1487), and “In-Space and On-Surface Manufacturing from Recycled and Reused Materials and Components” (ID 1489) (NASA, 2024). Additional information on technology alignment for ISM is shown in the Appendix.

Figure 1 shows the four primary pursuit areas for ISM (Courtright, 2024). While these strategic pursuits align with STMD shortfalls, they also address challenges identified by other government organizations such as DARPA, NIST, NSF, AFRL, Space Force, and NRL. Once matured, these technologies may be infused into Exploration Systems Development Mission Directorate (ESDMD) missions to reduce risk to life and systems and enable the economic sustainability of those missions.

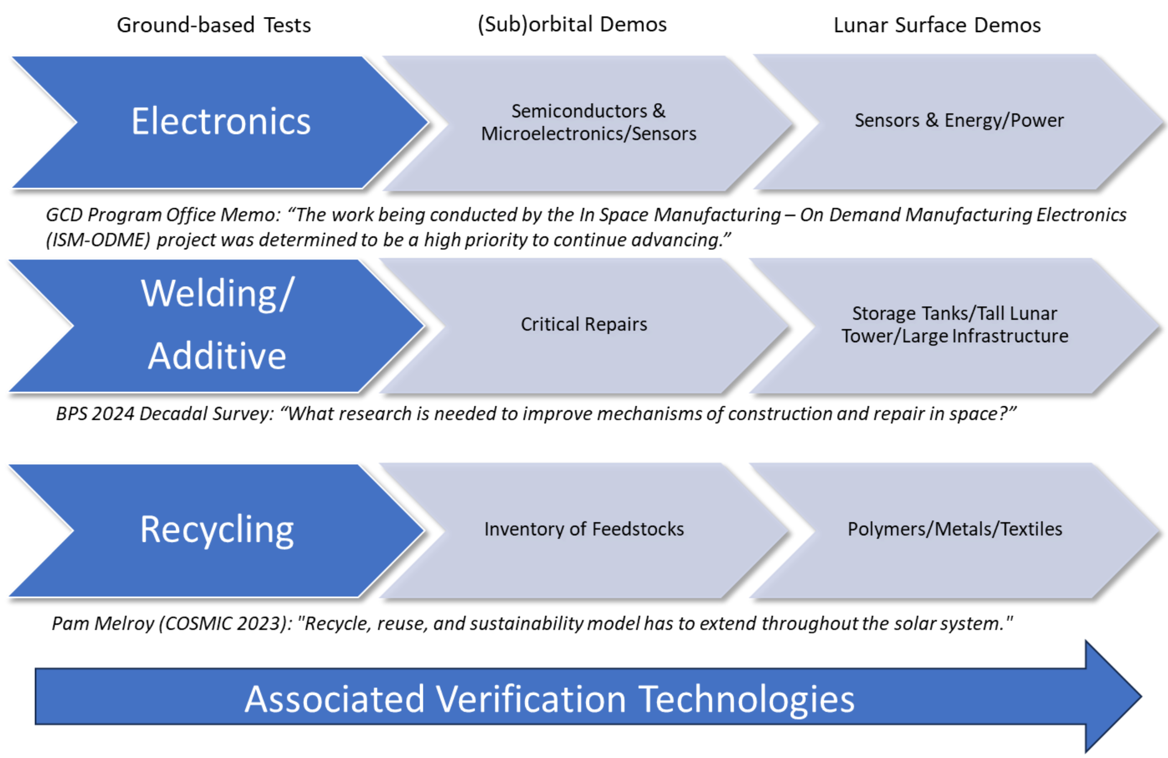


Figure 1: ISM Portfolio Focus Areas

In pursuit of closing the identified technology gaps, technologies of particular interest include: 1) manufacturing of electronics, sensors, and semiconductors, 2) welding, cutting, forming, and additive manufacturing, 3) recycling, and 4) nondestructive evaluation, high-throughput testing, and electrical performance validation. The projects that develop these technologies are detailed in the following sections, and the technologies that are currently under development as of the writing of this document are shown in Table 3: ISM Technology Summary3 of section 2.

NASA MSFC has been identified as the lead center for Advanced Manufacturing, which includes ISM.

1.1.1. Electronics & Semiconductors

In-space electronics manufacturing adds value by: 1) producing sensors and other electronic devices as they are needed to provide operational flexibility, 2) reducing mass if using recycled or ISRU feedstock, and 3) producing microelectronics, sensors, and semiconductor devices at a higher quality or lower defect rate than industrial electronics manufacturing processes.

a. On-Demand Manufacturing of Electronics (ODME)

STMD/Game Changing Development (Enable) funds the ODME project to develop the FabLab – Printer Module as an Expedite the Processing of Experiments to Space Station (EXPRESS) rack payload for the ISS. Initial funding for ODME was received in 2020 and joint development funds for the preliminary combined On-Demand Manufacturing of Metals/Multi-materials (ODMM)/ODME FabLab design were provided by STMD and ESDMD. As of the cancellation of the ODMM FabLab project, the ODME FabLab – Printer Module became an independent payload fully funded by STMD/GCD (Enable). The project has passed the Preliminary Design Review (PDR), a delta PDR, an Interim Design Review (IDR), and is on track to kickoff the Critical Design Review (CDR) by the end of Q3 FY25. An Engineering Design Unit (EDU) (Figure 2) was completed in May of 2024. The project is proposing the flight of the payload and an ISS demonstration.

Figure 2: FabLab – Printer Module with Advanced Toolplate Engineering Development Unit (EDU) (Credit: Redwire Space Technologies).

The ISS payload demonstration will be focused on additively manufactured sensors and sensor boards, and the tools included in the payload design are scoped accordingly. Toolheads for the initial demonstration include direct ink write printing, Fused Deposition Modeling (FDM) printing, milling, laser curing, laser point scanning, and device pick and place. Anticipated sensor manufacturing demonstrations may include an additively manufactured CO_2 sensor board, an ECLSS conductivity sensor, and a flexible strain sensor. These demonstrations will exercise the capabilities of the payload and are currently on track to be the inaugural demonstration of electronics manufacturing in space, thereby securing a leadership position in this area for NASA.

A wide range of electronics manufacturing processes have been developed through the ODME project. Many of these processes are being added to the Printer Module Advanced Toolplate to create a multi-material, multi-process fabrication system for microgravity manufacturing of a wide range of polymers, metals, electronics materials, and semiconductor materials. These next generation processes and materials will enable manufacturing of sub-micron resolution microelectronics and semiconductor devices, and fabrication of advanced on-demand printed power generation and energy harvesting devices.

These new electronics fabrication capabilities will not only support increasingly complex NASA mission architectures by producing parts at their point of use but will also enable next-generation electronics systems by producing advanced semiconductors and other devices in microgravity that will transform and enable a LEO Manufacturing economy. ODME technologies could potentially produce semiconductors with properties significantly better than ground-based alternatives and may drive down logistics costs to generate favorable economics regarding semiconductor material launch, production in space, and return costs.

In fiscal year 2024, Booz Allen Hamilton assessed the current and future potential ODME technologies and the current stakeholders and applications in the ODME trade space. The identified areas of benefit fostered by printed electronics development in space are shown in *Table 1*.

Table 1: Areas of Potential Impact for On Demand & Space Electronics Manufacture

Areas of Need	
AI In Space	Advanced Sensors
Quantum Computing	Quantum Communications
Quantum Sensing	Advanced materials and production methods
Edge Computing	National Security
Logistical Advantage	4th Generation Industry

The STMD/ODME partnership with the SOMD/InSPA LEO Commercialization program has significantly accelerated technology maturation of materials and processes technologies for in-space electronics fabrication. In addition, the effort has facilitated industrial partnerships to begin the process of enabling infrastructure for LEO/microgravity manufacturing. Figure 3 shows the development relationships of ODME to other NASA Directorates and Technology Maturation Efforts.

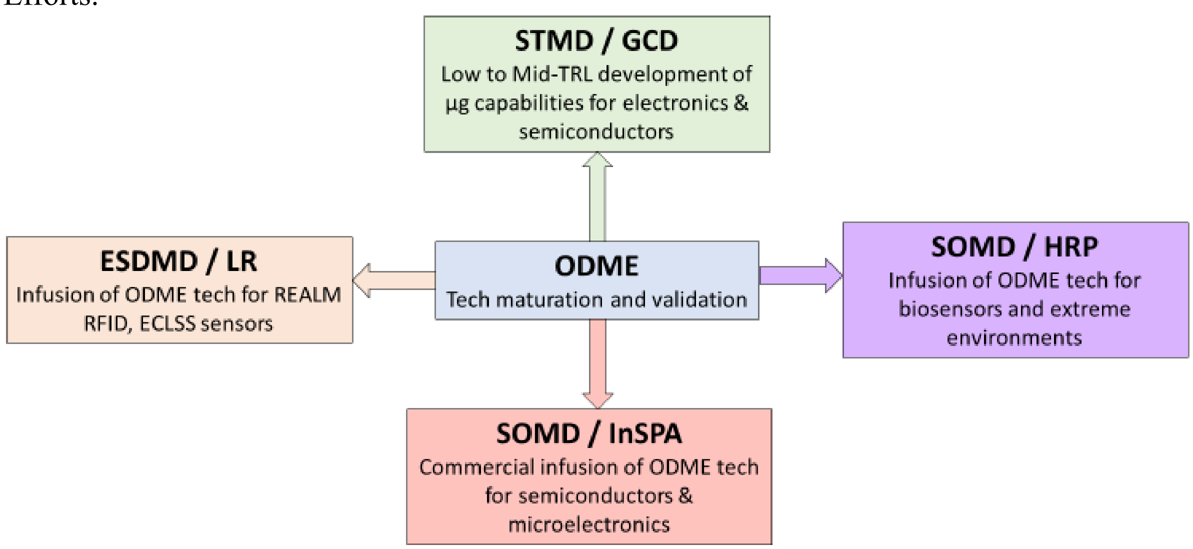


Figure 3: ODME Development Relationships

The capability to produce high-performance, low-cost printed sensors in-space for use in-space is a valuable capability enabled by ODME technologies. ODME is leading the development of on-demand printed sensors for a wide range of applications, including Structural Health Monitoring, Environmental Sensors (including radiation and many gas sensors), and Crew Health Monitoring Sensors (Figure 4). ODME is also developing printed power generation devices (thermoelectric, printed fuel cells, etc.) and energy storage devices (supercapacitors). These devices will enable independent sensor networks without the need for external power or batteries.

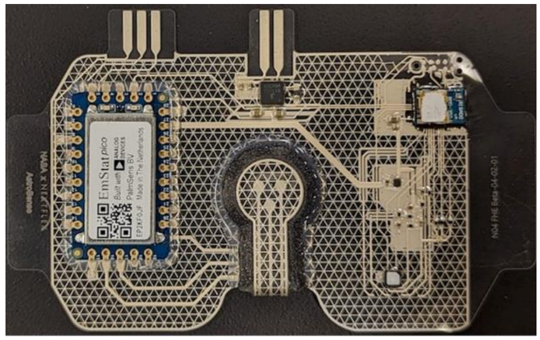


Figure 4: AstroSense Wireless Crew Health Sensor Module (Credit: NextFlex)

1.1.2. Laser Processing & Additive Manufacturing

Laser processing and additive manufacturing of metals and polymers add value by 1) making parts that cannot fit into a fairing or are too fragile to launch, 2) providing operational flexibility and repair, 3) reducing launched mass, 4) and enabling a sustained presence on the Moon or Mars by potentially manufacturing with a combination of shipped feedstocks and in-situ resources. While laser processing is the primary metal manufacturing focus area in ISM currently, solid-state welding and additive manufacturing processes are also of interest due to their robust potential for operation in a reduced gravity, thermally volatile, and low-pressure environment.

a. Laser Processing

High-energy beam welding processes such as Electron Beam Welding (EBW) and Laser Beam Welding (LBW) are desirable due to their minimal usage of consumables and applicability to a variety of materials. Laser processing of metal is an important technology for continued development because laser processes can cut, weld, bend/form, drill, ablate, and additively manufacture metal parts. Laser processes, including LBW, are of great interest as modern diode-based lasers have achieved greater energy and mass efficiency while offering benefits such as variable atmosphere operation, elimination of ionizing radiation exposure, and decoupling of the heat source from the process head by an optical fiber. These confer laser method with operational flexibility over electron beam processes. Thus, laser processes are now viable for infusion into ISM applications. However, much remains unknown about how laser processes perform in the space environment (Figure 5) and focused research and development are required for technology infusion (Sowards et al, 2021).

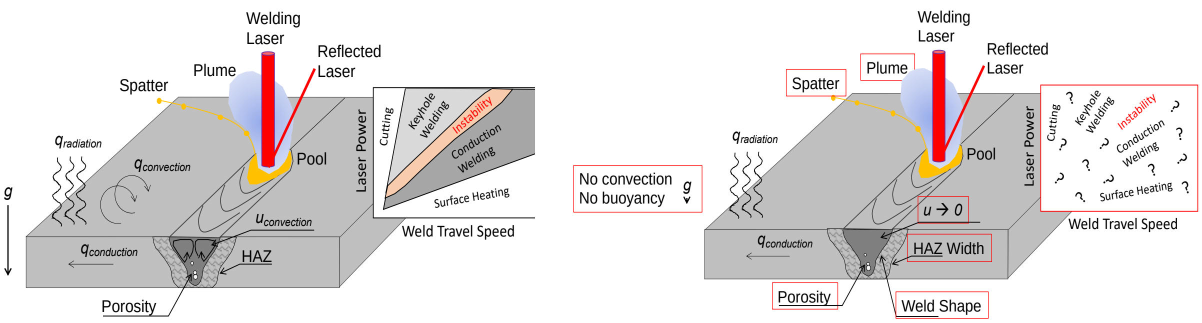


Figure 5: LBW in the terrestrial environment (left) and the space environment with changes in red (right) (Sowards et al, 2021).

The ISM portfolio is maturing LBW by developing relevant hardware systems and testing them through a progression of parabolic and suborbital flights to access reduced gravity and pressure conditions. Development in this area was spurred by NASA MSFC investing Center funds across a series of Center Investment awards. The Biological and Physical Sciences (BPS) Division of SMD and the STMD Flight Opportunities Program have also contributed funds to parabolic flight experiments.

MSFC-funded projects include a parabolic flight demonstration of LBW in collaboration with The Ohio State University. This effort included retrofitting a vacuum chamber suitable for parabolic flight originally integrated by NASA/LaRC for electron beam AM (Hafley et al, 2007) with a laser generator and optics suitable for LBW. The design and fabrication of a vacuum LBW system, the Disk-Shaped Configurable and Modular vAcuum uNit (DISCMAN), suitable for orbital flight, is in progress. Figure 6 depicts these projects. The DISCMAN payload has progressed to the maturation of a protoflight system using MSFC center investments and was recently awarded STMD funding for the final testing, flight, and post-flight analysis of the payload and test specimens.

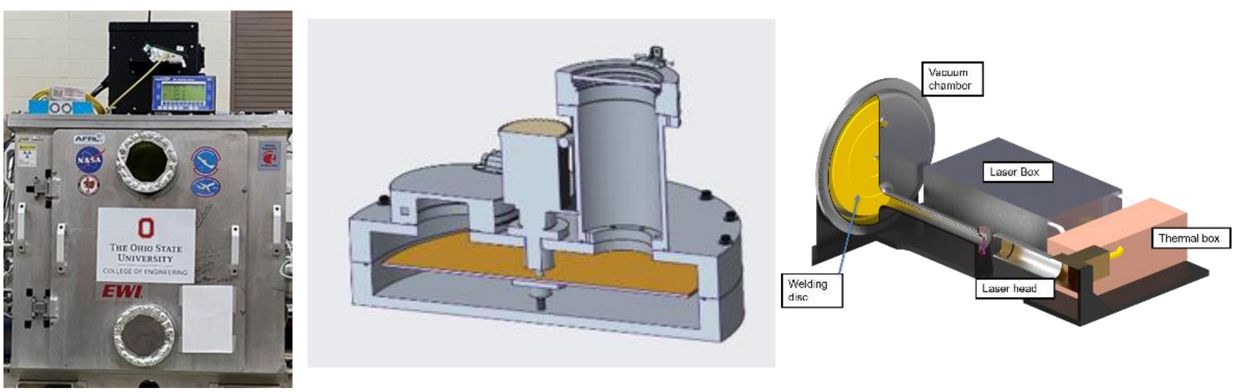


Figure 6: Parabolic flight hardware showing vacuum chamber with welding head mounted (left); CAD model cut-away of a vacuum chamber with access ports and optical/vacuum feedthroughs (middle); conceptual suborbital design from Advanced Concepts Office (right)

NASA STMD awarded an Early Career Initiative (ECI) project called Lunar Assembly and Servicing by Autonomous Robotics (LASAR) to a MSFC-led team with support from NASA/LaRC and NASA/JSC along with external partners Laserline, Motiv Space Systems, and PickNik Robotics. LASAR is focused on LBW within a Thermal Vacuum (TVAC) chamber. This project will weld, inspect, and repair truss joints of an advanced snowflake geometry using a ruggedized laser beam welder mounted on a supervised autonomous robotic arm (Figure 7) in a TVAC environment. This TVAC-rated robotic arm and laser welding system is applicable to other in-space additive manufacturing tasks as well.

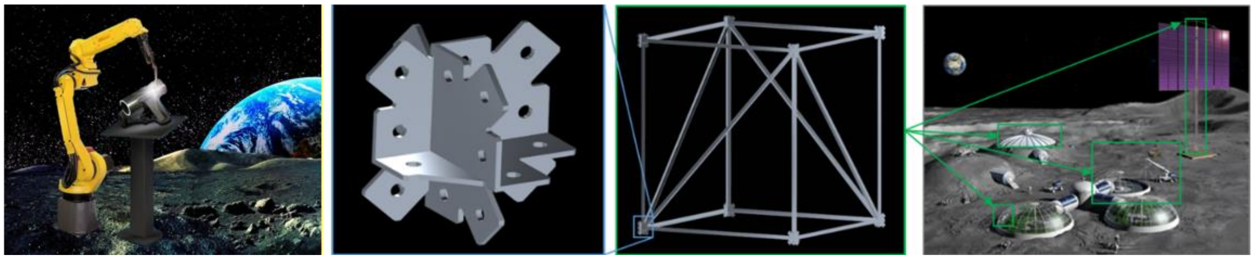


Figure 7: Artist's depiction of an autonomous robotic laser manufacturing platform on the Lunar surface (leftmost panel); LASAR will demonstrate laser welding to join TLT-like trusses (three rightmost panels; Credit: NASA Langley Research Center)

Several external partnerships related to in-space welding also exist:

- A Space Act Agreement (SAA) with ThinkOrbital to characterize their in-space electron beam welded specimens.
- A Commercial Space Capabilities (CCSC-2) agreement with NASA/JSC to support testing and development of ThinkOrbital's in-space EBW capabilities in TVAC.
- An SAA with Lockheed Martin to support their on-orbit joining demonstration Tipping Point project (JOINS) through scientific and test support.
- An intergovernmental agreement with the Defense Advanced Research Projects Agency (DARPA) Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D) program to mature in-space laser forming by performing laser forming of sheet metal in a TVAC environment and maturing Integrated Computational Materials Engineering (ICME) models to better understand the laser forming process.
- A Memorandum of Understanding (MOU) with the Air Force Research Laboratory to enable collaborations on in-space welding efforts. A joint roadmap was developed to facilitate pursuing collaborative technology maturation opportunities for ISM.

Finally, in FY24, the MSFC Advanced Concepts Office conducted a study on the feasibility of lunar surface manufacturing of storage tanks as compared to launching tanks fully intact. The study considered 4 scenarios: launching full tanks, launching tank components and welding/assembling tanks on the lunar surface, launching AM wire feedstock and tank components and manufacturing and assembling the tanks on the lunar surface, and utilizing in situ resources to manufacture and assemble tanks on the lunar surface.

b. Metal Additive Manufacturing

The ODMM project was active in some form from 2018-2023 and focused on the development of hybrid additive manufacturing technologies for demonstration aboard the ISS as well as auxiliary technologies such as recycling and reuse.

The primary payload under development was a fully integrated system that uses Bound Metal Deposition (BMD) to produce titanium (Ti6Al4V) parts. This system (FabLab) was developed by Redwire Space Technologies in collaboration with MSFC. FabLab was designed for integration into an EXPRESS rack on the ISS (Figure 8) (Prater et al, 2018).

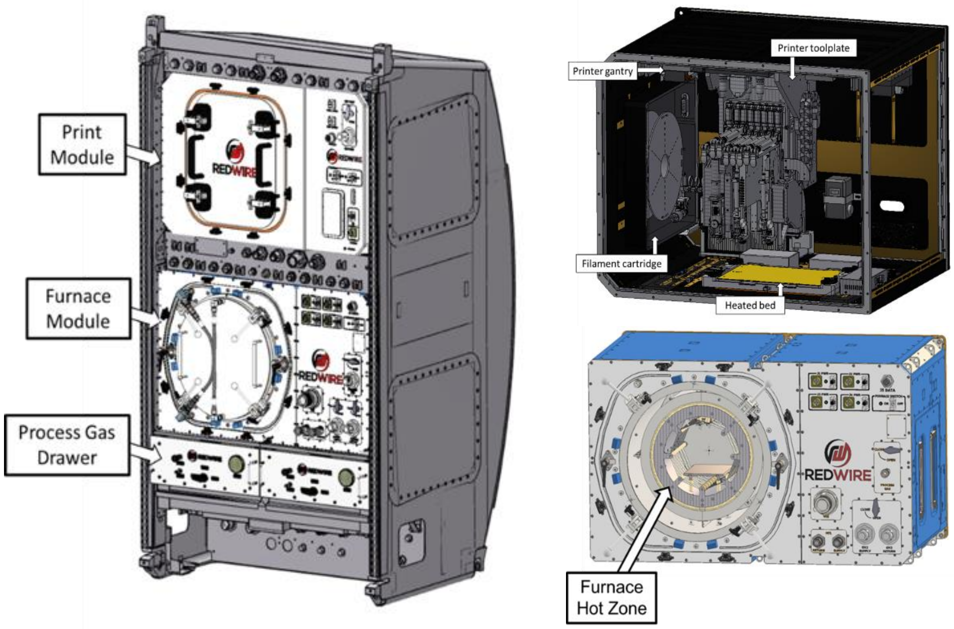


Figure 8: The FabLab system installed in an EXPRESS rack (left). Details of the print module (top right) and furnace module (top left) (Credit: Redwire Space Technologies).

The FabLab prototype system produced several Challenge Build parts out of Ti6Al4V (Ti64). Parts were printed via BMD and direct ink write before being thermally cured to sinter the part and boil off solvents and binders. Structured light scanning showed deviations from the Computer Aided Design (CAD) were within +/- 0.015” (Figure 9).

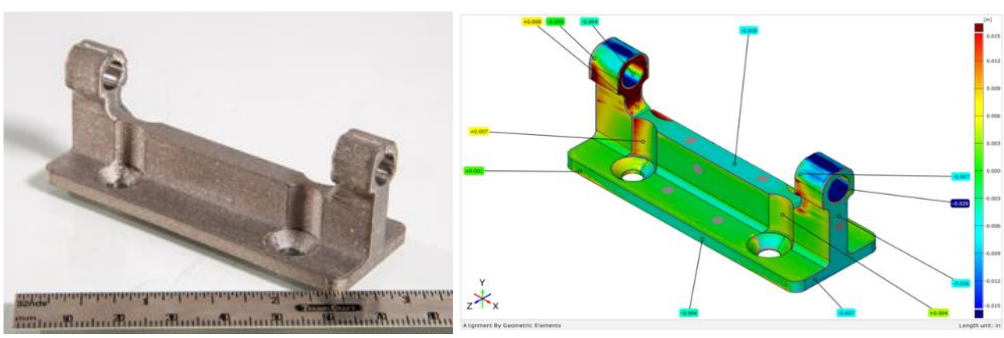


Figure 9: Additively manufactured Ti64 base (left) with structured light results of part for dimensional accuracy relative to CAD model (right). Colors correspond to degree of deviation. Deviations only range from +0.015" (dark red) to -0.015" (dark blue) (Left image credit: Redwire Space Technologies).

The ODMM project’s Key Performance Parameter (KPP) goal for Ultimate Tensile Strength was met by Ti6Al4V parts sintered at 1150°C. The KPP threshold for Bulk Density was also met by Ti6Al4V parts sintered at 1150°C, and the density was only 0.9% away from the project goal. Power draw for the FabLab furnace module was reduced to approximately 2.25 kW, slightly above the target requirement of 2.0 kW. This represents a decrease of over 5 kW from the original prototype. Several potential mitigation strategies were identified to close the remaining gap in power draw.

The FabLab payload successfully completed a contractor led delta preliminary design review in April 2023 showing a feasible path forward to flight. The Payload Safety Review Panel (PSRP) Phase I was completed in May 2023. In May of 2023 the project was given direction to close out all work related to metals-only additive manufacturing. The Redwire FabLab contract was modified to descope all work related to the furnace module and the process gas drawer, and only work on the printer module for ODME continued.

In FY24, the ISM project received center funding to conduct a series of technology assessments related to metal ISM. Yet2 was engaged to do a tech search on alternatives to furnace thermal curing for BMD printed parts. While the search identified a few lower TRL options that could be worth investing in for development, the furnace developed by Redwire was the most energy efficient high TRL option available.

In addition, MSFC/ES22 (Thermal & Mechanical Analysis Branch) updated their thermal model of the Redwire furnace. Initial modeling indicates that additional layers of molybdenum radiation shielding could bring the furnace power draw down to within ISS requirements.

Finally, ASTM/Wohlers Associates performed a landscape analysis on in-space metal manufacturing in a habitable environment and interviewed and surveyed experts in the field. The overall finding was that multiple AM technologies could be adapted for use within an in-space environment, however, due to several considerations including power needs, post-processing requirements and feedstock challenges, it is believed that Directed Energy Deposition (DED) processes, such as Laser-Wire DED, would be the most suitable for an in-space metal AM capability.

c. Polymer Additive Manufacturing

Polymer additive manufacturing is already available on the ISS (Figure 10) through the Manufacturing Device (ManD), formerly the Additive Manufacturing Facility (AMF). The ManD is a commercially available 3D printer that is owned and operated by Redwire Space. To date, ManD has produced more than 115 end-use parts. The ManD has been used by government and private customers for parts that are used on the ISS as well as parts that have been returned to Earth. It is still operating on the ISS.

Figure 10: Astronauts show parts manufactured using the ManD platform on the ISS.

The FabLab – Printer Module payload in development for the ODME project has polymer FDM printing capabilities. ODME uses polymer printing to create substrates and dielectric layers in printed circuit boards. However, this payload could also be used to print additional polymer filaments and designs.

1.1.3. Recycling

Plastics and metals are used in space and can be recycled. A recent study of trash removed from the ISS during the return of the NG-19 resupply mission found that at least 15% of trash was made of thermoplastics and 29% was made from metals. NG-19 returned 4,636 kg of waste, with about 700 kg of plastics and 1350 kg of metal waste.

Plastics and metals recycling systems (Figure 11) both have the potential to greatly exceed cost savings beyond the costs of payload development and delivery by producing valuable feedstock in space and reducing launch burden associated with delivering parts to space. Both plastic and metal recycling have a great potential to produce parts for a variety of different performance requirements. Plastics can be recycled at lower temperatures but can degrade from recycling, so material and performance loss must be considered while designing plastic recycling systems. Metals must be processed at a higher temperature but bolster greater resilience against recycling processes if the alloys selected can be used in an as-built condition or only require minimal post-processing. Recycling systems can add value by saving mass and providing operational flexibility and sustainability.

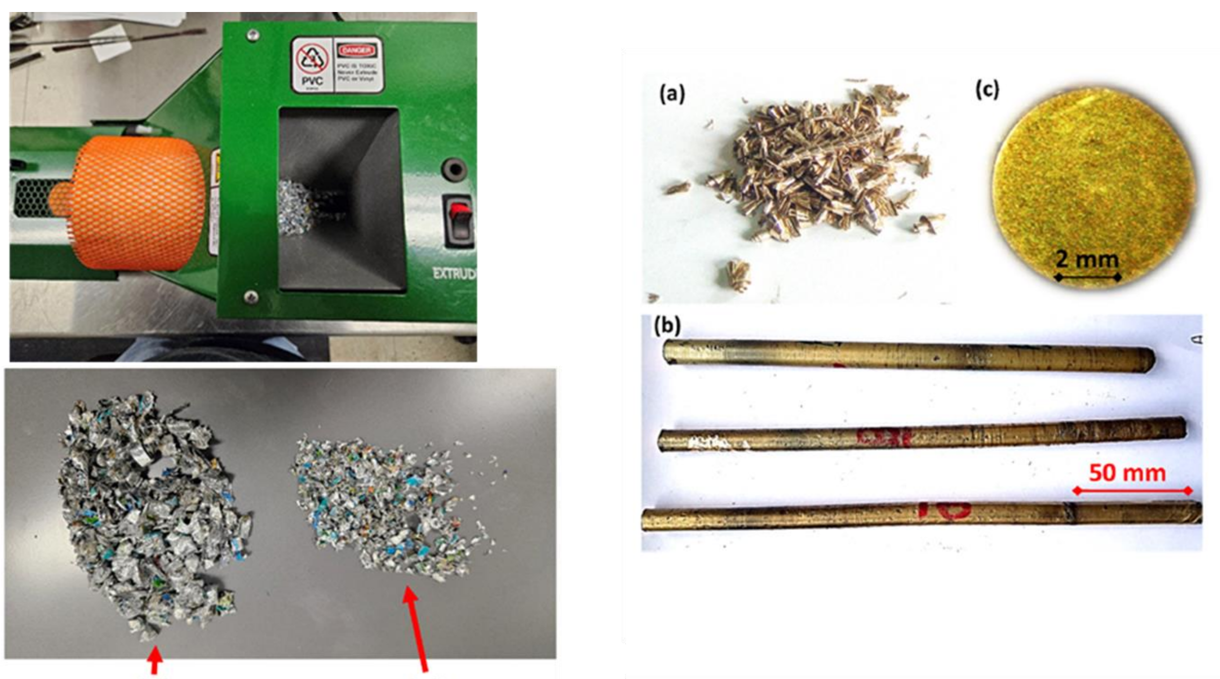


Figure 11: (left) Plastic bottles shredded for recycling at MSFC. (right) Metal chips recycled into brass shaft feedstock.

a. Plastic Recycling

The Refabricator was an ISS payload that was designed to recycle plastic into filament and 3D print new parts from that plastic. Unfortunately, the Refabricator was not able to complete the planned technology demonstration and was returned to Earth. An informal inspection of the hardware post-flight indicated that filament breakage and Foreign Object Debris (FOD) incursion were likely the driving factors preventing the payload from operating as planned. The lessons learned were documented and can be used to buy down risk for future plastic recycling endeavors.

The ISM portfolio is investigating recycling plastic material to reduce the quantity of material that must be sent to space and returned to Earth. A rack mounted plastics recycler and printer is expected to weigh approximately 100 – 200 kg. Therefore, a system capable of cleaning, grinding, and 3D printing plastics is expected to weigh much less than the plastic it can recycle, and such a system can potentially buy its way on to LEO mission as well as deep space missions. Internal Research and Development (IRaD) work is being pursued to develop in-space recycling of plastics and metals.

b. Metals Recycling

Metals recycling encompasses a variety of processing steps necessary to transform metals into useful products. Early metals recycling effort targets the wealth of metals already in orbit to save the launch mass penalty of ISM. Resident Space Objects (RSO) such as spent upper stages, ISS payloads and retired satellites, including massive structures made from aluminum and stainless steel. The early applications under development for materials recovered include generating feedstocks for additive manufacturing, electrical wire, and fuel rods for novel solid metal propellant thrusters.

These same recycling technologies have applications on the lunar surface. Metals on the lunar surface include derelict items and structures such as the Apollo lunar lander hardware, as well as the metals concentrated in the slag from molten lunar regolith electrolysis platforms designed to harvest oxygen. Iron and aluminum are two early base metals targeted for technology development, typically with the understanding that common alloying elements such as carbon to make steels and scandium and copper for high strength aluminums may need to be imported from Earth or alternate waste streams.

A standalone solid state extrusion system has demonstrated the capability to process aluminum-lithium alloys in the form of machining chips to generate solid wire sections which can then be further processed to create additive manufacturing wire feedstock. The recycled metal feedstock from this demonstration was then successfully printed with the MSFC cold metal transfer wire arc additive manufacturing system.

1.1.4. Verification and Qualification

Hardware produced in space would need to be qualified and certified to ensure they meet necessary requirements for safety and mission success in the harsh environment of space. Therefore, the ISM portfolio is interested in methods of ensuring the qualification of complex manufacturing processes, consistent production of high-quality parts, and methods of verification and validation of parts made in-space.

ICME technologies are of interest to ISM for their ability to capture material characterization in computational tools and apply those integrated models to rapid development of manufacturing processes and engineering applications.

Digital Twins (DT) are virtual representations of a physical system (Mingorance et al, 2023). In the case of materials engineering, they can model material Process-Structure-Property (PSP) relationships to enable rapid and custom design and manufacturing of new materials and processes for specialized uses and can greatly speed up the qualification and certification thereof for both new and legacy materials and processes. Beyond materials and process development, DTs can be utilized for higher level system applications, such as mission planning, maintenance, repair, and the upgrade of systems.

Nondestructive Evaluation (NDE), High-Throughput Testing, and Electrical Performance Validation are additional technologies that can be used to verify that materials, processes, and specific components made in space meet their design and performance requirements.

a. ICME and Digital Twins

Certification of complex and process-sensitive technologies like additive manufacturing remains an extraordinarily expensive and time-consuming challenge (Courtright et al, 2025) (Bevans et al, 2024) (Wells and West, 2018). The current experiment-intensive approach to process and material characterization for terrestrial applications will be heavily resource-constrained, if not impossible, for ISM applications. This reality necessitates a transition to a faster and cheaper integrated computational approach to manufactured product certification.

In line with this grand challenge, NASA has established a Space Technology Research Institute, funded by STMD, to advance this technology with the potential for revolutionary impact on future aerospace capabilities, including ISM. The institute, called the Institute for Model-based Qualification and Certification of Additive Manufacturing (IMQCAM) led by Carnegie Melon University and Johns Hopkins University, will further the advanced manufacturing community's understanding of materials PSP relationships for advanced manufacturing processes, including ISM, through advanced computational toolsets coupled with innovative experiments, laying the foundation for accelerated product certification (Space Technology Research Grants, 2023). The institute's goals include the development of a DT of metals additive manufacturing that comprises an integrated set of verified, experimentally validated, uncertainty-quantified computational models and simulation and design tools that will mirror the entire materials PSP and life linkage in metal additive manufacturing, starting with laser powder bed fusion of Ti-6Al-4V and Inconel 718. The project kicked off in December 2023, continuing for 5 years. NASA's BPS is also highly interested in applying ICME to augment microgravity materials science, enhancing understandings of fundamental physical phenomena while also accelerating science for space exploration (O'Connor et al, 2025) (National Academies of Sciences, 2023).

A proposal was submitted to the FY25 MSFC Digital Transformation (DTr) Proposals Call as a joint effort between the MSFC Digital Transformation Lead, the Advanced Manufacturing Principal Technologist for STMD, and the ISM Portfolio. This proposal focused on the broad development of DTr capabilities at MSFC with a focus on using the in-space welding DISCMAN orbital flight payload as a pathfinder for DTr development at MSFC.

b. NDE for Metals Manufacturing

Two main NDE techniques are currently being considered for Metals ISM. Extreme temperatures, high radiation, and near-vacuum conditions limit the use of many NDE techniques typically employed on Earth for space applications. Electromagnetic Acoustic Transducer (EMAT) is an ultrasonic testing system that offers distinct advantages in space (Figure 12). Its non-contact nature eliminates the need for coupling media and makes it suitable for harsh environments such as vacuum and extreme temperatures.

Welds and critical space hardware require inspections during fabrication and repair and periodically for maintenance and safety checks. EMATs can inspect electrically conductive materials without direct surface contact. Unlike conventional techniques, EMATs require minimal to no surface preparation before inspection, a significant advantage given the challenges of cleaning hardware surfaces in space environments.

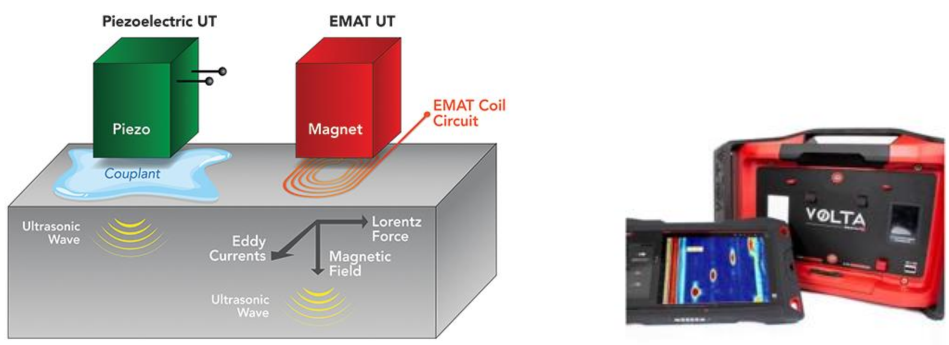


Figure 12:(left) Conventional UT and EMAT comparison (Innerspec, n.d.)(Poudel, 2022). (right) EMAT equipment at MSFC

MSFC has recently procured an EMAT system to develop an inspection technique for space applications. Ongoing research is focused on characterizing signal responses from weld defects in the space environment. An ISM-funded collaboration with Southwest Research Institute (SwRI) is currently underway to test and evaluate EMAT sensors for a wide range of temperature variations. SwRI is developing EMAT sensors capable of performing inspections over a temperature range of -130°C to +150°C. Additionally, there is in-house work, associated with the LASAR ECI, in MSFC's Damage Tolerance and Assessment Branch (EM21) to integrate the EMAT system into an automated robotic system. As space exploration expands, EMATs are expected to play an increasingly crucial role in ensuring the reliability and safety of space infrastructure.

Efforts are also underway to develop and implement in-situ monitoring capabilities for the Wire-Arc Additive Manufacturing (WAAM) Machine at MSFC. Due to its use of wire feedstock WAAM and Laser-Wire DED are better suited for ISM operations than powder feedstock processes. A melt pool thermal imaging tool will be implemented to measure melt pool temperatures during the WAAM process and in-situ solidification conditions to map microstructure and identify the onset and severity of defects such as cracks and pores. This work will directly benefit the development of Laser-Wire DED using equipment and lessons learned from ISM Laser Processing efforts. Other efforts include repurposing a laser powder bed fusion machine to develop the process and parameters for using Lunar and Martian regolith simulants as the feedstock. Thermal Tomography, Long Wave Infrared (LWIR), and Recoat Sensors will be installed to monitor the printing of these simulants. Future efforts include investigating and procuring in-situ monitoring systems for laser welding.

c. Electronics

Electronics inspection methods are primarily based on functional testing or high-resolution imaging. The ISM project team completed a technology search on the methods that could be used to verify printed electronics in space with yet2 in FY24. This identified three "highly interesting" technologies that could be integrated into the FabLab – Printer Module system. These technologies are hyperspectral light detection from Fraunhofer, laser profiler and confocal displacement sensor from Keyence, and a benchtop flying probe system from Astronics.

As we move towards detailed planning for the demonstration of printed electronics in the FabLab – Printer Module, a verification plan will be created for each test article. There is an opportunity to include verification in the FabLab – Printer Module project, if the budget and timeline allow for that development.

d. Destructive Testing

While every effort should be made to develop and qualify ISM processes in their applicable environments using nondestructive, computational, or machine-learning-driven methods, physical verification of mechanical performance is necessary. Mechanical testing methods ranging from tension and compression testing to high-throughput indentation-type testing must be applied to quantify manufactured part/process performance capabilities. Additionally, optical microscopy must be applied to produce a suitable snapshot of a given part or process's capability at any point during the development cycle. These tests will need to conform to the environments present in space, be operable with little-to-no human interaction, utilize minimal resources (e.g. material, power, controlled environment volume, etc.), and enable the production of sufficient experimental data for qualification. To achieve this, the processes of sample preparation, testing, data analysis, and storage should be designed to perform in a closed-loop automated fashion. Mechanical test data gathered should be applied in conjunction with nondestructive test data, optical imaging data, and computational data to inform and validate machine-learning-driven models. This must be done, in addition to defining adequate safety factors for performance, to mitigate challenges associated with the discrepancy between the 100s to 1000s of standardized tests performed for terrestrial process qualification and the far lower number of standardized and non-standardized tests that will be fiscally possible for space-based process qualification.

The current interest of the ISM portfolio to address the need for destructive testing in space is focused on high-throughput indentation-type tests and optical microscopy. These methods both require the ability to polish the surface of a sample, typically using an abrasive, laser, or chemical etchant. This will result in the generation of offal or fumes that must be captured to avoid contamination of surrounding objects. A ground-based demonstration of a closed-loop microindentation and microscopy system is being considered as a focus area for the In-Space Manufacturing Advancement Center (ISMAC) currently being developed by the MSFC Materials and Processes Laboratory.

1.2. Value Proposition

All technologies must be evaluated by their potential for adding value in the foreseeable future. ISM technologies add value by 1) improving the packing efficiency in a fairing, 2) providing operational flexibility and repair, 3) reducing the launched mass of in-space systems, 4) enabling a sustained presence on the Moon or Mars by manufacturing with feed stock produced with in-situ resource utilization, and 5) enabling better processes (cost or quality) than ground-based alternatives.

A technology's ability to add value is discounted by 1) the time between now and when the technology could begin to add value, 2) the probability that missions that could use the technology occur, 3) the probability that other technologies that this technology is dependent upon are available when they are needed, and 4) the probability that the technology can find funding for flight. Unfortunately, we cannot know everything required to properly discount the value of the technologies, but assessments are still made to guide ISM's portfolio decisions. Below, Table 2 shows how existing and past ISM projects align with the four ISM strategic pursuit areas.

Table 2: Existing and past ISM project alignment with ISM strategy.

Project Name	**ISM Strategic Pursuit Area**	**Years Active**	**Project Note**
ODME*	Electronics & Semiconductors	2020-present	Electronics printing, Advanced Toolplate multitool system, ISS demonstration with FabLab – Printer Module. FabLab payload development, joint with ODMM, started in 2018.
LASAR	Laser Processing & Additive Manufacturing / Verification and Qualification	2024-2026	Demonstration of autonomous robotic laser welding and repair in a simulated lunar thermal vacuum environment. Repair validated with a nondestructive evaluation technique that's conducive to the Lunar environment.
DARPA NOM4D Laser Bending	Laser Processing & Additive Manufacturing	2024-2025	Maturation of laser forming of relevant aerospace alloys in thermal vacuum environments. Experimental data used to inform ICME models.
In-Space Welding TIP1	Laser Processing & Additive Manufacturing	2023	Flat floor assembly and parabolic flight laser welding demonstrations
In-Space Welding TIP2	Laser Processing & Additive Manufacturing	2024	Suborbital laser welding payload development

DISCMAN STMD Center Call	Laser Processing & Additive Manufacturing	2025-2027	In-space LBW under vacuum in a highly instrumented test setup for ICME validation datasets and informing process parameters for ISW demonstrations
ODMM/FabLab	Metals & Additive Manufacturing	2018 - 2023	The ODMM FabLab system originated under a BAA Phase A in 2018 under Advanced Exploration Systems (AES). In October of 2018, the project was transferred to Game Changing Development Program (GCD) as the ISM Project. In October of 2020, the ISM project was divided into three to create the ISM portfolio: ODMM, ODME, and Recycling and Reuse (R&R). In May of 2023 the project was given direction to close out all work related to metals-only additive manufacturing.
RnR/ODMM	Recycling	2020-2023	At R&R closure in FY22, ODMM (as "On Demand Manufacturing of Multimaterials") absorbed the relevant ongoing contracts and carried them to closure. All R&R contracts were fully closed in January 2023.
ODMM/Vulcan	Laser Processing & Additive Manufacturing	2020-2022	WAAM process. In part due to significant budget cuts in Q1 and further cuts in Q2 of FY22, during a TAPR on February 10th, 2022, GCD decided to discontinue the Vulcan WAAM development.
Refabricator	Recycling	2015 - 2021	SBIR contract with Tethers Unlimited. ISS Payload for printing with recycled ULTEM filament. Payload installed on ISS in 2019 and returned from the ISS in 2024. Final report issued in 2021.

* The umbrella of the ODME project supports several smaller related projects which are being monitored due to their association with the project. However, they are under the budget threshold required for direct ISM project management and/or primarily conducted and managed by a partner. These projects include SBIRs, EPSCoRs, CANs, CIF/TIPs, Flight Opportunities, NASA Spark Tech Searches, In Space Production Applications (InSPA) semiconductor funding, and Mars Campaign Office funding for Logistics Reduction. All these projects are related to additively manufactured electronics and/or semiconductors. While not included in the GCD

ODME FY25 project scope, these projects enhance the technology development efforts of the ODME project team and facilitate future opportunities.

2. Technology Overview

As described in the Portfolio Overview (Figure 1), ISM develops technologies through several stages of development. This starts with ground testing, continues with parabolic flight or suborbital zero gravity testing, and culminates in the goal of orbital and/or lunar surface demonstrations. The status of ISM Technologies is shown in Table 3: ISM Technology Summary3.

Table 3: ISM Technology Summary

Demo Platform	Technology	TRL Est.†	Type	Value Proposition*					Operational Power (W)**	Architectures
				Fairing Packaging	Operational Flexibility	Mass Reduction	Manufacturing with ISRU	Superior to 1G processes		
FabLab – Printer Module	Biosensing Electronics	4	Electronics		+				500	ISS, Artemis, M2M
	Printed Sensors	4	Electronics		+				500	ISS, Artemis, M2M
	Power Harvesting Electronics	3	Electronics	+	+	+	+		500	ISS, Artemis, M2M
	Energy Storage	3	Electronics	+	+	+	+		500	ISS, Artemis, M2M
	Multilayer Electronics	4	Electronics		+				500	ISS, Artemis, M2M
TBD	LASED Thin Film Electronics	3	Electronics		+	+	+		500	ISS, Artemis, M2M
TBD	EHD Inkjet, Memory Chips	3	Electronics		+			+	500	ISS, Artemis, M2M
	EHD Inkjet, Semiconductors	3	Electronics		+			+	500	ISS, Artemis, M2M
TBD	CVD Crystal Growth	4	Electronics					+	250	ISS, Artemis, M2M
TBD	Plastic Shredder	3	Plastics		+	+	+		150	ISS, Artemis, M2M
	Regrind Preconditioner	2	Plastics		+	+	+		200	ISS, Artemis, M2M
	Regrind Printer	2	Plastics		+	+			200	ISS, Artemis, M2M
TBD	Metal Shredder & Wire Extruder Recycling	2	Metal		+	+	+		1000	ISS, Artemis, M2M
TBD	Laser Welding	4	Metal	+	+	+	+		3000	Artemis, M2M
	Laser Bending	3	Metal	+	+	+	+		1000	Artemis, M2M
	Laser Additive	5	Metal	+	+	+	+		3000	Artemis, M2M

	Laser Ablation	3	Metal		+				300	Artemis, M2M
	Laser Cutting	3	Metal		+	+			3000	Artemis, M2M
TBD	Metal Additive Manufacturing	3	Metal	+	+	+	+		2000	ISS, Artemis, M2M

† The TRL estimates are not official assessments, but rather a high-level estimate.

*Value Proposition is assessed if likely to have a positive effect (+).

**Power values are best estimates from available information.

All processes require verification and validation technology development as well, and those are discussed in Section 1.1.4 Verification and Qualification.

3. Organizational Structure

The current ISM Portfolio Office structure (Figure 13) is depicted below. The structure will be updated as approved projects are added to the portfolio. Currently, the *Electronics & Semiconductors* and *Laser Processing & Additive Manufacturing* pursuit areas include Principal Investigators (PI) because these pursuit areas include multiple funded projects exceeding $1M in annual funding. The other two pursuit areas fall under the ISM New Starts category in the ISM organizational structure and do not yet require a dedicated PI. A primary goal of the ISM portfolio is to grow each of these four pursuit areas to a size sufficient to achieve our strategic goals. As this growth is realized, a hierarchical project management structure may be employed to include Pursuit Managers as well as PI for each pursuit area. The chart in Figure 13 shows only the core leadership team and there are many more team members involved in planning and implementing the ISM vision.

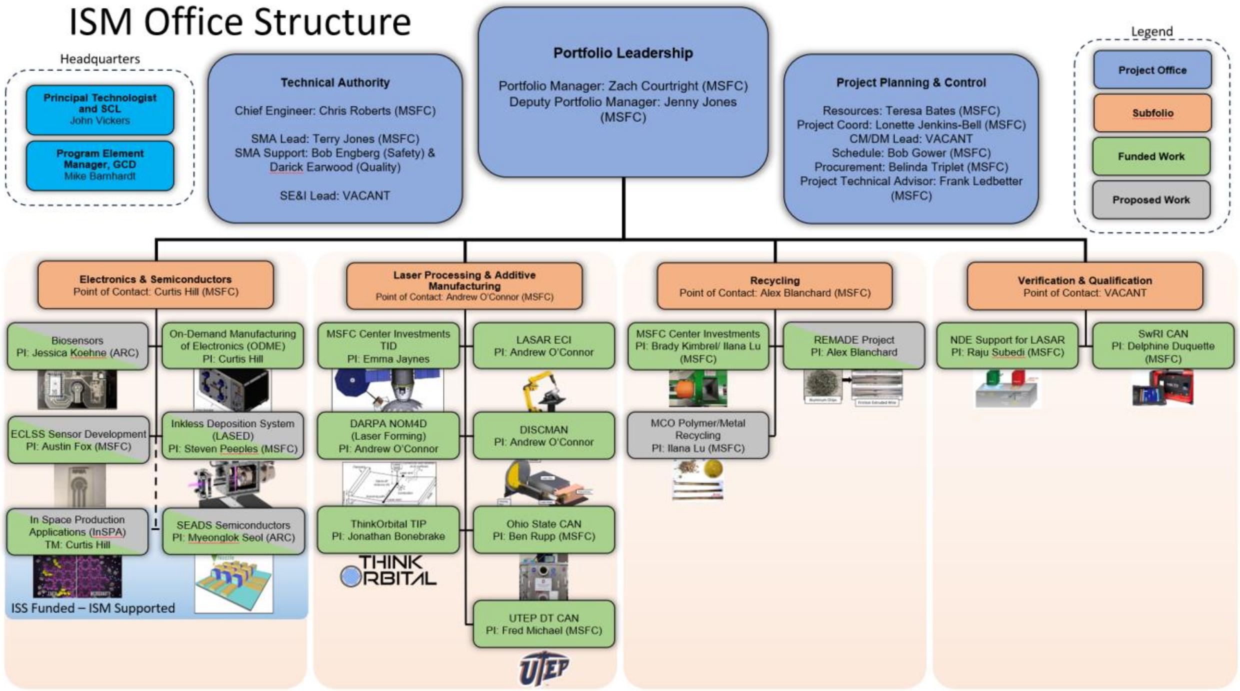


Figure 13: ISM Org Chart

4. Management and Technical Approach

ISM projects are managed by the ISM Portfolio Office when the projects exceed $500k/year in total funding. Projects that are below this threshold are monitored by the ISM Portfolio Office and incorporated in overall strategic planning, but the PIs manage the projects themselves.

The ISM projects funded by GCD follow NASA Procedural Requirements 7120.8 as Research and Technology focused efforts. The LASRA ECI and DARPA NOM4D Laser Bending projects follow an adaptive agile approach to project management enabling autonomy while maintaining accountability with Project Control Boards and Milestone Tracking.

Project key and control milestones, and the schedule to meet those milestones, are monitored by the ISM Portfolio Office to determine how and when to take action to ensure milestones are met within schedule. The ODME project also has an Integrated Master Schedule which is managed by the payload developer. The project receives by-weekly updates to the schedule and reviews it to ensure that progress remains on track.

All ISM projects work towards rapidly raising TRL and reaching flight readiness. ISM works with Flight Opportunities and STMD stakeholders to secure parabolic flight and suborbital payload opportunities.

5. Roles and Responsibilities

The Portfolio Manager's responsibilities are to: 1) identify funding opportunities, 2) communicate funding opportunities to the partners at MSFC and in industry, 3) manage the submission of proposals to funding opportunities, 4) provide technical advice to the PIs, 5) manage stakeholders, 6) manage budget, 7) manage schedule, 8) assist the PIs in fulfilling their responsibilities as appropriate, and 9) act as the decision-making authority for ISM projects. The Deputy Portfolio Manager's responsibility is to assist the Portfolio Manager with their responsibilities and to report to the Portfolio Manager. The ISM Chief Engineer is primarily responsible for organizing Technical Maturation Plans and acting as the Technical Authority for ISM projects. ISM Principal Investigators are assigned to oversee the fulfillment of technical goals, objectives, and Key Performance Parameters for the ISM project(s) falling within their purview.

6. Requirements Management

The ISM Portfolio will use the requirements management process defined in the NASA Systems Engineering Handbook (NASA SP-2016-6105) to:

- Identify, control, decompose, and allocate requirements across all levels of the WBS.
- Provide bidirectional traceability.
- Manage the changes to established requirement baselines over the life cycle of the system products.

Requirements management activities apply to the management of all stakeholder expectations, customer requirements, and technical product requirements down to the lowest level product component requirements. This includes physical, functional, and operational requirements, including those that result from interfaces between systems in question and other external entities and environments.

7. Board Structures

The ISM Portfolio will control project documentation, resources, and requirements by using a joint Project Control Board (PCB) and Engineering Control Board (ECB). The PCB consists of the Project Manager (Chair), Deputy Project Manager, Chief Engineer, Risk Manager, Safety and Mission Assurance Office representative, and Project Element Lead. The ECB is chaired by the

Chief Engineer with Safety and Mission Assurance and subject matter expert support. The project manager and PI may also serve as voting members. The PCB provides overall project control and configuration management and the same membership serves as the Risk Management Board (RMB). The ISM PCB and ECB will be the formal decision analysis process for the Systems Engineering Process and will be the official body and source of documentation for any approved changes to requirements, schedule changes, changes affecting resources, or other changes affecting the achievement of the project's objectives. The PCB meetings will be called at the discretion of the Project Manager who serves as the ISM PCB Chair. The PCB and ERB Chairs reserves the right to process changes out-of-board when appropriate. All formal documents for ISM will be stored at MSFC on the ISM SharePoint site.

8. Strategic Planning

The ISM Portfolio leadership team will use the following informal strategic planning process to create the vision and plan for the development of ISM:

i. Evaluate the current state of the technology and potential customer needs.
ii. Determine how the technology needs to mature to support customer needs.
iii. Develop a Technology Maturation Plan (TMP) to meet these needs.
iv. Execute the TMP.
v. Revise the TMP as needed.

9. Configuration Control

The ISM Portfolio will control project documentation, resources, and requirements through PCB and ECB. The PCB provides overall project control and configuration management. The PCB also serves as the RMB for the project. The ISM Portfolio PCB is the formal decision authority for the project and will serve as the official body for the approval of baseline of documentation and approval of any changes to the baselines (requirements, schedules, allocation/expenditure of resources, and any other end item requiring project control). The PCB meetings will be called at the discretion of the Portfolio Manager who serves as the ISM PCB Chair. The PCB Chair reserves the right to process changes out-of-board when appropriate. All formal/baselined documents for ISM will be stored at MSFC on the ISM SharePoint site.

10. Technology Maturation Plans

There are several critical technologies and gap areas that must be addressed before ISM can be effectively infused into NASA missions and beyond. The purpose of the TMPs is to provide an integrated plan for the systematic maturation of critical technologies that do not currently meet specific Technology Readiness Levels (TRLs). TMPs for these critical elements of the ISM portfolio have been developed and will continue to be refined as the portfolio moves forward.

11. Systems Engineering Management Plan

The project manager or their systems engineering designee will perform the technical insight and oversight activities consistent with the NASA Systems Engineering Handbook and NPR 7123.1B for each project within the ISM portfolio. The project technical team will plan, schedule, and participate in the reviews necessary to assure project workflow, processes, and technical product performance requirements are clear, well defined, and documented. Each project will perform appropriate life-cycle reviews as required by Marshall Space Flight Center governing project management systems engineering practices and requirements. These reviews will provide a periodic assessment of the project's technical and programmatic status at key points in the life cycle. If required by the Program Office, a more detailed approach to systems engineering will be documented in a separate Systems Engineering Management Plan.

12. Safety and Mission Assurance Plan

Safety and Mission Assurance (S&MA) Plans will be developed for approved ISM Projects as required. The S&MA Plan shall demonstrate Safety and Mission Assurance is incorporated into all phases of the Project lifecycle. The S&MA Plan shall document the key activities/tasks in each discipline (System Safety, Reliability and Maintainability, Quality Assurance, and Software Assurance) supported by additional process details such as flow diagrams (where applicable), analysis tools/technologies verification and validations system/tools to monitor the effectiveness and timely response of the product assurance system.

13. Risk Management Plan

The ISM project will use Continuous Risk Management (CRM) processes for identifying, analyzing, mitigating, monitoring, and tracking risks throughout the project lifecycle. Decisions shall be made based on CRM principles, processes, and techniques. Risk is characterized by the combination of the probability that a project or activity will experience an undesired event and the impact of the undesired event, were it to occur. Such an event may impact project cost, schedule, technical, and/or safety.

The ISM Portfolio uses a risk database to capture newly identified risks, maintain existing risks and assessment rankings, and to manage changes in status of the risks and respective mitigation plans. This risk database is managed and controlled by the ISM RMB.

14. Education and Public Outreach Plan

NASA is dedicated to STEM education and public outreach to share the NASA vision and message. NASA Programs are required to report EPO metrics to their stakeholders.

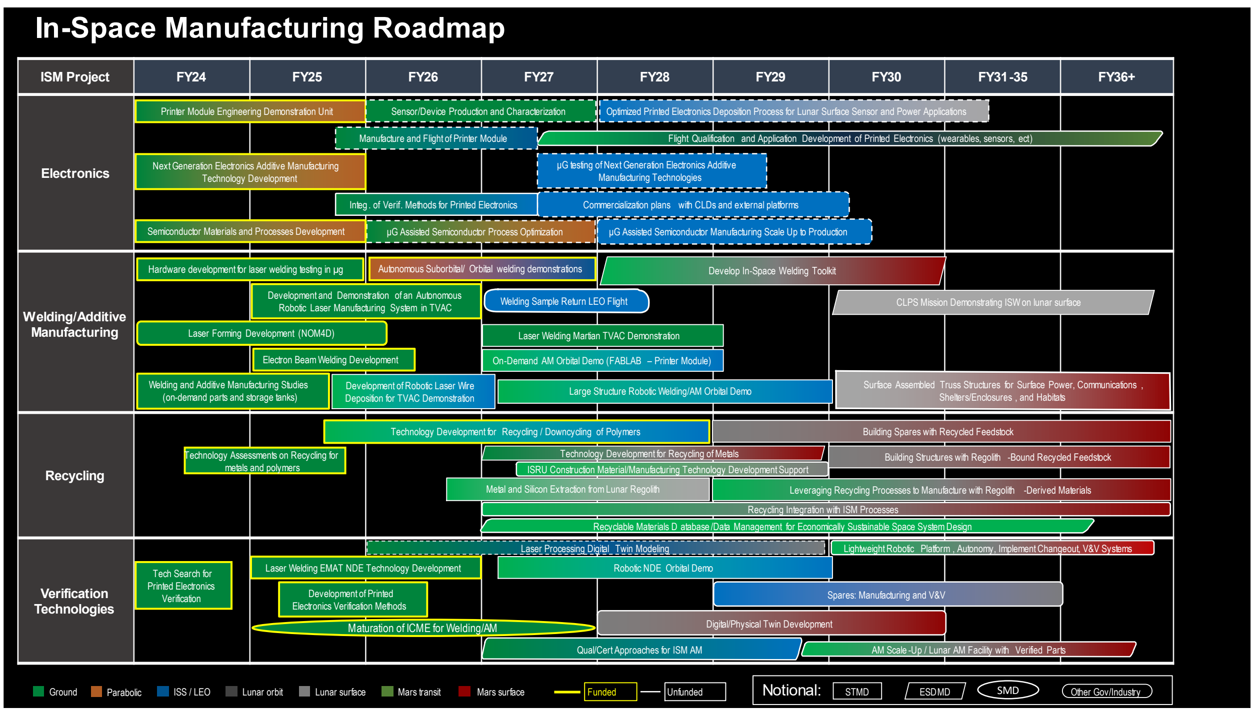
The ISM Portfolio will support stakeholder Program’s education and public outreach activities by creating a NASA Fact Sheet, providing relevant and hi-resolution images and video when available, and by assisting the Program Communication Managers in the creation of handouts, exhibits, video products, and news releases. The ISM Portfolio will report to the Programs quarterly on EPO activities which will include (at a minimum): student support, conferences attended, papers published, and events held.

15. Technology Infusion Plan

The ISM Portfolio is developing technologies that will have infusion points in many different NASA requirements/missions as well as numerous applications on Earth. The development of manufacturing technologies for many applications on the surface of the moon, during Mars transit, and on the surface of Mars would significantly reduce mission risk and logistical requirements while enabling Earth independent human spaceflight. Also, the use of these technologies in remote, military, or disaster-stricken areas on Earth could revolutionize how we deal with problems here at home.

16. Appendix

16.1. ISM Roadmap



Year	Projected Funding Needs Based on ISM Roadmap
FY24	$10M
FY25	$11.5M
FY26	$16M
FY27	$30M

FY28	$50M
FY29	$80M
FY30	$50M
FY31-35	$200M
FY36+	TBD => Commercialization

16.2. Primary STMD Identified Technology Shortfalls

ID	Shortfall Title
1486	In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction

Description

This shortfall addresses the need to assess and qualify products that are manufactured, assembled, and constructed in space to ensure performance over the expected lifetime of the final component. This may be accomplished via in situ non-destructive evaluation (NDE), in situ modeling and simulation to predict the final part on the microstructure-performance paradigm, or a combination of both. Key challenges to close this shortfall include: a) NDE techniques suitable for use in the space environment; b) non-contact NDE techniques; c) low size, weight, and power NDE techniques; d) modeling and automated data processing to determine optimized inspection for autonomous in-space implementation and guide data-informed decisions, multiscale/multi-fidelity modeling of manufacturing processes, including thermophysical properties, solidification microstructures, mesoscale and macroscale properties, and component-level performance; e) integrated computational materials engineering (ICME) to build a digital twin of in-space manufacturing processes; f) application of simulations using onboard computing to predict part/process performance and to qualify joints/parts with minimal or no inspection; g) uncertainty quantification of joints/part properties and performance predictions; h) In-situ monitoring or inspection. NDE techniques will be required for all advanced processes developed for space manufacturing/construction, including but not limited to ISS, Gateway, a free flyer, depot, and future surface habitation. Without the parallel development of NDE techniques along with manufacturing process development, a sustainable architecture cannot be achieved. Anything produced in space needs to inspected to verify part quality before use; therefore, NDE needs to be adapted for in-space use.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials [robotic assembly of]
MANU-1401: Autonomy and robotics for horizontal assembly [welding of]
MANU-646, MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing
MANU-658: Accelerated Certification and Analysis Approaches
MANU-653: Space-Based Verification and Validation
AV-526: High Performance Spaceflight Computing (HPSC) Single Board Computer (SBC)

Metrics

- Modeling and simulation validation % error
- Detectable defects (size, morphology, composition, severity, etc..) via *in situ* NDE techniques, including real-time
- Uncertainty quantification (& reduction) of property & performance predictions of welds

ID	Shortfall Title
1485	In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks

Description

To support a thriving human presence and exploration throughout the solar system, in-space manufacturing is an essential next step as the space ecosystem undergoes rapid expansion. An on-demand and in-situ approach to manufacturing, maintenance, repair, and logistics will lead to the development of capable and affordable space architecture models. Both a sustained lunar presence and deep space exploration missions would benefit from the capability and flexibility to manufacture parts on demand due to long durations, limited resupply options, communication delays, and the inability to fully predict mission needs in the event of an unexpected failure. Currently, the capability to manufacture new products, spare parts, replacement units, or specialty tools in-situ does not exist beyond small demonstration components fabricated from polymers. Multi-materials printing, including but not limited to metals, electronics, and polymers is necessary to provide a manufacturing capability that can address needed spare parts and repair for Low Earth Orbit destinations, Gateway, lunar surface missions, and deep space exploration missions. This multifunctional manufacturing capability needs to be tailored to the space environment and may leverage this environment to produce high-quality products. Spare electronic parts include sensors, such as those used for Environmental Control and Life Support Systems (ECLSS), small electronic devices, and supporting components for energy and power applications. Metal and polymer parts include outfitting, structural components, basic tools, materials for daily crew use, and custom-designed parts for mission-critical needs.

Related Shortfalls

MANU-642, 952: On-demand manufacturing of metals, electronic components, recycling and reuse
MANU-643, 801: ISRU-derived materials for feedstocks (e.g.., Al, Si) – lunar and Martian
MANU-644: Lunar surface manufacturing and outfitting with metals, polymers, and composites
MANU-646, 722, 855: ISAM - welding in space, recycling and reuse
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1342: Recycling of Orbital and Surface Debris from Active Debris Remediation for advanced manufacturing.
MANU-1343: Recycling/Reuse: On-surface Resource Utilization of Hardware, Trash, and ISRU Byproducts for surface manufacturing
MANU-1066: Manufacturing approaches to support habitat outfitting
MANU-1180: High performance materials tailored for in-space applications
MANU-1095: Ability to robotically construct lunar surface landing/launch pads and berms using in-situ regolith materials.

Metrics

- Metal feedstock options for 3D printing of spare parts on-demand.
- 20% of spare parts in space systems can be produced by ISM platforms and integrated into system
- Majority of systems designed for maintainability and accessibility to facilitate integration of spares produced on-demand rather than orbital replacement unit changeout.

ID	Shortfall Title
1487	In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction

Description

Welding is a critical manufacturing technology used in more than 70% of finished goods on Earth. In-space welding (ISW) will be important to achieving NASA's goals for returning to the Moon and establishing a sustainable presence in space. These goals will be achieved in the form of infrastructure manufacturing, assembly, and repair. ISW is also a critically enabling technology for In-Space Servicing, Assembly, and Manufacturing (ISAM). This is especially true for large structures relevant to science and communications that cannot be contained within a single rocket fairing or would otherwise need complicated packaging and deployment mechanisms. Finally, the 2023 Biological and Physical Sciences (BPS) Decadal Survey specifically highlighted ISW as a focus area in need of further basic scientific understanding as the community aims to implement the technology in future NASA missions. This capability will also allow for the decoupling of launch design constraints from space structures by enabling the shipment of raw materials (wire, plates, and other feedstock) rather than finished components to space.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials [robotic assembly of]
MANU-1401: Autonomy and robotics for horizontal assembly [welding of]
MANU-646, MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing

Metrics

- Models guide manufacturing and processing in the microgravity environment
- Reliable and efficient in-space welding tools
- Models enable adjustment of process parameters for environment based on process signals and observations
- Available geometries and build rate of large-scale AM are suitable for Lunar structures

ID	Shortfall Title
1489	In-Space and On-Surface Manufacturing from Recycled and Reused Materials and Components

Description

NASA estimates that there is about 500,000 pounds of waste on the Moon left behind from previous missions. A technology driven recycle and reuse approach is necessary otherwise waste will continue to accumulate resulting in logistics problems, physical dangers, and an environmental disaster. Since launching materials from Earth is costly, the capability to recycle and reuse waste materials greatly simplifies logistics, reduces mission cost and risk, and minimizes the disturbance to local environments by reducing the need for long-term waste storage. This capability also meets the objective of developing sustainable architecture for exploration. Technologies that convert waste materials into feedstock for in-space manufacturing directly address these objectives by generating customizable, high-utility products from waste resources. Potential waste materials for this activity include but are not limited to logistics packaging, end-of-life structures, surface or orbital debris, and in-situ resource utilization (ISRU) products, where applicable. A waste management process that inventories, sorts, cleans, and separates materials into a relatively pure form is essential. Recycling technologies that convert materials into feedstocks for processes, such as joining and Additive Manufacturing (AM), and reuse technologies that are extensible to in-situ resource processing must be developed and will likely be material dependent. Similarly, in-space manufacturing methods, such as bound metal deposition, fused deposition modeling, and wire-fed AM, will need to be tailored to the available recycled or ISRU material feedstocks. Safety hazard reduction within the recycling process must be undertaken if the mission architecture would require use in a habitable environment. A robust and dependable recycling and reuse process coupled with in-space manufacturing would be beneficial for LEO destinations, Gateway, lunar surface missions, and long-duration space exploration missions.

SUPPORTS M2M Objective OP-12: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.

Related Shortfalls

MANU-642, MANU-952: On-demand manufacturing of metals, electronic components, recycling and reuse
MANU-643, MANU-801: ISRU-derived materials for feedstocks (e.g.., Al, Si) – lunar and Martian
MANU-644: Lunar surface manufacturing and outfitting with metals, polymers, and composites
MANU-646, MANU-722, MANU-855: ISAM - welding in space, recycling and reuse
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1342: Recycling of Orbital and Surface Debris from Active Debris Remediation for advanced manufacturing.
MANU-1343: Recycling/Reuse: On-surface Resource Utilization of Hardware, Trash, and ISRU Byproducts for surface manufacturing
MANU-1066: Manufacturing approaches to support habitat outfitting
MANU-1180: High performance materials tailored for in-space applications
MANU-1095: Ability to robotically construct lunar surface landing/launch pads and berms using in-situ regolith materials.

Metrics

- Materials designed for reuse must meet application requirements such as flammability, toxicity, and off gassing.
- Materials designed for reuse must be recyclable at least five times with minimal degradation.
- Maximum instantaneous power required to repurpose the material must be less than 2kW.

16.3. Full ISM Relevant STMD Technology Shortfall List

Elements	Technology Areas	Shortfall #'s
ODME	Advanced Habitation Systems, Advanced Manufacturing, Autonomous Systems & Robotics, Avionics, ECO, Power, Sensors & Inst., Small Spacecraft, Surface Sys, Thermal	1519, 1524, 1485, 1548, 1551, 1552, 1553, 1555, 1480, 1593, 1596, 1627, 1598, 1599, 1603, 1432, 1433, 1611, 1612, 1615, 1617, 1622
In-Space Welding	Advanced Habitation Systems, Advanced Manufacturing, Cryo Fluid Mgmt., ISAM & RPOC,. Surface Systems,	1523, 1487, 879, 755, 513, 1612, 1615, 1617
Qualification & Certification	Advanced Manufacturing	1486, 1492, 1493, 1494
Additive Manufacturing	Advanced Habitation Systems, Advanced Manufacturing, Avionics, ECO, Power, Surface Systems, Thermal.	1523, 1485, 1488 1489 1490, 1491, 1495, 1496, 1555, 1480, 1593, 1615, 1617, 1622

ISRU and Other	**Advanced Manufacturing, ISRU, Surface sys.,**	**1485, 1489, 1490, 1582, 1584, 1615, 1617**

16.4. ODME Prioritized STMD Technology Shortfalls

Integrated Rank	Average Integrated Score	Shortfall ID	Capability Category	ODME relevance / technology maturation
1	8.1035	1618: Survive and operate through the lunar night	Thermal Management Systems	Power scavenging (thermoelectric)
2	7.6118	1596: High Power Energy Generation on Moon and Mars Surfaces	Power	Power scavenging (thermoelectric)
3	7.4345	1554: High Performance Onboard Computing to Enable Increasingly Complex Operations	Avionics	Wide bandgap semiconductors
4	7.3831	1557: Position, Navigation, and Timing (PNT) for In- Orbit and Surface Applications	Communication & Navigation	Microelectronics, printed antennas, RFID (REALM)
5	7.2076	1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation	Autonomous Systems & Robotics	Wide bandgap semiconductors
6	7.1961	1552: Extreme Environment Avionics	Avionics	Wide bandgap semiconductors
7	7.1679	1519: Environmental Monitoring for Habitation	Advanced Habitat Systems	Wide range of environment on-demand sensors
16	6.9478	1526: Radiation Monitoring and Modeling (Crew and Habitat)	Advanced Habitat Systems	Printed radiation sensors (GT project joint w/MMPACT)
32	6.4985	1592: High Power, Long Distance Energy Transmission Across Distributed Surface Assets	Power	Lunar printed cables and interconnects. (Proposed previously with Astrobotic in Tipping Point)
57	6.1356	1595: Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars	Power	Printed supercapacitors & fuel cells (previous initial research with Cal Tech & Georgia Tech)
67	5.9391	Quantum sensors (that use atoms, ions, and spins)	Sensors & Instruments	New diamond semiconductors (wide bandgap)
73	5.8983	1598: Quantum Sensors That Use Photons	Sensors & Instruments	Doped optical fibers manufactured in space
92	5.5088	1485: In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks	Advanced Manufacturing	All of ODME advanced deposition systems for microelectronics, sensors, and semiconductors

16.5. ISM Alignment with LEO Microgravity Strategy

Focus	Goal
Space and Earth Science	**Leverage opportunities provided by human-enabled platforms to address high priority space and Earth science questions.**
SES-1	Perform science and technology demonstration projects (in space and Earth science) best accomplished by leveraging the capabilities of human-enabled platforms.
Exploration Technology	**Leverage the unique environment of low Earth orbit to advance technologies that enable future human exploration on and around the Moon and Mars.**
ET-2	Test and demonstrate the performance of materials through long duration exposure to the space environment and inform materials selections for future missions.
ET-3	Demonstrate advanced manufacturing techniques and non-destructive evaluation in microgravity.

ET-4	Demonstrate in-space assembly of structures to enable increasingly complex mission concepts.
Transportation and Habitation	**Enable and leverage commercial low Earth Orbit infrastructure to support NASA's mission.**
THI-1	Enable the commercial sector to build and deliver safe, reliable, and sustainable destinations in low Earth orbit that support NASA activities.
THI-2	Enable the use of sustainable, commercially-owned-and-operated cargo and crew transportation capabilities.
National Research and Development	**Enable infrastructure to support research and development in low Earth orbit to provide benefits to the nation.**
RD-1	Facilitate broad use of commercial low Earth orbit destinations for government-sponsored microgravity research and development.
RD-2	Promote in-space applications for terrestrial use that leverage the unique environment of low Earth orbit.
Operations	**Conduct human missions in low Earth orbit that provide the capability for the U.S. government to develop and maintain proficiency in operating in the microgravity environment to support NASA's human deep space exploration missions, which will operate for extended durations in microgravity.**
OPS-2	Enable capability for U.S. ground-based workforce to develop skills and maintain proficiency in designing systems, preparing science for use in microgravity, and implementing successful deep space exploration missions.
OPS-3	Enable and organize joint missions with international partners to maintain proficiency in joint mission planning and integration.
Workforce Development and STEM Engagement	**Engage, develop, and retain the U.S. workforce needed to conduct future NASA missions by leveraging authentic connections to human space operations in low Earth orbit.**
WSE-2	Provide opportunities for post-secondary students to conduct research and technology development in microgravity.

16.6. ISM Alignment with Moon to Mars Strategy

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