Made in Space: Manufacturing in Microgravity

Companion Lesson X-STEM All Access Episode "Manufacturing in Space"

Grade Band: Middle School - High School	**Topic**: Materials Science and Engineering

Brief Lesson Description: Students investigate how space-based manufacturing in microgravity improves material quality.

Performance Expectation(s):
MS-PS1-1: Develop models to describe the atomic composition of simple molecules and extended structures.
HS-PS2-6: Communicate scientific and technical information about why the molecular-level structure is important in the functioning of materials.
MS-ETS1-1 / HS-ETS1-2: Define a design problem that can be solved through engineering.

Specific Learning Outcomes:
Students will be able to:
- develop and refine visual or physical models to describe how crystal structures form at the atomic or molecular level, and how those structures are influenced by physical conditions like gravity or heat distribution.
- communicate scientific information about how microgravity reduces physical forces (e.g., convection, sedimentation) that cause material defects, leading to more consistent molecular-level structures that improve the performance of high-tech materials such as semiconductors.
- define and explore a space-based innovation by identifying a material or product whose performance depends on structural consistency, then propose a solution for a material or product that leverages the unique advantages of microgravity manufacturing and present their idea using an annotated model, diagram, or conceptual design that addresses key requirements and constraints.

Narrative / Background Information

As technology advances, the demand for higher-performing, more reliable systems pushes us to explore new frontiers—not just in innovation, but in location. In the microgravity environment of space, manufacturing processes can achieve a level of consistency and precision that is difficult to replicate on Earth. This lesson immerses students in the science behind space-based manufacturing, highlighting how microgravity reduces defects and improves quality in materials like semiconductors. By investigating how physical phenomena impact manufacturing and exploring real-world research from scientists like Dr. Jessica Frick, students discover how better materials lead to better performance. Through hands-on exploration and design thinking, they take on the role of engineers solving 21st-century challenges—connecting Earth-based needs with space-enabled solutions.

Prior Student Knowledge: Before engaging in this lesson, students should be familiar with:
- *Basic Particle Behavior*: Understanding that matter is made of atoms and molecules that behave differently under varying temperatures and forces.
- *States of Matter & Density*: Familiarity with solids, liquids, and gases, including how temperature and gravity affect behavior (e.g., convection, sedimentation).
- *Heat Transfer Concepts*: General understanding of conduction, convection, and radiation as mechanisms of thermal energy movement.
- *Structure Determines Function*: Prior exposure to the idea that the way something is built at a small scale (e.g., molecules, crystals) affects its properties and performance.
- *Purpose of Manufacturing*: Broad awareness that many products are made using engineered processes that aim for precision, reliability, and consistency.
- *Role of Gravity*: Basic understanding of gravity as a force acting on mass and influencing physical systems on Earth and in space.

Science & Engineering Practices:	**Disciplinary Core Ideas:**	**Crosscutting Concepts:**
Developing and Using Models Develop a model to predict and/or describe phenomena. (MS-PS1-1) **Obtaining, Evaluating, and Communicating Information** Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS-PS2-6) **Asking Questions and Defining Problems** Define a design problem that can be solved through the development of an object, tool, process or system and includes multiple criteria and constraints, including scientific knowledge that may limit possible	**PS1.A: Structure and Properties of Matter** Solids may be formed from molecules, or they may be extended structures with repeating subunits (e.g., crystals). (MS-PS1-1) **ETS1.C: Optimizing the Design Solution** Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. (HS-ETS1-2) **PS2.B: Types of Interactions** Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. (HS-PS2-6)	**Structure and Function** Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem. (HS-PS2-6) **Scale, Proportion, and Quantity** Time, space, and energy phenomena can be observed at various scales using models to study systems that are too large or too small. (MS-PS1-1) **Connections to Engineering, Technology, and Applications of Science** **Influence of Science, Engineering, and Technology on Society and the Natural World** The uses of technologies and any limitations on their use are driven by individual or societal

solutions. (MS-ETS1-1)		needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. (MS-ETS1-1)

Possible Preconceptions/Misconceptions:

- **Gravity doesn't affect small-scale processes:** Students may not realize that even microscopic material behaviors—like convection currents or sedimentation—are gravity-influenced.
- **Space is just a harder place to do everything:** Students may assume space makes all tasks more difficult and not recognize that microgravity can actually improve certain processes**.**
- **As long as something works once, it's good enough:** Students may not yet understand that tiny inconsistencies in materials—like uneven crystal structures or microscopic defects—can dramatically impact performance, especially in high-precision systems like computers or sensors. They may overlook how repeatability and uniformity are essential for reliability at scale.
- **We only manufacture in space for astronauts or satellites.** Students may not grasp that space-based manufacturing is being developed for Earth-based applications, especially high-performance tech.

LESSON PLAN – 5-E Model

ENGAGE: Opening Activity – Access Prior Learning / Stimulate Interest / Generate Questions:

Purpose: Illustrate why consistency and precision in manufacturing are essential, especially when it comes to performance, reliability, and compatibility with other systems.

Materials:

- A few hand-struck replica coins (e.g., Roman or early American—real or reproduction) or images of hand-struck coins.
- A set of modern coins (quarters, dimes, pennies)
- *Optional*: scale, calipers, and a coin-operated device (gumball machine, toy dispenser, or coin sorter)

Process: Pass around the hand-struck and modern coins. Have students observe and compare:

- Shape, weight, thickness
- Uniformity
- Clarity of markings

Discussion Questions:

"Which type of coin would be easier to stack? Count? Fit in a vending machine?"
"Why would it be important that each coin is nearly identical to the next?"

*Then connect to modern manufacturing**: "When we make electronics, or semiconductors, why might uniformity matter even more than in coins?" "What happens when you introduce variability at the microscopic level in a complex system?"***

*Bridge to space**: "Now imagine you're trying to make something with even tighter tolerances than a coin—but gravity, uneven thermal distribution, and vibration keep getting in the way. What would happen if you took those things away?"***

EXPLORE: Lesson Description – Materials Needed / Probing or Clarifying Questions:

Purpose: Students will explore how sedimentation and uneven cooling affect the formation and consistency of materials, simulating the conditions that can lead to defects in crystals or layered structures during manufacturing.

Station worksheet for students

Station 1: Sedimentation Simulation

Materials:

- Clear plastic cups, water, small solid particles (e.g., sand, glitter, plastic beads), laboratory scoop, stopwatch or timer

Procedure:

1. Drop particles into one cup of still water and one cup of agitated water from the same height and observe their behavior.
2. Have students sketch and describe where particles end up, how fast they settle, and how consistent the "layer" of material is at the bottom.

Discussion Questions:

How do particle size, motion, or gravity affect where materials settle?
What might happen to a crystal if different elements settle at different rates during formation?
How might microgravity change the outcome of this experiment?

Station 2: Cooling and Convection

Materials:

- aluminum foil (3 equal sized pieces), beaker (400 mL) gloves (heat-resistant), hot plate, laboratory scoop (pointed), magnesium sulfate ($MgSO_4$ Epsom salts), magnifying lens, marker, masking tape, large-sized test tube (~50 mL), thermometer (°C), test tube tongs, watch (or clock), water (distilled), water (tap- 200 mL), Ice pack

Procedure:

1. Prepare a hot water bath in a beaker (40–50°C).
2. Students observe magnesium sulfate crystals with a magnifier and describe their physical properties prior to dissolving in solution.
3. Mix equal parts magnesium sulfate and distilled water in a large test tube, then gently tap to help dissolve.

4. Heat the test tube in the hot water bath for 3–6 minutes. Create three foil “boats” while heating.
5. Label one foil boat "Sample 1" (placed on the warm hot plate, turned off), and the other "Sample 2" (placed on a lab table) and “Sample 3” with one half of the boat on an ice pack.
6. Students observe using a magnifier and a watch/clock and record crystal formation time and the characteristics, noting any differences caused by cooling rate.

Guiding Questions:
How does the cooling rate affect the crystal size, texture or structure?
What would this mean for the performance of a material that needs to be uniform?
If this were a semiconductor or crystal for electronics, how might these features impact its performance?
In microgravity—without convection—how would crystal growth differ? (more uniform, fewer defects.)

Group Wrap-Up Discussion:
After both stations, bring students together to discuss:
What phenomena interfered with consistency? (gravity, convection, agitation, etc.)
How might these issues be eliminated or reduced in space?
What could these defects mean for electronics, sensors, or high-performance systems?

Connect observations to the idea that in microgravity, sedimentation and convection are greatly reduced, allowing for more uniform materials and fewer defects.

EXPLAIN:
Purpose: Support students in explaining how gravity affects material formation, how microgravity reduces those effects to produce higher-quality materials, and why that matters for the performance of technologies like semiconductors.

Show the Companion Lesson X-STEM Video “Manufacturing in Space” with Dr. Jessica Frick. Ask students to reflect on the following questions:
Why might space be a better place to manufacture the tiny, intricate crystals used in our computers and phones?
How does conducting research in space help scientists and engineers overcome the limitations of Earth-based manufacturing?

Research Jigsaw:
1. Form expert groups of 3–4 students (mixed-ability or leveled as needed).
2. Provide each student with a reading and/or video on the same concept.
3. Students identify key points, complete their section of the graphic organizer, and prepare to teach others.
4. Re-group into jigsaw teams so each group has a student from A, B, and C.
5. Each student shares their concept and why it matters to space manufacturing.
6. Close with a whole-class synthesis discussion.

Expert Group Concepts with Resource Examples:
Group A Concept: How gravity affects material formation (convection, buoyancy, sedimentation).
- NASA Microgravity: Earth and Space
- SciShow Fire, Lightning, and Crystals in Space: 20 years on the ISS (only the crystals portion of the video)
- Microgravity protein crystallization

Group B Concept: How microgravity improves manufacturing outcomes (more uniform crystals, fewer defects, more efficient thermal transfer).
- Space Manufacturing is Not Science Fiction (Video)
- How Space Factories Are Becoming A Reality (Video)
- International Space Station Protein Crystal Growth (video)
- Past/Ongoing Microgravity Materials Science Research

Group C Concept: Why performance depends on material quality, especially in microelectronics (semiconductors).
- Crystal Growth- ISS National Lab
- How to Identify High-Quality Semiconductor Materials

Discussion Question:
How does gravity interfere with the process of making materials like crystals or semiconductors on Earth? What evidence did you find to support this?
What advantages does microgravity offer for improving the quality and consistency of materials, and why might that matter for industries here on Earth?
If high-quality materials lead to better-performing technologies, what does that tell us about the relationship between manufacturing environments and innovation?

ELABORATE: Applications and Extensions:
Purpose: Students will apply what they've learned by identifying a product or material (other than semiconductors or pharmaceuticals) that could benefit from production in microgravity. They will define the requirements for the material/product, describe the issues caused by Earth’s gravity, and explain how microgravity might improve the outcome. They will demonstrate their thinking through a simple diagram, short write-up, or model.

Prompt: Scientists have already discovered that microgravity helps make better semiconductors and more effective medicines. What's next? Choose a product or material that might benefit from being made in space—then explain how and why.

Student Task Breakdown:

1. Identify a product or material
    - Must have clear performance needs (e.g., strength, uniform texture, purity, consistency).
    - Examples to brainstorm: metal foams, fiber optics, chocolate, ultra-light aerogels, high-end glass, skin graft materials, bioplastics, even musical instrument components (ex. purest bell sound made by a better alloy).
2. List key manufacturing requirements
    - What does it need to be or do? (e.g., "must cool evenly", "must be defect-free", "requires consistent layering")
3. Describe the limitations of Earth-based manufacturing
    - How do gravity-driven phenomena (e.g., sedimentation, convection, buoyancy) interfere?
4. Explain how microgravity could help
    - Refer to earlier readings or experiments (fewer defects, more uniform crystals, etc.)
5. Create a labeled diagram, annotated sketch, or simple prototype
    - Show how your process or product might work in space

Outcome Format (Teacher Choice):

- Poster or one-pager
- Small group pitch
- Mini design gallery walk
- Flipgrid video or short slide deck

Discussion Questions:

Why did you choose this product or material for space manufacturing?
What makes it valuable—to science, society, industry, or even personal interest?
What challenges would engineers, scientists, or business leaders face in making this product in space?
Think about cost, access, energy, safety, and Earth-space transport.
How could your innovation support future space exploration—or improve life on Earth?
Could this be part of a larger system (space station, lunar base, supply chain, etc.)?

EVALUATE:

Formative Monitoring (Questioning / Discussion):
Questions in bold, italics can be used to check student understanding throughout the lesson. Additionally, student presentations in the explore section can be used to monitor student progress.

Summative Assessment (Quiz / Project / Report): Students will present their proposed material or product innovation using one of the outcome formats described in the Elaborate section. To assess their understanding, teachers may choose from the evaluation options provided—either as a standalone assessment or integrated with the final project.
Evaluation Options:

- Claim-Evidence-Reasoning (CER) Defend or refute this statement using evidence from the lesson and sound scientific reasoning. "Space is a better place to grow semiconductor crystals than Earth."
- Peer review of designs
- Performance rubric evaluating understanding of material/product for manufacturing in space and justification.

EXTEND:
Here are optional extension activities that go beyond the core lesson, focusing on economic implications, policy considerations, and space exploration logistics—perfect for students ready to think systemically and apply their knowledge in a broader context.

Cost vs. Benefit Analysis Challenge

- **Objective:** Students evaluate whether manufacturing their proposed product in space is worth the investment.
- **Activity:**
    - Research the estimated cost of launching 1 kg of material into orbit (provide a baseline, e.g., ~$3,000–$10,000 depending on provider).
    - Estimate the value or potential market of the product if it were manufactured in space.
    - Write a short position paper or record a "pitch" arguing for or against investment in space-based production of their item.
- **Key Questions:**
    - Is the economic return high enough to justify space manufacturing?
    - Could your product eventually offset launch costs (e.g., by enabling space infrastructure)?

Space Supply Chain Systems Map

- **Objective:** Model how materials and manufacturing would flow in a future space-based industry.
- **Activity:**
    - Students create a systems map of a supply chain for their innovation.
    - Include inputs (materials, energy, launch logistics), processing (space station, moon base, etc.), and outputs (products returned to Earth or used in space).
    - Identify logistical barriers and propose solutions.
- **Key Questions:**
    - Where would the raw materials come from? Earth? Asteroids? The Moon?

- How might in-space manufacturing reduce the need for Earth-based supply chains?

Policy Brief: Who Should Control Space Manufacturing?

- **Objective:** Students explore legal, ethical, and regulatory frameworks for space-based production.
- **Activity:**
    - Write a one-page policy brief answering: Who should regulate space manufacturing—governments, companies, or international coalitions?
    - Support their position with evidence from past agreements (like the Outer Space Treaty), environmental concerns, or economic implications.

CAREER CONNECTIONS

From precision electronics that power satellites to fiber optics grown aboard the International Space Station, space-based manufacturing is unlocking new possibilities in technology and innovation. Scientists and engineers working in microgravity environments push the boundaries of what's possible—producing materials with fewer defects, greater consistency, and superior performance. Their expertise spans materials science, aerospace engineering, and applied physics, contributing to fields like telecommunications, computing, defense, and climate monitoring. As industries begin to harness space as a manufacturing frontier, careers in this field offer students the chance to shape the future of high-performance materials, support space infrastructure, and redefine how and where we build the technologies of tomorrow.

1. **Explore Career Clusters**: Have students visit USA Science & Engineering Festival Resources and explore careers in the Microelectronics and Materials Science industry clusters to discover opportunities in these growing fields.
2. **Choose a Career**: Students will select one career from the chosen industry cluster that interests them.
3. **Research the chosen Career**: Using the provided graphic organizer or a class notebook, students will gather the following information about their chosen career:
    - Job description: Typical responsibilities and duties
    - Education and training required: Degrees, certifications, or technical training
    - Skills and qualities needed: Key traits for success in the field
    - Average salary: Typical earnings for the role
    - Work environment and schedule: Typical working conditions and hours
    - Professional Organizations, Educational Programs, and Internship & Apprentice Opportunities
4. Students will select one of the following choice board activities to synthesize their research:

Career Profile Research the job description, required skills, and average salary for your chosen career. Summarize your findings in a blog entry.	**Career Path Match** Create a visual timeline or flowchart showing the education, training, and steps required to enter and advance in this career.	**Day in the Life** Write a diary entry or create a video/blog describing a typical day for someone in this career. Use research to make it realistic.

5. **Share findings**: Provide an opportunity for students to share their findings. This could be a class presentation, a gallery walk with posters or a peer discussion group.

SOCIAL EMOTIONAL LEARNING ACTIVITY

CASEL Competencies Addressed: Self-Awareness and Responsible Decision-Making

Purpose: To help students reflect on how they respond to challenges, uncertainty, and new ideas—and how their decisions (especially under pressure or ambiguity) shape outcomes in group and personal goals.

PART 1: Opening Reflection – Thinking Beyond the "Impossible" (Self-Awareness)

Prompt: "What's something that felt impossible to you until you figured out how to do it—or saw someone else do it?"

1. Students journal quietly for 3–5 minutes.
2. Pair share: What emotions did you feel before/during/after? What changed?
3. Optional class discussion prompts:
    - What helped you succeed?
    - Did failure or uncertainty show up, and if so—how did you handle it?

Transition with "Scientists, engineers, and creators often have to imagine beyond what seems possible—and manage frustration, uncertainty, or failure as they figure it out."

PART 2: Choice Under Pressure – Group Scenario Discussion (Responsible Decision-Making)

Scenario: "You're working with a group to design something entirely new—like a system to manufacture materials in space. There's no example to copy, and your group has different ideas. Some people dominate the conversation, others stay quiet. The clock is ticking. What do you do?"

Discussion Questions: (Think–Pair–Share or class discussion)

- What kinds of decisions matter in situations like this?
- How do your values or emotions influence your choices?

- Is it better to act quickly, slow things down, speak up, or listen more? Why?

PART 3: Decision Mapping – What Would You Do? (Responsible Decision-Making)

Inside/Outside Circle Share Setup:

1. Give students a short decision-making template and provide them time to fill it.
2. Arrange students in two concentric circles—an inner circle facing outward and an outer circle facing inward so that each student has a partner.
3. Ensure circles have equal or nearly equal numbers; if uneven, some students may pair in groups of three.

Directions:

1. Explain the task: Students will share their responses to the Decision Mapping worksheet prompt: "I'm in a group and we can't agree on a design. What choice would you make, and why?"
2. Share: Partners take turns sharing their decision and reasoning. Each student listens actively and asks one clarifying or follow-up question. Encourage respectful, focused conversation.
3. Rotate: After 2–3 minutes, signal for the outer circle to move one person to the right so students get a new partner.
4. Repeat: Continue sharing rounds for 3–4 rotations or as time allows.

PART 4: Closing Reflection – Confidence & Growth

Prompt (written or discussion): "What do you know about yourself now that helps you navigate uncertain or challenging tasks? What's one decision you want to approach differently next time?"

Materials Required for This Lesson/Activity	
Quantity	**Description**
1 per class	Computer with Projector and Internet Access
1 per student/group	Computer with Internet Access for Research
1 per student	Copies of lab worksheet found in the Explore section, rubrics as found in the Evaluate section, and Jigsaw note catcher from the Explain section.
One complete set of materials is needed for each Station setup; multiple stations require multiple material sets	***Station 1 materials***: Clear plastic cups, water, small solid particles (e.g., sand, glitter, plastic beads), laboratory scoop, stopwatch or timer
	Station 2 materials: aluminum foil (3 equal sized pieces), beaker- 400 mL, gloves, heat-resistant, hot plate, laboratory scoop, pointed, magnesium sulfate ($MgSO_4$ about 42g), magnifying lens, marker, masking tape, large-sized test tube (50 mL), thermometer (°C), test tube tongs, watch (or clock), water (distilled), water (tap- 200 mL), Ice pack, cardboard
1 set per group	Hand-struck or replica ancient coins (inexpensive replicas are fine); alternately, images of said coins
	Modern U.S. coins (e.g., quarters, dimes, nickels and pennies)
	Magnifying glasses or loupes (for close comparison of coins, etc.)
1 per student	Goggles

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