Earth to Orbit: Materials in Extremes

Companion Lesson X-STEM Video "Extreme Materials" by Dr. Jamesa Stokes

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

Brief Lesson Description: Students explore material properties connected to their performance in extreme settings.

Performance Expectation(s):
MS-PS1-3: Gather and make sense of information to describe that synthetic materials come from natural resources and impact society.
MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
HS-PS2-6: Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.

Specific Learning Outcomes:
Students will be able to:

- Explain how given materials are engineered to meet specific performance needs in extreme environments (e.g., space travel, aeronautics).
- Evaluate how the use of synthetic materials has influenced space exploration and technology in society.
- Investigate how different materials (metals, ceramics, polymers) behave under thermal and mechanical stress.
- Use experimental results to infer how particle-level structures (e.g., bonding, arrangement) influence observable properties such as brittleness, elasticity, or thermal conductivity.
- Explain how these properties relate to their use in applications like heat shields, jet engines, or space probes.
- Justify which material or combination of materials is best suited for a design challenge (e.g., protecting a heat-sensitive payload).

Narrative / Background Information

Modern exploration and innovation demand materials that can withstand extreme forces, temperatures, and environments. From spacecraft heat shields to 3D-printed alloys used in aviation, these engineered materials are designed with precision at the molecular level to solve high-stakes challenges. This lesson engages students in investigating how structure determines function, encouraging them to test, compare, and evaluate materials through real-world performance criteria. As they take on the role of engineers and problem-solvers, students connect scientific concepts to emerging technologies, strengthening their ability to analyze, design, and justify solutions. Through this lens, they begin to see materials science not just as chemistry or physics, but as a driving force behind modern innovation and future possibilities.

Prior Student Knowledge: Before engaging in this lesson, students should be familiar with:

- Common categories of materials (metals, polymers/plastics, ceramics, and composites) and their general properties, such as strength, flexibility, and density
- The particle nature of matter and how atomic or molecular structure influences material behavior
- The distinction between natural and synthetic materials
- Foundational science practices such as planning and carrying out investigations, analyzing and interpreting data, and constructing evidence-based explanations
- Basic understanding of criteria and constraints in engineering design

Science & Engineering Practices:	Disciplinary Core Ideas:	Crosscutting Concepts:
Engaging in Argument from Evidence Evaluate competing design solutions based on jointly developed and agreed-upon design criteria. (MS-ETS1-2) **Obtaining, Evaluating, and Communicating Information** Gather, read, and synthesize information from multiple appropriate sources and assess the credibility, accuracy, and possible bias of each publication and methods used, and describe how they are supported or not supported by evidence. (MS-PS1-3) 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)	**PS1.A: Structure and Properties of Matter** Each pure substance has characteristic physical and chemical properties (for any bulk quantity under given conditions) that can be used to identify it. (MS-PS1-3) **ETS1.B Developing Possible Solutions** There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. (MS-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) **Stability and Change** Structures can be designed to serve particular functions by taking into account properties of different materials, and how materials can be shaped and used. (MS-PS1-3) **Connections to Engineering, Technology, and Applications of Science** **Interdependence of Science, Engineering, and Technology** Engineering advances have led to important discoveries in virtually every field of science and scientific discoveries have led to the development of entire industries and engineered systems. (MS-PS1-3)

Possible Preconceptions/Misconceptions:

- **Stronger materials are always better** – Students may assume that the strongest material is always the best choice, without considering trade-offs like weight, flexibility, or cost.
- **All synthetic materials are artificial and harmful** – Some students may believe that synthetic equals "bad" or environmentally unfriendly, without understanding how they can be designed for sustainability or high performance.
- **Materials behave the same in all conditions** – Students might not recognize that materials can dramatically change their properties under extreme temperatures, pressures, or forces.
- **3D printing only uses plastic and is for hobbyists** – Students may have limited awareness of the variety of advanced materials used in additive manufacturing, or its widespread applications in aerospace, medicine, and engineering.
- **The appearance of a material reflects its properties** – Students often assume that shiny, smooth, or heavy materials are automatically strong or heat resistant, overlooking internal structure and molecular composition.

LESSON PLAN – 5-E Model

ENGAGE: Opening Activity – Access Prior Learning / Stimulate Interest / Generate Questions:
Purpose: Brainstorm initial ideas and questions regarding materials designed for extreme conditions.
Show dramatic footage or images of materials surviving extreme conditions, such as the Artemis 1 reentry video (watch from 1:10-2:28 to experience the compression and friction portion of reentry), the Space Shuttle tiles, or turbine blades glowing red-hot in jet engines.

Discussion Questions:
What makes some materials survive where others would fail?
How do we design materials to withstand conditions like re-entry, deep space, or the surface of Venus?

EXPLORE: Lesson Description – Materials Needed / Probing or Clarifying Questions:
Purpose: Students experience hands-on stations modeling material testing in extreme conditions.
Prepare lab stations around the room, each with clearly labeled materials, safety equipment (including goggles), and printed instructions.
Suggested stations include:

- **Thermal Resistance**: Test different materials by exposing them to heat.
- **Abrasion/Impact Resistance**: Drop-weight impact test with various material samples.
- **Cryo Stress Test**: Use dry ice or simulated freezing to see brittleness differences
- **Flexion & Malleability**: Test how well different materials can bend (flex) or permanently deform (malleability) without breaking.

Each station should allow students to collect qualitative and quantitative data on how materials respond to specific environmental conditions. After completing all stations, bring the class back together for a brief discussion.

Discussion Questions:
How did different materials perform under each extreme condition (heat, cold, impact, flexion)?
What patterns did you notice, and were there any surprises?
If you were designing a spacecraft or an aircraft, which materials would you consider using—and which would you avoid—based on what you observed in these stations?
What trade-offs might engineers have to consider when selecting materials?

EXPLAIN:
Purpose: Students analyze their data and connect observations to material structure and properties (e.g., thermal conductivity, tensile strength, flexibility, microstructure, additive vs. subtractive manufacturing).

Show the Companion Lesson X-STEM Video "Extreme Materials" featuring NASA materials research engineer Dr. Jamesa Stokes. Ask students to reflect on the following questions:
Why is it important to test materials for space or extreme environments here on Earth?
What challenges do scientists and engineers face when simulating those extreme conditions?

Mini-lessons or videos: Whether you're using direct instruction, assigning videos for independent viewing, or facilitating small group learning, this graphic organizer will help students track their thinking and make meaningful connections back to the hands-on exploration activities.
Cover key science concepts such as:

- Structure of metals vs. ceramics
- How polymers respond to temperature
- Use of composites in spacecraft and aircraft- Is This the Best Insulation Material? video
- Role of additive manufacturing in custom, lightweight, or heat-resistant parts

Introduce real-world examples:

- Heat shields (carbon-carbon composites)- How NASA Tests Spacecraft Reentry video
- Aerogels for insulation- Flamethrower vs Aerogel video
- 3D printed components used in aerospace engineering.

Discussion Question:
How do you think the microscopic or atomic structure of a material affects its macroscopic properties like strength, flexibility, or resistance to temperature?

Why is this important for real-world engineering challenges?
Based on what you learned today, what qualities would you prioritize if you were choosing a material for a spacecraft? Why?

ELABORATE: Applications and Extensions:
Purpose: To challenge students to apply their understanding of material properties, such as thermal resistance, impact resistance, flexibility, and performance in extreme environments, by selecting and justifying materials for a specific engineering scenario.

Engineering Challenge:
Design a material system (or a "tile" sample) to protect a small payload (e.g., a marshmallow, crayon or other heat-sensitive object) from simulated re-entry or extreme temperatures.
Steps:
1. Collaboratively define constraints (mass, temperature tolerance, size, etc.)
2. In teams of 3-4 create a thermal resistant design using available materials (e.g. cardboard, foil, polymers, ceramics, insulation).
3. Students will justify their design choices using their prior test data.
4. Test using ring stand and bunsen burner or propane torch to simulate reentry.

Discussion Questions:
Which materials did you choose for your engineering solution, and why?
What properties made them the best fit for your scenario?

What trade-offs did you have to consider when selecting materials (e.g., strength vs. flexibility, durability vs. mass)?
How did those trade-offs impact your final decision?

If you could improve or redesign your solution, what would you change?
What new information or data would help you make better material choices in the future?

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 and case study handouts in the elaborate section can be used to monitor student progress.

Summative Assessment (Quiz / Project / Report): Students present their material system/design and justify it using evidence from tests and scientific reasoning. Performance rubric evaluating understanding of materials, justification, and use of engineering practices.
Options:
- Claim-Evidence-Reasoning (CER) write-up.
- Peer review of designs.

EXTEND:
Purpose: Students will use what they've learned about material properties to design a fictional product or structure that must survive an extreme environment.

Scenario Prompt:
You're an engineer tasked with designing something for an extreme environment. Based on what you know about materials, create a product, vehicle, structure, or wearable item that could withstand one of the following:
- The surface of Venus (extreme heat and pressure)
- A deep-sea trench (crushing pressure, freezing temps)
- A Martian dust storm (abrasive particles, cold, wind)
- A volcano rescue mission (extreme heat and impact)
- Arctic exploration (freezing cold and shifting ice)

Student Deliverables:
- A labeled sketch or model (digital or physical) of their design
- A short write-up or presentation explaining:
    - What extreme conditions the design must endure
    - What materials were selected and why
    - How those materials protect or enhance the function of the design
    - What trade-offs they had to make (e.g., cost, weight, flexibility)

Optional Fun Twist: Create a "Materials Innovation Expo" where students display their designs, wear "lab coats," and pitch their ideas to the class or other visitors as if they're at a science and tech convention.

CAREER CONNECTIONS

From heat shields that protect spacecraft during re-entry to alloys that endure the crushing pressures of the deep ocean, the development of advanced materials drives innovation across countless fields. Materials scientists and engineers work at the intersection of chemistry, physics, and engineering to design substances that can withstand extreme temperatures, stress, and environmental conditions. Their work supports industries such as aerospace, energy, automotive, and even space exploration, where breakthroughs in ceramics, composites, and metals enable missions to the Moon, Mars, and beyond. Careers in materials science are vital to building the next generation of technologies, from sustainable infrastructure to cutting-edge spacecraft, and offer students an opportunity to be at the forefront of solving global challenges.

1. **Explore Career Clusters**: Have students visit USA Science & Engineering Festival Resources and explore careers in the Materials Science Industry 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:

Resume for the Future Create a resume as if you are applying for a job in your chosen career 10 years from now. Include education, experience, and skills.	**Work Environment Design** Draw or digitally create an image of the typical work environment for this career. Annotate it with labels explaining the features.	**Career Advertisement** Create a commercial (video or audio) to promote your chosen career to others. Highlight its benefits and opportunities.

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 Competency Addressed: Self-Awareness, Self-Management, Responsible Decision-Making
Purpose: Just like materials are tested to withstand extreme conditions, people also encounter stress, pressure, and challenges. This lesson helps students draw connections between material strength and personal resilience. Students will explore how their thoughts, emotions, and choices influence how they respond to challenges, and practice strategies to build their own ability to "bend without breaking."

Objectives: Students will…
- Recognize how they respond to stress or pressure in various situations.
- Identify and evaluate strategies to manage stress and remain flexible under pressure.
- Reflect on personal strengths and areas for growth in resilience.

Materials:
Resilience Reflection: Bending, Not Breaking Handout (can be digital or paper)
Writing implements

1. **Opening Activity- Perseverance Under Pressure**
- Start by asking students:
    - "Can you name a material that you think is fragile?" (Students may say glass, ceramic, etc.)
    - "Now, what's a material you think is really strong?" (Students might say metal, Kevlar, etc.)
- Then pose the question:
    - "What do you think would happen if those two materials met under pressure?"
- Introduce the Prince Rupert's Drop—a seemingly fragile piece of glass—and a hydraulic press, which applies immense force. Share that the drop is made from glass, and the press is made of strong metal.
    - Have students predict what will happen when the two meet, and then show them this video: Prince Rupert's Drop vs. Hydraulic Press
- Discussion Prompt- After watching, ask:
    - "Did the outcome surprise you?"
    - "What does this make you think about how we sometimes seem fragile but may be stronger than we or others realize?"
    - "Have you ever faced a situation where you felt like you were being pushed to your limits? What helped you get through it?"

2. **Resilience Reflection: Bending, Not Breaking**
- Distribute the *Resilience Reflection: Bending, Not Breaking* handout and give students time to work through it individually, encouraging honest and thoughtful responses. Once they've had a chance to reflect, have them pair up with a partner to discuss their answers, especially focusing on how they personally experience and navigate challenges.

- After partner discussions, bring the class back together for a whole-group debrief. Use the following questions to guide the reflection:
    - What patterns or common responses did you notice in your conversations?
    - How does recognizing your reaction to stress help you build resilience?
    - Which strategies for staying flexible or adapting stood out as most useful—and why?
    - How might understanding your own stress response help you support others during difficult times?

3. **Putting it all together:**
    - In small groups, students create a visual or metaphor that represents resilience (e.g., a spring, a bridge, a tree in wind). They should explain what makes the image a strong example of resilience.
4. **Close with a self-assessment:**
    - On a scale from 1–5, how resilient do I feel in stressful situations?
    - One strategy I will try next time I feel pressure is…

Extension:
Have students track a time they used a resilience strategy and journal about the outcome.

Materials Required for This Lesson/Activity	
Quantity	**Description**
1 per class	Computer with Projector and Internet Access
1 per group	Computer with Internet Access for Research
1 per student	Copies of rubrics as found in the Evaluate section
1 per station	Timers or stopwatches- *For recording duration of tests or timed observations.*
	Tongs for manipulating hot or cold materials
	Ruler or meter stick for measurement
4-6 per station	Assortment of materials for testing- aluminum foil, copper wire, plastic strips (e.g., packaging), thin wood slats (craft sticks), rubber bands, wax paper, cardboard, metal paper clips, foam, felt, plastic utensils, drinking straws, balloon pieces, acrylic sheet, rubber mat, cotton fabric, cork, ceramic tile, etc.
1	Thermometer or digital temperature probe- *for use in thermal resistance stations to measure water temperature at start and after heating.*
1-2	Glass Petri Dish- *for use in thermal resistance station*
1	150 mL glass beaker- *for use in thermal resistance station*
1	Hot plate- *for use in thermal resistance station*
1 strip	Medium grit sandpaper- *for use in abrasion/impact resistance station*
10-15	Small metal weights or bolts- *for use in abrasion/impact resistance station and malleability/flexion station*
2-4	Binder clips or clamps- *for use in abrasion/impact resistance station and malleability/flexion station*
1	Styrofoam cooler containing dry ice or ice-salt slush- *for use in the cryo testing station*
1 set up	Ring stand and bunsen burner or propane torch- *for use in the engineering challenge in the elaborate section*

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