Submerged Systems: Submarine Science & Engineering

Companion Lesson X-STEM All Access Episode "Ships, Subs & STEM"

Grade Band: Middle School - High School	**Topic:** Engineering and Physics
Brief Lesson Description: Students investigate how submarines use science and engineering to explore the ocean.	
Performance Expectation(s): MS-PS3-3: Apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer. MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution. HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy. HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems.	
Specific Learning Outcomes: Students will be able to: - Explain how buoyant force and Archimedes' Principle determine whether an object sinks, floats, or remains neutrally buoyant—and apply this understanding to submarine design. - Use evidence from hands-on investigations and simulations to model how changes in mass, volume, or fluid properties affect buoyancy and stability. - Identify key engineering systems in modern submarines (ballast tanks, hull design, propulsion, and cooling systems) and explain how they work together to maintain function and safety. - Evaluate how innovations in submarine technology (e.g., anechoic coatings, magnetic signature reduction, pump-jet propulsion) improve stealth, safety, and environmental protection.	
Narrative / Background Information	
The ocean covers more than 70% of our planet, yet most of it remains unexplored—a vast, high-pressure frontier where submarines serve as our silent explorers. These complex vessels blend physics, materials science, and engineering to survive and operate in extreme conditions. Professionals like John Ornellas, Nuclear Engineering and Planning Manager at Pearl Harbor, lead teams that service the Navy's fleet of nuclear-powered submarines, ensuring these systems perform flawlessly under immense pressure. In this lesson, students investigate how submarines dive, surface, and stay hidden, exploring the science behind buoyancy, energy, and future stealth technologies that make these underwater marvels possible. **Prior Student Knowledge:** Before engaging in this lesson, students should be familiar with: - *Density and Buoyancy*: Understanding how mass and volume determine whether an object sinks, floats, or achieves neutral buoyancy. - *Heat Transfer Concepts*: General understanding of conduction, convection, and radiation as mechanisms of thermal energy movement to then understand energy flow and heat management (especially in nuclear propulsion and stealth cooling systems) - *Forces and Motion*: Recognizing how balanced and unbalanced forces influence movement and stability (applies to diving, surfacing, and propulsion). - *Energy Transfer and Conversion*: Understanding that energy changes forms (e.g., nuclear → thermal → mechanical) in propulsion systems. - *Structure and Function*: Recognizing that an object's design affects its ability to perform a function, particularly under specific environmental conditions (like pressure or temperature).	

Science & Engineering Practices:	**Disciplinary Core Ideas:**	**Crosscutting Concepts:**
Constructing Explanations and Designing Solutions Apply scientific ideas or principles to design, construct, and test a design of an object, tool, process or system. (MS-PS3-3) Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-PS3-3) **Developing and Using Models** Develop and use a model based on evidence to illustrate the relationships between systems or between components of a system.	**PS3.A Definitions of Energy** At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-3) **PS3.B: Conservation of Energy and Energy Transfer** Energy is spontaneously transferred out of hotter regions or objects and into colder ones. (MS-PS3-3) **ETS1.B: Developing Possible Solutions** When evaluating solutions it is important to take into account a range of constraints including cost, safety, reliability and aesthetics and to consider social, cultural and environmental impacts. (HS-ETS1-3)	**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. **Systems and System Models** Models can be used to represent systems and their interactions—such as inputs, processes and outputs—and energy and matter flows within systems. **Connections to Engineering, Technology, and Applications of Science** **Influence of Science, Engineering, and Technology on Society and the Natural World** Modern civilization depends on major technological systems. Engineers continuously modify these technological systems by

		applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. (HS-PS3-3)

Possible Preconceptions/Misconceptions:

- **Heavier objects always sink:** Students often think weight alone determines whether something floats or sinks, overlooking how *density and displacement* work together to create buoyancy.
- **Pressure is the same everywhere underwater:** Many students don't realize that *pressure increases with depth*, and that this increase can crush or deform objects — a key concept for submarine hull design.
- **Nuclear power means explosives or weapons:** Some equate "nuclear-powered submarine" with nuclear bombs, rather than recognizing that it refers to a *nuclear reactor producing thermal energy* to power turbines safely.
- **Submarines move underwater the same way boats move on the surface:** Students may not grasp how *propulsion, steering, and drag* differ underwater—especially how *hydrodynamics* and *pump-jet systems* reduce noise and improve maneuverability.

LESSON PLAN – 5-E Model

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

Purpose: Spark curiosity about how submarines operate and the engineering challenges involved.

Opening Hook:

1. Play a short video clip of a modern submarine surfacing, diving, and/or maneuvering underwater (submarine surfacing)
2. Encourage students simply to observe and wonder:
    - "What forces do you think are acting on the submarine right now?"
    - "How does it change depth or direction?"

A look back in time: Early Submarines:

1. Provide a few quick visuals showing the evolution of submarine technology:
    - 1620 – Cornelis Drebbel's submersible: A leather-covered rowboat powered by oars.
    - 1775 – The Turtle (American Revolution): Hand-cranked wooden sub designed for underwater sabotage.
    - 1860s – Confederate Hunley: First submarine to sink an enemy ship, though at great risk to its crew.
    - 1900s – Diesel and electric propulsion: The dawn of practical military subs.
    - 1950s – Nuclear propulsion (USS Nautilus): Submarines capable of remaining submerged for months.
2. Invite students to notice patterns in how submarines evolved:
    - "What problems were early engineers trying to solve?"
    - "How did power sources and materials change over time?"

Optional- Literary Connection: 20,000 Leagues Under the Sea:

1. Read aloud (or display) a short excerpt from Jules Verne's 20,000 Leagues Under the Sea (1870) describing the Nautilus. For example, Captain Nemo, Twenty Thousand Leagues Under the Sea: Chapter XII, Some Figures
2. After reading, ask:
    - "What words or ideas make this sound futuristic?"
    - "What parts of Verne's description actually came true in modern submarine design?"
    - "Why do you think people were so fascinated by this idea long before it existed?"

Discussion Questions:

"What challenges might engineers face when designing something to survive deep underwater?"

Transition: "Let's explore how design, physics, and energy systems all come together to make submarines work."

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

Purpose: Students investigate buoyancy, pressure, and propulsion through hands-on stations and digital simulations.

Station Rotation (Directions)

Teacher Note: Set up all stations before students begin exploring. This ensures they have sufficient time to complete their observations and use what they learn to design and build their own mini-submarine. Two or three sets of stations could be run simultaneously to ensure students get through stations quickly and efficiently.

1. **Station 1: Pressure over depth** (how to set it up)
   Concept: Water pressure increases with depth because of the weight of the water above. Submarines must have strong hulls to withstand deep-sea pressures.
2. **Station 2: Cartesian diver** (how to set it up)
   Concept: Increasing pressure compresses air inside the diver, increasing its density so it sinks. Submarines adjust buoyancy using ballast tanks that fill or release water and air.
3. **Station 3: Virtual Simulation-- PhET "Buoyancy"** (PhET Buoyancy Simulation Link)
   Concept: Buoyancy depends on the balance between weight and the upward force of displaced water. Submarines manipulate this balance to control depth.

Synthesis: Mini Submarine Design

After all rotations, bring students together as a group and give them the challenge prompt as well as materials.

Challenge Prompt:

"Using what you learned about pressure, density, and buoyancy, design a mini submarine that can dive, hover, and surface in a container of water."

Materials (flexible based on time/resources):

- Materials for building: plastic bottles, film canisters, pipettes, balloons, tubing, washers, rubber bands, tape, flexible straws, etc.
- Water bins for testing

Guiding Questions:
How will your design control buoyancy (air vs. water volume)?
How will you make it stable?
What materials will help withstand pressure or maintain structure?

Group Wrap-Up Discussion:
After stations and synthesis, bring students together to discuss:
"What engineering trade-offs did you have to make between stability and control?"
"How did system design (shape, volume, materials) influence function?"

EXPLAIN:
Purpose: Connect student observations to real-world submarine systems and introduce nuclear power as an energy solution.
Teacher Input / Mini Lecture:

1. Explain key systems in submarines:
    - Ballast tanks → control buoyancy
    - Hull design → withstand pressure
    - Propulsion systems → diesel-electric vs. nuclear (good video resource, play from 4:22-7:28)
2. Discuss how nuclear submarines convert energy from fission into heat → steam → turbines → motion.
3. Introduce systems thinking: energy flow from reactor → propulsion → environmental exchange.

Student Processing:
Students create labeled diagrams or models showing energy and matter flow through submarine systems. (Graphic Organizer from Wonder of Science)
Encourage linking structure and function of parts to the submarine's overall mission (stealth, endurance, safety).

Optional Mini Submarine Design Evaluation:
Have students watch this video of a LEGO-powered submarine and analyze how the creator dealt with buoyancy, pressure, propulsion, and suggest one potential improvement.

Show the Companion X-STEM All Access Video "Ships, Subs & STEM" starring Mr. John Ornellas.
Ask students to reflect on the following question:
How does working in a complex, high-stakes environment like a naval shipyard challenge engineers and technicians to maintain precision, safety, and reliability in ways that other careers might not?

Discussion Questions:
Why must submarine hulls be designed to withstand pressure, and how do the principles of fluid dynamics influence the shape and efficiency of a submarine moving through water?
How do the interactions between pressure, buoyancy, and propulsion systems demonstrate the importance of integrating multiple scientific principles when designing complex engineering systems like submarines?

ELABORATE: Applications and Extensions:
Purpose: Apply systems thinking and engineering knowledge to design a next-generation submarine that balances function, stealth, and sustainability.
Prompt: "You're part of a design team developing the Submarine of the Future. Your mission: create a stealth research or defense vessel that can operate undetected, efficiently, and safely in deep-ocean environments."
Design Criteria:

1. **The submarine must:**
    - Move efficiently through water (propulsion + hydrodynamics)
    - Withstand extreme pressure (materials + structure)
    - Manage heat and energy transfer (power + cooling systems)
    - Evade detection using advanced stealth technology

Introduce Future-Focused Innovations- Students conduct research on the following innovations:

1. **Anechoic tiles:** rubber-like coatings that absorb or scatter sonar waves, reducing detectability.
2. **Thermal management systems:** circulate or cool exhaust water to reduce infrared signatures.
3. **Degaussing systems:** minimize magnetic fields that can trigger mines or detection sensors.
4. **Pump-jet propulsors:** reduce cavitation and wake, making propulsion quieter.

Student Challenge: In teams, integrate at least two of these innovations into your submarine design.

1. **For each innovation:**
    - Explain how it works (structure-function connection).
    - Justify why it matters for stealth, efficiency, or sustainability.
    - Describe trade-offs (cost, complexity, power usage, etc.).

Outcome Format (Teacher Choice):

- Poster or one-pager
- Annotated sketch or digital model of "Future Submarine."
- Brief written design proposal or video pitch summarizing your team's innovations.
- Small group pitch

- Mini design gallery walk
- Flipgrid video or short slide deck

Discussion Questions:

What trade-offs exist between stealth and efficiency?

How might emerging materials or AI improve future submarine systems?

What environmental or ethical considerations arise as submarines become more autonomous or covert?

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 will present their submarine designs in teams using one of the outcome formats described in the Elaborate section. To assess student understanding, peers evaluate teams based on clarity, feasibility, and systems-level reasoning using this rubric. Students may also self evaluate using the same rubric.

EXTEND: Students may apply their engineering and science understanding to real-world technological challenges through one of the following extension activities:

Invite students to explore:

1. Sustainability in naval engineering: Can future submarines use alternative energy (fusion, hydrogen fuel cells, or hybrid systems)?
2. Biomimicry: How might marine animals inspire stealth or efficiency (e.g., whale skin reducing drag, cephalopod color-changing camouflage)?
3. Autonomous submarines (AUVs): Explore the rise of AI-driven unmanned subs used for deep-sea research or under-ice exploration.
4. Ethics of stealth technology: Discuss global security, ocean conservation, and data transparency.

Optional Product:

A short research brief or "Design the Future" poster summarizing one innovation students believe will define submarine technology in the next 50 years.

CAREER CONNECTIONS

From nuclear engineers ensuring safe reactor operation to naval architects shaping hydrodynamic hulls, submarine technology represents the cutting edge of applied science and engineering beneath the waves. Professionals in this field blend physics, materials science, fluid dynamics, and advanced manufacturing to design vessels that can navigate extreme underwater environments. Their work spans propulsion systems, sonar technology, robotics, and environmental protection—each critical to maintaining safety, efficiency, and stealth. As innovations like anechoic coatings, magnetic signature reduction, and pump-jet propulsion redefine underwater performance, careers in naval engineering, oceanography, nuclear systems, and marine technology offer students the opportunity to pioneer the next generation of exploration, defense, and sustainable ocean operations.

1. Begin by showing this career short video to provide students with real-world insight into the complex engineering, safety, and teamwork involved in maintaining the Navy's nuclear-powered submarines—an inspiring example of STEM careers in action.
2. **Explore Career Clusters**: Have students visit USA Science & Engineering Festival Resources and explore careers in the Land, Air, and Sea Vehicles and Nuclear Engineering industry clusters to discover opportunities in these growing fields.
3. **Choose a Career**: Students will select one career from the chosen industry cluster that interests them.
4. **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
5. Students will select one of the following choice board activities to synthesize their research:

Career Interview	Pros and Cons Chart	Career Poster
Write a set of 5-7 questions you would ask someone in this career. Include the responses based on your research.	Make a T-chart listing at least five pros and five cons of the career based on your findings.	Design a poster or infographic showcasing key details about the career (e.g., job tasks, salary, skills, and job outlook).

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.

FUTURE-READINESS TOOLKIT

Competency Addressed: Collaboration
Purpose: This lesson emphasizes teamwork, shared problem-solving, and effective communication in confined or high-stakes environments (like life aboard a submarine). Students develop social awareness, relationship skills, and cooperative strategies—all essential for collaboration in STEM and real-world engineering contexts.

1. **"Life in a Tight Space"**
   - Ask: *"Think of a time you had to share space or work closely with others for a long time—maybe a group project, family trip, sports tournament, or classroom activity. What made it easy or hard?"*
   - Briefly share that submarine crews face similar challenges—living and working together in small spaces for long periods.
2. **Challenge Brainstorm**
   - In small groups, brainstorm common stress points that occur when people work closely together (e.g., communication issues, sharing space, personality differences, uneven workload).
   - Then, have groups list what emotions might come up in those situations and how people might react.
3. **What Helps Teams Thrive**
   - Facilitate discussion or short mini-lesson on effective coping and communication strategies for collaboration: (You can connect these to submarine crews, astronauts, or athletes to make it concrete.)
     - Taking breaks or "cool-down" moments
     - Practicing active listening
     - Using "I" statements to express needs
     - Showing appreciation or humor
     - Setting clear shared goals
4. **Scenario Challenge**
   - Present a few short scenarios (below) and have groups choose one to role-play or discuss how they'd respond using collaboration strategies.
   - Example Scenarios:
     1. Two team members disagree about how to divide a project.
     2. Someone is frustrated that their idea isn't being heard.
     3. The group is tired and arguing after a long work session.
     4. You're stuck in a small space (like a submarine, car, or classroom) and tensions rise.
5. **Reflection & Takeaway**
   - Have students journal or discuss:
     - What strategies help you manage your emotions under stress?
     - What can you do to support your group when things feel tense?
     - How might we build a "crew mindset" in our class?
   - Exit ticket: One skill or habit I'll use next time I work in a group is…

Optional Extension
Students design a "Crew Code of Conduct" for how they want to collaborate this semester—borrowing ideas from submarine crews, astronauts, or explorers. They can include strategies for communication, problem-solving, and emotional regulation.

Materials Required for This Lesson/Activity

Quantity	Description
1 per class	Computer with Projector and Internet Access Water bin for testing mini submarines (18-20 gallon plastic bin)
1 per student/group	Computer with Internet Access for Research
1 per student	Rubrics as found in the Evaluate section
One complete set of materials is needed for each Station setup; multiple stations require multiple material sets	***Station 1 materials***: 2 liter bottle, water, tape, something to punch holes in the bottle, station directions
	Station 2 materials: A small soft drink bottle, a plastic pipette, water, scissors, two nuts to fit the pipette, station directions
	Station 3 materials: Computer with internet access and station directions
1 set per group	Materials for building mini submarines: plastic bottles, film canisters, pipettes, balloons, tubing, washers, rubber bands, tape, flexible straws, scissors, tape, etc. Copies of lab station directions found in the Explore section

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