**TEACHER GUIDE**

Chemistry

**Hypersonics: Mission Re-entry**

**Topic(s):** Chemistry, Material Science, Physics

**Grade level(s):** 11th – 12thgrades (AP)

**Time:** 60-75 minutes

**NGSS Alignment**: HS-PS3-4

**TEKS Alignment**: CHEM.11.A, CHEM.11.B, CHEM.11.D

**Virginia Science SOL Alignment**: CH.7A.

**ACTIVITY OVERVIEW**

In this activity, students are tasked with using chemical properties to uncover the identity of an unknown material and then use their knowledge of the material’s thermal properties to develop a simulated re-entry capsule that will safely protect astronauts on their journey back from low-earth orbit. Students will use calorimetry to determine an unknown material’s specific heat, and then work together to find the identity of the unknown material using specific heat and density. In doing so, students will understand the concepts of a material constant, what specific heat and thermal conductivity are, and how the laws of thermodynamics can be used to measure heat exchange. Once materials are identified, students utilize a computer simulation to develop a model space shuttle that will prevent heat transfer into the capsule to protect astronauts as they re-enter the earth’s atmosphere.

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**ALIGNMENT TO STANDARDS**

**NGSS:**

**HS-PS3-4:** Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperatures are combined within a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics).

**TEKS:**

**CHEM.11.A:** Describe energy and its forms, including kinetic, potential, chemical, and thermal energies.

**CHEM.11.B:** Describe the law of conservation of energy and the processes of heat transfer in terms of calorimetry.

**CHEM11.D:** Perform calculations involving heat, mass, temperature change, and specific heat.

**Virginia Science SOL:**

**CH.7A.** Heat energy affects matter and interactions of matter.

**LEARNING OUTCOMES**

Students will know:

* What hypersonic movement is and how it relates to the speed of sound.
* The constraints of hypersonic vehicle design.

Students will understand:

* The difference between specific heat and thermal conductivity.
* The Law of Conservation of Energy.
* Why understanding material properties is important in engineering aircraft.

Students will be able to:

* Conduct a procedure and perform calculations to determine the constant value for a calorimeter
* Conduct a procedure and perform calculations to determine the specific heat and density of an unknown material
* Identify an unknown material by comparing measured/calculated values to known values
* Apply an understanding of thermal conductivity and specific heat to design a space capsule with the lowest internal temperature change.

**CAREER CONNECTIONS**

**Aerospace Engineer**

Aerospace engineers design, develop, and test aircraft, spacecraft, satellites, and missiles.

**Work Environment:** Aerospace engineers typically work in an office setting, often using a computer.

**Duties:** Professionals in these jobs have the following duties and more: Coordinate and direct the design, manufacture, and testing of aircraft and aerospace products, assess project proposals to determine whether they are technically and financially feasible, determine whether proposed projects will be safe and meet defined goals, evaluate designs to ensure that products meet engineering principles, customer requirements, and environmental regulations

**Median Salary:** $126,880 (US Bureau of Labor, 2022)

Source: [https://www.bls.gov/ooh/architecture-and-engineering/aerospace-engineers.htm#](https://www.bls.gov/ooh/architecture-and-engineering/aerospace-engineers.htm)

**Materials Engineer**

Materials engineers develop, process, and test materials used to create a wide range of products.

**Work Environment**: Materials engineers generally work in offices where they have access to computers and design equipment. Others work in factories or research and development laboratories.

**Duties:** Professionals in these jobs have the following duties and more: Supervise the work of technologists, technicians, and other engineers and scientists, design and direct the testing of processing procedures, monitor how materials perform and evaluate how they deteriorate, determine causes of product failure and develop ways of overcoming such failure, evaluate technical specifications and economic factors relating to the design objectives of processes or products.

**Median US Salary**: $100,140 (US Bureau of Labor, 2022)

Source: <https://www.bls.gov/ooh/architecture-and-engineering/materials-engineers.htm>

**Analytical Scientist**

Analytical scientists are chemists and materials scientists who research and analyze the chemical properties of substances to develop new materials, products, or knowledge

**Work Environment**: Many analytical scientists work in work in laboratories, offices, and manufacturing facilities.

**Duties:** Professionals in these jobs have the following duties and more: Prepare solutions, compounds, and reagents used in laboratory procedures, analyze substances to determine their composition and concentration of elements, conduct tests on materials and other substances to ensure that safety and quality standards are met, plan and carry out research projects, such as development of products and of testing methods.

**Median US Salary**: $81,810 (US Bureau of Labor, 2022)

Source: <https://www.bls.gov/ooh/life-physical-and-social-science/chemists-and-materials-scientists.htm>

**BACKGROUND INFORMATION**

In this activity, students will use a combination of laboratory skills and a computer simulation to understand how material properties affect its ability to withstand heat and heat exchange. Students will apply this knowledge to the hypothetical scenario of a re-entry capsule moving at hypersonic speeds. They will make the connection between increased speeds and friction, and increased heat that materials must overcome to make a successful flight module.

To begin, students are introduced to hypersonic movement and its constraints. The specific constraint we highlight in this activity is heat buildup and transfer during hypersonic movement, and how materials science and engineering can be used to overcome these challenges before construction begins. Students will be provided the definitions of several different material constants such as specific heat, thermal conductivity, and thermal diffusivity, and asked to identify the differences between each. In this activity, students will be responsible for identifying unknown materials using these material properties and then using said materials to develop a hypothetical product.

Part one of this activity walks students through a laboratory procedure where they will be tasked with uncovering an unknown material’s identity using calculated values; its specific heat and volumetric density. This activity utilizes an experimental procedure, calorimetry, where students use the Law of Conservation of Energy to identify heat transfer from the material, into the surrounding water until it reaches equilibrium. In order to successfully complete this procedure, students will first identify their calorimeter constant, which is the rate at which heat moves from the system to the calorimeter. Upon completion of their calorimeter constant, students conduct a similar procedure where they use the unknown material at their disposal. Once all stations have completed, they will have to work with the other two groups at their tables to identify the average specific heat for their unknown material and then compare that and their densities to a list of provided known values to come up with the identity of their material. We will then discuss as a class the true identities of their unknown materials and discuss how they might change or adjust their experimental procedure in the future to ensure accurate and consistent results.

The second half of this activity asks students to use what they’ve learned about heat transfer and material properties and apply that to a simulated re-entry capsule. The students will act as the analytical scientists running tests and utilizing the different metrics they’ve been working with in the first part of the activity to find a model that best insulates and protects the astronauts within. Students will be given 5 different materials and can use the materials lists at their disposal to make educated trials as to what they believe may prevent heat transfer the best.

Resources about Hypersonic Movement

Understanding Hypersonics:

* <https://nstxl.org/understanding-hypersonics/>

What is the speed of sound?

* <https://www.livescience.com/37022-speed-of-sound-mach-1.html>

History of Hypersonic Flight:

* <https://airandspace.si.edu/stories/editorial/hypersonic-flight>

Why are there no Hypersonic planes?

* <https://www.cnn.com/travel/article/hypersonic-airplane-hermeus/index.html>

How fast do space capsules move?

* <https://www.grc.nasa.gov/www/BGH/hihyper.html#:~:text=As%20a%20spacecraft%20re%2Denters,twenty%20five%2C%20M%20%3C%2025>.

Resources about friction and heat transfer

What is Friction?

* <https://www.livescience.com/37161-what-is-friction.html>

Why does friction produce heat?

* <https://energyeducation.ca/encyclopedia/Friction>

Where does air resistance come from?

* <https://www.universetoday.com/73315/what-is-air-resistance/>

Factors that affect drag (aerodynamic resistance)

* <https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/factors-that-affect-drag/>

Resources about chemical constants (specific heat, thermal conductivity)

Heat Capacity, Specific Heat, and Calorimetry

* <https://www.youtube.com/watch?v=yhNHJ7WdT8A>

Difference between specific heat and thermal conductivity

* <https://www.rheologylab.com/services/thermal-conductivity-specific-heat-capacity/#:~:text=Thermal%20conductivity%20measurements%20can%20tell,the%20temperature%20of%20a%20material>.

What does density tell us?

* <https://www.acs.org/middleschoolchemistry/lessonplans/chapter3/lesson1.html>

What is a chemical property?

* <https://www.electrical4u.com/chemical-properties-of-materials/>

What is Calorimetry?

* <https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Thermodynamics/Calorimetry>

**PRE-LAB RECOMMENDATIONS**

**Equipment Safety Game: Musical Test Tubes**

This is a quick game designed to introduce students to using a test tube and test tube clamp, and how to carefully place test tubes into the beakers they will be using during the experiment.

Time: 15-20 minutes

Materials:

* Plastic Test Tubes (1 per student)
* Test tube clamp (1 per student)
* Heat safe gloves
* Plastic cups (Dixie or other 9oz cups, 1 per student)

Setup:

* Place enough cups for each student to have one randomly around classroom
* Have each student standing, holding test tube in clamp in gloved hand (no heat will be used during this game, but students should prepare themselves for the PPE they will be using during the lab)

Rules:

* While music is playing, students are to move about the room continuously
* When music stops, students must carefully place their test tube into the cup nearest them
  + If the cup is knocked over by over-zealous student, that student is out and has a seat
* Once music begins again, students must pick up their test tubes using the clamp, again, if the dixie cup is knocked over the student is out and they have a seat
* Play a few rounds without removing any cups, so that students can practice using the clamp with little pressure.
* Once students have the hang of the game and using the test tube clamps, introduce a bit of pressure by removing one cup at a time from the classroom
  + Rules remain the same, if cups are knocked over student is out
  + If two students are involved in a cup being knocked over, both are out.
* Continue until last student standing

**Difference between Thermal Energy, Heat, and Temperature:**

Have students watch video linked [HERE](https://www.youtube.com/watch?v=K0SiEq3GAj0) (<https://www.youtube.com/watch?v=K0SiEq3GAj0>) and then use this simulation to observe the relation between energy and temperature:

<https://teachchemistry.org/classroom-resources/simulation-activity-heating-curve-of-water>

Ask Students to select points on the graph and make observations about the total energy required for the system:

* Why is energy still required to maintain a constant temperature along the graph?
* Is more or less energy needed to increase the temperature?

**PREPARATIONS**

Computer Prep

* Load the Energy2D simulation file onto student group computers
* Keep hidden until Pt. 2

Table Prep

* Set out hot plate out on table and set to 100°C and place beaker of water with 200ml in it, set thermometer and monitor temperature of water constantly.
* Ensure waste container central to each of the stations is clearly labelled “Waste”
* Set out and tare scales, set to grams.
* Prep samples of cold and warm water for each table
  + Easiest method for this will be to have mini water bottles/small amounts of liquid pre-portioned out for each station. Place one set in a fridge/on ice before the start of the experiment and warm the “warm” samples either in a microwave or on another hot plate. Samples should be noticeably different temperatures but safe to the touch.
* One keyboard will be out at each table
* Materials sheet containing examples of materials thermal conductivities, specific heats, and densities (Linked alongside this guide and student handout)

**STUDENT STATION SET-UP**

Students will work in pairs at an individual station and will share the computer with the other groups at their table during part 2.

Each student station receives:

* 1 paper towel
* 1 test tube rack (with one test tube)
* 1 Test tube clamp
* Test tube or cup of unknown material
  + Example unknown materials that work well: steel, copper, and aluminum shot. Utilizing metals with varying densities and specific heats will work best to help students identify their material at the end of the experiment
  + On the side of the container of the unknown metal, label with the density of whatever material it belongs to but do not write the name of said material. (for example, if using multiple different metals write Unknown A: 1.6g/ml)
* 2 weigh boats
* 2 calorimeters (one labelled W and one labelled C)
* 1 Thermometer
* 1 Burette clamp and stand (to hold thermometer)
* 1 25ml graduated cylinder
* 2 pencils

**LESSON PLAN**

**Introduction (5-10 min)**

* Welcome students to the lab and direct them to take a seat after retrieving a pair of gloves. Have students sit in pairs and evenly distribute groups around tables.
* Ask students if they have ever heard the phrase “hypersonic” or what it makes them think of.
  + Many students may reference “sonic the hedgehog” or the Sonic drive-thru restaurant, build off of that
    - What does “sonic” mean? Sound, specifically, how fast sound moves
    - Hypersonic: movement that is 5 times the speed of sound, also known as Mach 5
* Explain that even with all of our technological advancements, we only designed an aircraft to hit Mach 5 under its own power for the first time in 2004
  + NASA X-43
* Ask students why it might be difficult to develop an aircraft that can sustain such high speeds
  + Fuel requirements and drag may be answered and are correct
  + Push until a student brings up heat
* Friction from the drag on the aircraft leads to aerodynamic heat buildup that most aircraft are not designed to withstand
  + Re-entry from low earth orbit can cause spacecraft to reach temperatures of 1,480°C
* Explain that we will be testing materials today to find properties that might indicate whether or not they will be successful in insulating a space capsule along re-entry
  + Specific Heat: How much heat that is required to raise the temperature of a material by 1°C
  + Thermal Conductivity: The rate at which heat flows through a material from one side to the other
  + Thermal Diffusivity: How hast a temperature change propagates through a material.
* Give brief explanation as to the experimental procedure for this experiment.
  + Students will first work in their groups of 2 do determine an unknown material’s specific heat. This will give us a good understanding of the property and will also allow us to watch the heat transfer in real time.
  + Then we will shift to working with our entire table to run a computer simulation where we will be getting to use what we learned in pt 1 about heat transfer and apply that to our own space capsule.

**Part 1: Calorimetry and Materials Chemistry (30-45 min)**

* Have students turn to page 2 and introduce laboratory procedure and concepts: specific heat and calorimetry.
* Ask students to each identify the sample of unknown material provided to them at their stations.
  + Make visual observations about the sample.
* Explain that each table will be testing a different material and each of these materials has a different density, specific heat, and thermal conductivity.
  + Reference the materials sheet at their table, as students to make preliminary hypotheses about what material they believe they will be testing using visual observations.
* Go over equipment at table.
  + Hotplate safety: don’t touch, only use tongs and test tubes. Emphasize that any time something needs to be added to or removed from the hotplate heat protectant gloves should be used.
  + Metric scale: we’ll go over how to use in the next step but ask them if they are familiar with this tool, what does it measure (not weight, mass in grams)
  + Thermometer: Ask students what the thermometer is set to measure (Temperature,Celsius or Fahrenheit)
* **Specific Heat**
  + Introduce the law of conservation of energy, ask if anyone has heard of that and ask to give examples
    - Prompt with “Energy cannot be what?” Created or destroyed, only transferred
    - We can apply this to a process known as calorimetry, where energy of our hot object is equal to the energy of a calorimeter+the energy of the water inside
  + Before we begin the next phase of our activity, we actually want to get our samples heating up to have the best chance at a successful heat transfer lab, have students skip to steps 2.b and 2.c under the Specific Heat procedure
  + Remind students of their laboratory safety measures and the hazards at their table, we will be using very hot water and we need to take extra precautions to not spill and hurt each other
  + Prompt students to measure out approximately 5g of their unknown material (and record it on their papers
    - Once students have massed their sample and poured it into the test tube provided, instruct them to carefully place the tube into the glass of hot water in the center of the table, there will be space for all three groups to go at once.
    - Ask students about the material the test tube is made of, will this insulate or conduct heat from the water to the sample? Will the heat move slowly or quickly?
  + Switch back to calorimeter procedure
  + Pick up calorimeter and ask students what they think of it, what does it feel like, have they felt anything like this before?
    - Many students will be familiar with Styrofoam and may even bring up a coffee cup
    - Coffee cups are made out of Styrofoam, why for?
      * To keep our drinks hot
      * We will be using Styrofoam calorimeters for the same reason, Styrofoam is a highly efficient insulator and will be good at maintaining the temperature in the system
  + Explain that we will be using these calorimeters to measure a change in temperature when we heat up our materials
    - Our hot material will have its temperature measured, then will be poured into the calorimeter filled with lukewarm water, and a temperature change will be recorded
  + Ask students again what the thermometer is measuring?
    - Temperature
  + Will that temperature tell us all that we need to know? What does the law of conservation of energy actually tell us?
    - How **energy** moves, temperature is one variable in that equation. The variable we are actually searching for in this experiment is **C** or specific heat. We will talk more about this when it comes to our calculations, but keep in mind that while we will be measuring the temperature in our experiment, in the end, we will be looking at energy.
  + Have students review our final equation, each ∆q for each portion of the equation is broken down into a series of variables.
    - q= energy
    - C= specific heat
    - m= mass
    - T= temperature
  + Both the ∆q for the water and our unknown metal contain the variable C, for specific heat, but the calorimeter’s contains a bolded phrase “calorimeter constant”
    - This is because each calorimeter is going to have slightly different qualities that make them transfer heat a bit differently, unlike a known material like water or our metals. Each student is going to need to follow the procedure to find their specific calorimeter constant to use for their calculations later in the activity.
  + Walk students through experimental procedure and calculations
    - When completing calculations for the calorimeter constant, make sure students utilize the absolute value of each of their end q=mCT.
      * For example: if the end q=-76 the actual energy will be 76.
      * Ask students why we use the absolute value?
        + Because energy cannot be negative, the negative symbol is just telling me directionality
    - Ask at the end to compare calorimeter constants, are they all the same? Are they close?
  + For clean up: have students pour their water into the waste water bucket and move their cold calorimeter to the side, we will only be using the warm calorimeter for the remainder of this experiment
    - Use this as a chance to ask students why we’re only using the warm calorimeter: Because that is the one that we calculated the constant for.
    - Ask students again why we each needed to calculate our own, prompt to fill in the quick check on their page
  + Before beginning the final portion of the specific heat calculations, remind students of their laboratory safety measures and the hazards at their table, we will be using very hot water and we need to take extra precautions to not spill and hurt each other
  + Allow students to follow steps 2.d and 2.e on their own.
  + Once all groups are complete with step 2. e, show them how to take the temperature of their material in the test tubes.
    - Use thermometer and hold so that the end is in contact with the base of the test tube/material, wait until temperature is constant for 5 seconds, then remove and record temperature. If it continues to rise, give your sample another 60 seconds and check temperature again.
    - Ask students why we take the temperature of the material while it is still in the hot water: Because once we remove it, heat can begin to transfer elsewhere outside of our calorimeter.
  + Explain steps 2.g and 2.h before students remove their samples, as these will go quickly and we don’t want to lose any of that heat energy to the outside air.
    - Use docucam if available and demonstrate process of removing the material from the water and dumping it into the calorimeter, then using the thermometer to stir gently until the temperature is constant.
  + Students will record the final temperature of the water in their table and discard their water and materials in the same fashion they did for the density.
    - Ask students about their final water temperatures, what can we deduce from this measurement? Do we know our material’s final temperature?
      * Yes, our materials final temperature will match the water’s final temperature: Prompt further, why do we know that? What law can we reference that tells us that? Law of conservation of energy, equillibrium
      * No, or silence: prompt with a reminder of the law of conservation of energy, and explain that the energy moved from the hot object into the cool water, ask if they would be the same temperature
  + Students will then move onto the calculation phase once the final temperature of the water has been recorded. Give them around 10 minutes to complete this process.
    - Remind students that they will be going two steps further than they went for the calorimeter constant, instead of just calculating the energy for the calorimeter, they will be calculating the energy for all three aspects of the system (the material, the calorimeter, and the water)
    - Since we are solving for C of the material, the end equation will have them finding the value of ∆q(material) and then solving for C by dividing that by m∆T of the material
    - During this time, clear the stations of experimental materials so we can transition into the next phase of the activity
      * Heat blocks will be turned off and hot water removed only by staff member, at the discretion of the teacher. If space allows, just push the heat block away from student workstation until end of activity.
  + Once each station has completed their calculations, they will work together as a table to find the average between the three different trials taken
    - Ask why it is important to have multiple trials of the same material, why isn’t it reliable to just have one station of each?
  + Ask students to think back to their original hypotheses, and now compare their density and specific heats to the materials chart provided, and decide as a team which material their table had.
    - Once done, reveal the true identities to each table, ask students if they were correct and if not, what do they think went wrong?
  + Segue into next phase of experiment:
    - Ask students which material had the largest change in temperature, which one had the smallest? Which material has the highest specific heat? Would you want a material that insulates you to have a high or a low specific heat?
    - Ask them to use this knowledge to build their own space capsule to protect astronauts.

**Part 2: Space Capsule Re-Entry simulation (15-20 min)**

* Switch students computers over from docucam to Energy2D simulation and have students turn to page 9 in their handouts. Introduce the astronauts (students may laugh at the outdated Among Us joke) and explain that we need to get them home, but the hypersonic speeds our aircraft will be experiencing will produce too much friction heat for our bodies to handle.
* Thankfully, our astronauts are in space suits that can handle up to 121°C, so the students only need to get it down to 121° and keep it there for the entirety of the voyage (about 30 seconds)
* Prompt students on how many layers it appears the re-entry capsule has, why do they think we are using two different layers? What are the benefits as opposed to using one solid layer, where else may they have seen an insulated vessel similar to that?
  + Taking a sip out of a Stanley Cup or Hydroflask may help drive this point home, double-wall vacuum insulation using two layers.
* Each layer has 4 different available insulating materials, for a total of 8 types of materials
  + Students will notice that the materials listed in the module match the ones on their materials charts, they can use this chart to help make informed decisions about what they choose to select for their spacecraft.
* Walk students through steps 1-4 all together, showing students how to select materials, how to place them in the correct spot, and how to run the program
  + Students will need an external stopwatch or phone to keep time, once they hit start, they will need to time the trial for thirty seconds
* After everyone has witnessed one example trial, they will have 15 minutes to test as many models as possible and record the three best designs in the table provided. Walk around and assist as needed
  + Often students need help controlling the materials they are placing, or resetting to the beginning for a new trial
    - The easiest way to do this is to show them where the “reset” button is at the bottom of the screen, when the simulation prompts for a save action, have them select “No” and it will revert back to the original screen.

**Wrap Up/Conclusion (5-10 minutes)**

* Congratulate students for successfully getting their astronauts home
  + Make a game of it, ask which table got their internal temperature the lowest
* Discuss conclusions with students
  + What combinations did they find worked best?
  + Did anything not work how they expected it to?
  + Were there any patterns or trends relating to the specific heat and thermal conductivity that they noticed?
* Career discussions can happen here if there’s time
  + What careers do they think might utilize simulations like these?
    - Not just aerospace engineers, but scientists in most fields need to utilize chemical constants like these to understand their materials. That’s why every year or so a new cup company comes out of the wood work and develops the new popular drinking vessel that keeps your water slightly colder.
    - Not even just scientists, but electricians, contractors, and plenty of other occupations require an innate knowledge of how materials heat and move said heat.