Hypersonics STEM Curriculum

Material Engineering for Hypersonic Speeds

Grade	Time	Subject Area	Key Concepts
High School	35 min	Chemistry	Heat – melting point Thermal expansion

Lesson Overview

In this lesson, students will be given a set of ideal physical properties for materials used in hypersonic aircrafts as well as a set of data that lists possible materials and their melting point, density, and coefficient of linear thermal expansion. Students will analyze the data and create recommendations as to which materials they think will, and will not, work well for the aircraft.

NGSS Standards

HS-PS1-1 Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.

HS-PS1-3 Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.

HS-ETS1-1 Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

Learning Objectives

By the end of this lesson, students will be able to:

- Use physical properties of a material (melting point, density, and coefficient of linear expansion) to determine whether it is an ideal material to use on a hypersonics aircraft.
- Explain trends of where the ideal (and not ideal) materials for hypersonics aircrafts are within the periodic table.
- Brainstorm how to combine the properties of different materials to create a better material for hypersonics aircrafts.

Essential/Overarching Question

What materials are ideal for aircrafts that fly in extreme heat/temperature conditions?

Key Vocabulary

Speed – the rate at which an object is moving. Speed is calculated by dividing the distance travelled by the time it took to travel that distance.

Speed of Sound – the rate at which sound moves through a medium. The speed of sound depends on both the density and the temperature of the medium. The speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph).

Mach – the ratio of the speed of an object to the speed of sound or how many times the speed of sound an object is moving. It is often followed by a number indicating the ratio; for example: Mach 1 is the speed of sound, Mach 2 is twice the speed of sound, Mach 5 is five times the speed of sound.

Sonic – speeds equal to the speed of sound (Mach 1).

Subsonic – speeds smaller than the speed of sound (less than Mach 1).

Transonic – speeds near (Mach 0.8-1.2) the speed of sound where drag is highest (e.g. sound barrier).

Supersonic – speeds greater than the speed of sound (Mach 1 and greater).

Hypersonic – speeds greater than five times the speed of sound (Mach 5 and greater).

Fluid – a substance with no fixed shape; a liquid, gas, or plasma. A substance that flows when an external force is applied to it.

Flow – the motion of a fluid (liquid, gas, or plasma) when it experiences unbalanced forces.

Temperature – the measure of the average kinetic energy of the particles in an object. A quantity to describe how hot or cold an object is.

Melting Point – the temperature at which a solid will melt into a liquid. At this temperature, the solid and liquid form of a substance can exist in equilibrium.

Density – mass per unit volume. How compact an object is.

Coefficient of Linear Thermal Expansion – the rate at which a material will change its shape as temperature changes, the expansion per change in temperature.

Sublimation – the transition from the solid phase to the gas phase without going through the liquid phase.

Ablation – The dissipation of heat created by atmospheric friction by means of a melting heat shield. Or the reduction or removal of a heat-protective surface material (like a heat shield) by aerodynamic friction.

Stress – the force per unit area within a material that is caused by external forces.

Strain – the change in shape or size of a body due to an external force being applied on it, the degree of deformation per unit length.

Science Concepts Overview

As objects speed up from subsonic (slower than the speed of sound) to sonic (the speed of sound) to supersonic (greater than the speed of sound) and finally to hypersonic (greater than five times the speed of sound), the conditions that the aircraft experiences change and become more extreme. Additionally, the physics that describes those conditions changes as extreme speeds are reached.

One of the challenges of designing aircrafts to travel at hypersonic speeds is not only how do we get them to travel at those speeds, but also how do we use materials that can withstand those conditions, with the greatest challenge being heat. When choosing materials for hypersonic aircrafts, those material should be able to withstand high temperatures (1200 °C), should be able to travel through a variety of temperature conditions with minimal expansion, and should react to heat in a similar manner as other materials around it (i.e. expand in similar ways). In addition, hypersonic aircrafts should also be light, requiring less energy (fuel) to both launch and propel them.

As temperatures increase, the molecular kinetic energy of a material increases, which causes the molecules in the substance to vibrate more, causing a greater distance between them. This process causes the shape, area, and volume to increase. The rate that the molecules expand is different for each material. This can be problematic when designing aircrafts with a variety of materials. As temperatures increase, the different materials will expand at different rates and could cause issues with structural integrity.

Materials List

- ☐ Material Engineering for Hypersonic Speeds handout (one per student)
- ☐ Periodic Table of the Elements (one per student)
- ☐ Different colored sticky notes or stickers or markers

Lesson Preparation

Prior to the lesson, the instructor should make copies of the Material Engineering for Hypersonic Speeds handout and ensure that students have access to a copy of the periodic table. There are a couple of online, interactive periodic tables noted in the References & Resources section.

Safety

There are no additional safety concerns beyond normal classroom procedures for this lesson.

Procedure

Engage (5 minutes)

1. Watch the following video with your class: https://www.youtube.com/watch?v=oRLOwNPnieg
2. Ask students to read the Project Briefing section of the Material Engineering for Hypersonic Speeds handout either individually or as a class.

Explore (5 minutes)

3. For this lesson, students can either work individually or in small groups.
4. Students will explore the data provided in the Material Engineering for Hypersonic Speeds handout and answer the first question in the Analysis section:
    - What (if any) trends do you see when looking at the melting point, density, and coefficient of linear expansion data separately and all together?

Explain (10 minutes)

5. Students will explain how they would use the given materials by answering questions 2 – 4 in the Analysis section of the Material Engineering for Hypersonic Speeds handout:
    - Based on the data provided for you, what material, or combination of materials, would you use to build a hypersonic aircraft? What are the benefits of that (those) material(s)? What are the possible issues with that (those) material(s)?
    - Based on the data provided for you, what materials would you suggest that the engineers avoid using on their hypersonic aircraft? What are the possible issues with those materials?
    - Find the materials that you would (and would not) use on the periodic table (if they are on it). What do you notice about the placement of those materials on the periodic table? What does that tell you about the chemical properties of those materials, and therefore about the materials that are ideal (and less than ideal) for hypersonic aircrafts?

Elaborate (5 minutes)

6. Students will further elaborate how new materials could be made and by answering questions 5 – 6 in the Analysis section of the Material Engineering for Hypersonic Speeds handout:
    - If you were able to create a new material by merging the properties of a couple different materials, which ones would you choose and why?
    - Scientists are also looking to develop new materials that may be able to better handle these extreme conditions. If you were to pick one of the materials in the data table as the basis of this new material, what would you choose and why?

Evaluate (10 minutes)

7. List the different materials somewhere in the classroom such as on a white/chalk board or on a large sheet of paper. Using different colored sticky notes or stickers or markers, have students vote on their top and bottom two or three materials for hypersonic aircrafts. This gives both the instructor and the students a visual representation of the different ways the class analyzed the data.
8. Have a few students explain their reasoning for the materials they chose.
9. Instructors can also collect the Material Engineering for Hypersonic Speeds handouts from students to evaluate their individual understanding and give feedback to push their thinking further.

STEM Career Connections

- Aerospace engineer
- Materials scientists
- Chemical engineer
- Mechanical engineer
- Systems engineer

Extensions

As a further *elaborate*, students could choose one of the materials and research other physical and chemical properties of that material and whether those properties are ideal for hypersonic aircrafts.

References & Resources

Fisher Scientific. (n.d.). *Interactive periodic table of elements*. https://www.fishersci.com/us/en/periodic-table.html

Idaho National Laboratory. (n.d.). *Interactive periodic table of elements: Bringing the periodic table to life*. https://inl.gov/periodic-table/

National Air and Space Museum. (n.d.) *Hypersonic vehicles*. https://howthingsfly.si.edu/structures-materials/hypersonic-vehicles

National Air and Space Museum. (n.d.) *Materials*. https://howthingsfly.si.edu/structures-materials/materials

National Center for Biotechnology Information. (2022). *PubChem periodic table of the elements*. https://pubchem.ncbi.nlm.nih.gov/periodic-table/

Sean Lehan. (n.d.).Grade 9 chemistry, lesson 3 - Physical and chemical properties and changes [Video]. YouTube. https://www.youtube.com/watch?v=7zyiW-13jzk

Talented Tuber. (2017, April 11). *Difference between subsonic, supersonic and hypersonic speed* [Video]. YouTube. https://www.youtube.com/watch?v=LBJ3tXCjzN0

UVA Engineering. (2021, September 27). "Hypersonic flight- Hyper insulation" - Need for speed video contest [Video]. YouTube. https://www.youtube.com/watch?v=oRLOwNPnieg

Name: ____ Date: ____________________

Material Engineering for Hypersonic Speed

✈ Project Briefing

The Navy is working on a new material to use to build their hypersonic aircrafts. ***Hypersonics*** refers to objects traveling faster than five times the ***speed of sound*** (the speed of sound at ground level is roughly 343 m/s), or faster than Mach 5. When aircrafts transition from ***subsonic*** (slower than the speed of sound), to ***supersonic*** (faster than the speed of sound) to hypersonic, the conditions surrounding the object become more extreme. When flying that fast, aircrafts experience a lot of drag and fiction, and the amount of friction is dependent on the atmosphere (altitude) the aircraft is flying though. For example, re-entry vehicles start their descent at high altitudes and reach extremely high Mach numbers. As they reach lower altitudes, the atmosphere gets denser, increasing the drag and heat transfer.

When choosing materials for hypersonic aircrafts, those material should be able to withstand high temperatures (1200 °C), should be able to travel through a variety of temperature conditions with minimal expansion, and should react to heat in a similar manner as other materials around it (i.e., expand in similar ways). In addition, hypersonic aircrafts should also be light, requiring less energy (fuel) to both launch and propel them.

The Navy is looking into different options of aircraft materials that may better handle these extreme conditions. They are asking us to help their science and technology division analyze a set of data on possible materials and make recommendations. The Navy has provided us with data for twelve different materials on their melting point, density, and coefficient of linear thermal expansion for each. ***Melting point*** is the temperature at which the material goes from a solid to a liquid. ***Density*** is the material's mass per unit volume, or how compact an object is. And the ***coefficient of linear thermal expansion*** the rate at which a material will change its shape as temperatures changes. Review the data and answer the analysis questions.

✈ Data

Material	Symbol	Melting Point (°C)	Density (g/cm^3)	Thermal Expansion Coefficient ($x10^{-6}$ $(°C)^{-1}$)
Aluminum	Al	659	2.72	23.1
Beryllium	Be	1287	1.85	11.3
Copper	Cu	1084	8.92	16.5
Gold	Au	1064	19.28	14.2
Lithium	Li	1342	0.54	46
Nickel	Ni	1452	8.91	13.4
Silicon	Si	1414	2.33	2.6
Titanium	Ti	1668	4.55	8.6
Carbon Nanotube	C	3550	1.74	20
Stainless Steel	Cr+Ni+Mn+C	1371	7.93	17.3
Ceramic – Titanium Carbide	TiC	3160	4.93	7
Ceramic - Hafnium Carbide	HfC	3958	12.76	6.6

✈ Analysis

1. What (if any) trends do you see when looking at the melting point, density, and coefficient of linear expansion data separately and all together?

2. Based on the data provided for you, what material, or combination of materials, would you use to build a hypersonic aircraft? What are the benefits of that (those) material(s)? What are the possible issues with that (those) material(s)?

3. Based on the data provided for you, what materials would you suggest that the engineers avoid using on their hypersonic aircraft? What are the possible issues with those materials?

4. Find the materials that you would (and would not) use on the periodic table (if they are on it). What do you notice about the placement of those materials on the periodic table? What does that tell you about the chemical properties of those materials, and therefore about the materials that are ideal (and less than ideal) for hypersonic aircrafts?

5. If you were able to create a new material by merging the properties of a couple different materials, which ones would you choose and why?

6. Scientists are also looking to develop new materials that may be able to better handle these extreme conditions. If you were to pick one of the materials in the data table as the basis of this new material, what would you choose and why?