

Keep It Between 2 and 8: Choosing a Melting Pack for a Vaccine Cooler

Learning target: I can use a particle model of melting to predict how a pure substance will behave as it gains energy, and use that prediction with test data to choose and justify a design that meets criteria and constraints.

Transfer and design

About 55 min

Pairs

MS-PS1-4 · assesses

MS-ETS1-2 · practice

engineering design

data analysis

writing

Standards connections

MS-PS1-4 (assesses, predicting particle motion, temperature and state for a pure substance as thermal energy is added): Students predict, from melting points and the particle model, that a solid pack warms to its melting point and then holds that temperature while its particles leave their fixed positions, and they explain why more pack material holds longer and what happens once it has all melted. That prediction, applied to a new system, is evidence for the PE. No energy is calculated; the only arithmetic is cost.

MS-ETS1-2 (practice): Pairs evaluate four competing pack materials and three pack counts against stated criteria and constraints with a decision matrix before choosing. The criteria are given rather than written by students, so the sheet practices evaluation (ETS1-2), not problem definition.

Purpose: extend · **Time:** about 55 minutes · **Format:** pairs

Answers with reasoning

The problem

A county health clinic runs a mobile van that carries vaccines to rural schools and farmworker communities. On summer days the air outside can reach 35 °C or more. The vaccines ride in insulated coolers for up to 10 hours. Most vaccines must stay between **2 °C and 8 °C**: too warm and they slowly lose strength, and some are ruined if they get close to freezing. The clinic wants a reusable cold pack, a sealed pouch filled with one pure substance, that will hold the coolers in that range. Engineers often call these *phase-change packs*, because they work by changing state.

Criteria and constraints — Criteria (what success looks like): (1) the vaccines stay between 2 °C and 8 °C for at least 10 hours on a 35 °C day; (2) the vaccines never fall below 2 °C. **Constraints (limits on the design):** (3) the packs must be safe to ride in a closed van with people; (4) the packs must be made solid again overnight using only the clinic's refrigerator, which runs at 3 °C, or its freezer, which runs at −18 °C; (5) the clinic has \$250 for packs for its six coolers.

Four pack materials (real reference values at 101 kPa)

Option	Material	What it is	Melting point
A	Water (ice)	The familiar pure substance	0 °C
B	Tetradecane	A colorless, waxy compound made from petroleum	about 6 °C
C	Hexadecane	A similar waxy compound with longer molecules	about 18 °C
D	Dry ice (solid carbon dioxide)	Turns straight from solid to gas	−78.5 °C (sublimes)

Melting points are real reference values, rounded. Tetradecane and hexadecane are pure compounds of carbon and hydrogen; they have low toxicity but are harmful if swallowed, so the pouches must stay sealed and away from flames.

Part A: Predict with the model

1. For each option, predict the temperature the pack will hold near while it is changing state inside the cooler, and say whether that is too cold, in range, or too warm for vaccines.

Answer: A: about 0 °C while melting (and colder than that at first, because it starts at −18 °C); too cold. B: about 6 °C; in range. C: about 18 °C; too warm. D: about −78.5 °C while it sublimes; far too cold.

Why: A pure solid gaining energy holds at its melting point while it changes state, so the melting point predicts the temperature the pack holds near. Only tetradecane's melting point is between 2 °C and 8 °C.

Also acceptable: For A, accept 'starts at −18 °C, then holds at 0 °C' as a fuller answer.

- Each option's holding temperature equals its melting or sublimation point
- Only B judged in range
- A and D too cold, C too warm

2. Explain, using particles, why a pack of solid tetradecane can keep the inside of a cooler near 6 °C for hours even though energy keeps leaking in from the 35 °C air outside.

Answer: Energy flows into the cooler from the warm air and reaches the pack. First the solid tetradecane warms from 3 °C to its melting point of about 6 °C as its particles vibrate faster. Then the energy goes into letting the particles break out of their fixed positions and slide past one another as liquid, instead of making them move faster on average, so the pack's temperature stays near 6 °C. As long as some solid is left, the energy leaking in keeps melting more of it rather than warming the cooler, which holds the vaccines near 6 °C.

Why: This is the melting plateau of the PE model applied to a device. The explanation must connect added energy to a change in particle arrangement rather than a rise in average motion.

Also acceptable: Accept 'the energy is used up melting the pack instead of heating the cooler' if particle arrangement is also described.

- Energy is added to the pack from the warm surroundings
- The pack warms to its melting point first
- During melting the energy changes the particles' arrangement (fixed to sliding)
- So the temperature holds near 6 °C until the solid is gone

3. Which of the four packs can be made solid again overnight using the clinic's 3 °C refrigerator or –18 °C freezer? For each pack, name the appliance or explain why neither works.

Answer: A (water): only the freezer, because –18 °C is below 0 °C; the 3 °C refrigerator is above water's melting point. B (tetradecane): the refrigerator works because 3 °C is below about 6 °C, though only by about 3 °C, so the packs need the whole night (the freezer also works but would make the pack too cold at first). C (hexadecane): the refrigerator or freezer, since both are below about 18 °C. D (dry ice): neither; it is solid only below –78.5 °C at sea-level pressure, far colder than the freezer, so it must be bought new each day.

Why: A pack can be re-solidified only in an appliance colder than its melting point, so energy flows out and the particles settle back into fixed positions.

Also acceptable: Accept 'B: refrigerator or freezer' if the student notes the freezer would chill it below the range.

- Water needs the freezer
- Tetradecane works in the refrigerator
- Hexadecane works in either
- Dry ice cannot be made with clinic equipment
- Each reason compares the appliance temperature with the melting point

Part B: Evaluate the options

An engineer tested each option in identical coolers on a 35 °C day, with a temperature logger beside the vaccine boxes. She then tested different numbers of tetradecane packs.

Cooler test results and pack costs (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Option	Packs per cooler, and where they were stored overnight	Coldest reading at the vaccines (°C)	Hours with vaccines between 2 °C and 8 °C	Cost per pack	Notes
A	2 packs, from the –18 °C freezer	–5	4	\$4	Vaccines below 0 °C for the first 2 hours, then about 1–3 °C
B	2 packs, from the 3 °C refrigerator	4	11	\$18	Held near 6 °C until about hour 11, then rose above 8 °C
C	2 packs, from the 3 °C refrigerator	4	1	\$20	Rose above 8 °C within the first hour, then held near 18 °C
D	1 kg, bought that morning	–40	0	\$3 per kg, each trip	Vaccines frozen; gas pushed the cooler lid open

A teaching dataset: test results and prices are invented to be realistic and were not measured. Each test lasted 12 hours.

Number of tetradecane packs per cooler (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Tetradecane packs per cooler	Hours with vaccines between 2 °C and 8 °C
1	6
2	11
3	16

A teaching dataset from the same kind of 12-hour test on a 35 °C day.

4. Water ice melts at 0 °C, only 2 °C below the safe range, yet option A failed badly. Use the test data and the particle model to explain why.

Answer: The ice came out of the freezer at –18 °C, so for the first hours it pulled the vaccines below 0 °C (coldest reading –5 °C) while the ice warmed up to its melting point. Even after it reached 0 °C and began to melt, it held the cooler near its melting point, so the vaccines stayed at about 1-3 °C, mostly below the 2 °C minimum. Its flat step is simply below the safe range, and only 4 of 12 hours were in range.

Why: Two problems combine: the pack starts far below its melting point, and its melting point is below the range. A pack holds the temperature near its melting point, not inside the range you hope for.

Also acceptable: None.

- Notes the –18 °C starting temperature and the –5 °C reading
- Explains that the pack holds near 0 °C while melting, which is below 2 °C
- Uses the test numbers (–5 °C, 4 hours)

5. Complete the decision matrix. Write **yes** or **no** in each box, and in the last column say whether the option is still allowed.

Answer: A: no, no, yes, yes; not allowed (fails both criteria). B: yes (11 h), yes (coldest 4 °C), yes, yes (refrigerator); allowed. C: no (1 h), yes (coldest 4 °C), yes, yes; not allowed (fails criterion 1). D: no, no, no (gas builds up in a closed van and pushed the lid open), no; not allowed.

Why: Only tetradecane meets both criteria and all the constraints that can be checked in the matrix; the budget is checked in q6. Dry ice fails a safety constraint as well as both criteria.

Also acceptable: Accept 'unsure' for C or B in the van-safety column if the student notes the packs must stay sealed and away from flames; neither is ruled out by that.

- B is the only option allowed
- A fails criteria 1 and 2
- C fails criterion 1
- D fails both criteria and constraints 3 and 4

6. What would 2 tetradecane packs per cooler cost for all six coolers? What would 3 packs per cooler cost? Which plan fits the \$250 budget, and how much money would be left over?

Answer: 2 packs: $6 \times 2 \times \$18 = \$216$, which fits the \$250 budget with $\$250 - \$216 = \$34$ left over. 3 packs: $6 \times 3 \times \$18 = \$324$, which is \$74 over budget.

Why: Simple cost arithmetic; no energy calculation. The \$34 left over would buy one extra pack, enough for a third pack in one cooler.

Also acceptable: None.

7. Going from 1 pack to 2 packs nearly doubled the hours in range. Explain why more pack material holds the temperature longer, using particles. No calculation is needed.

Answer: Twice as much tetradecane means twice as many particles that must break out of their fixed positions before all the solid has melted. Energy leaks in at about the same rate, so it takes about twice as long to melt all of it, and the temperature stays near 6 °C for about twice as long.

Why: The length of the melting plateau grows with the amount of solid. The doubling is not exact (6 h to 11 h) because some time is spent warming the packs from 3 °C to 6 °C and the cooler itself also warms.

Also acceptable: Accept 'there is more solid to melt, so the flat step lasts longer' with particle language.

- More material means more particles to rearrange (more solid to melt)
- With energy entering at a similar rate, melting lasts longer
- No energy calculation

Part C: Decide and justify (write your own)

8. Write your recommendation to the clinic. Name the material and the number of packs per cooler. Justify it with every criterion and constraint, at least two numbers from the test data, and the particle model. Name one trade-off or risk of your plan and one way to reduce it.

Answer: Example: Use 2 tetradecane packs per cooler, stored overnight in the 3 °C refrigerator. In the test this held the vaccines between 2 °C and 8 °C for 11 hours, meeting the 10-hour criterion, and the coldest reading was 4 °C, so they never came near freezing. The packs are sealed and give off no gas, so they are safe in the van, and the refrigerator is colder than tetradecane's melting point of about 6 °C, so they become solid again overnight. Twelve packs cost \$216, under the \$250 budget. It works because the packs hold near their melting point while their particles break out of fixed positions, and 6 °C sits inside the safe range. Trade-off: 11 hours is only 1 hour more than required, so a hotter day or frequent lid opening could push the vaccines above 8 °C. To reduce the risk, use the \$34 left over for one extra pack in the cooler that travels farthest, keep coolers shaded in the air-conditioned van, and check a thermometer in each cooler every two hours.

Why: Score with the rubric. A full recommendation addresses both criteria and all three remaining constraints with evidence, explains the plateau with particles, and is honest about the small safety margin.

Also acceptable: A plan with 2 packs in most coolers and 3 in one, spending \$234, is a strong answer. A student who rejects all options and proposes a new design must still show how it meets every criterion.

- Names tetradecane and 2 packs per cooler (or a justified variation within budget)
- Addresses both criteria with test numbers
- Addresses safety, re-solidifying and budget
- Explains with the melting plateau and particle arrangement
- Names a trade-off (small margin, hotter days, combustibility) and a way to reduce it

9. Predict what will happen to the vaccines' temperature after the packs have completely melted, and describe what the particles in the packs are doing then.

Answer: Once all the tetradecane has melted there is no solid left to absorb the incoming energy by changing state, so the energy now makes the liquid tetradecane's particles move faster on average. The pack's temperature, and then the vaccines' temperature, rises above 6 °C and soon above 8 °C (in the test, after about hour 11).

Why: After the plateau ends, added energy raises average particle motion again, just like segment B of a heating curve.

Also acceptable: Accept 'it goes back to warming up like the cooler would without a pack' with particle language.

- The pack is now all liquid
- Added energy now speeds up the particles on average
- The temperature rises above the safe range

10. Propose one more test the clinic should run before using your plan all summer, and describe a result that would make you change your recommendation.

Answer: Examples: run the test on a 40 °C day, or with the lid opened for one minute every hour as it would be at a real clinic stop, or with a full load of vaccine boxes. If the vaccines leave the 2-8 °C range before 10 hours, the clinic should use 3 packs in the coolers at risk (within budget) or improve the insulation.

Why: Good tests target the conditions most likely to break the design, here the small time margin.

Also acceptable: Any realistic test (a longer route, a different cooler, packs that have been reused many times) with a decision rule.

- A test that changes one realistic condition
- A result that would change the decision, linked to the criteria

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
Model-based prediction (q1, q2, q7, q9)	Predicts each pack's holding temperature from its melting point; explains the plateau with particles leaving fixed positions while energy is added; explains longer hold with more material and the rise after melting.	Predictions correct; one explanation omits the particle arrangement or the after-melting stage.	Predictions partly correct, or explanations use 'cold' and 'heat' without particles.	Predictions unrelated to melting points.
Evaluation against criteria and constraints (q3, q4, q5, q6)	Matrix complete and correct; re-solidifying judged by comparing appliance temperatures with melting points; ice failure explained with data; budget calculated with money left over.	Matrix mostly correct with one error; budget correct.	Matrix incomplete, or options compared on one criterion only.	No systematic comparison.

Recommendation and justification (q8)	Clear choice of material and number, justified against every criterion and constraint with at least two test numbers and the particle model; names a real trade-off and a sensible way to reduce it.	Clear choice justified against most criteria and constraints; trade-off named but not addressed.	Choice stated with a general reason, few data, no trade-off.	No clear recommendation, or one that breaks a criterion or constraint.
Testing and improvement (q10)	Proposes a realistic test of the most likely failure and states a result that would change the decision.	Proposes a realistic test without a clear decision rule.	Proposes a test unrelated to the risks in the plan.	No test proposed.

Teacher notes

The melting points are real: water 0 °C, tetradecane about 5.9 °C, hexadecane about 18 °C, and dry ice sublimates at –78.5 °C at 101 kPa. The test results and prices are invented. The scenario reflects real practice: refrigerated vaccines are kept at 2–8 °C, freezing damages some of them, and health agencies warn against packing them directly against ice packs taken straight from a freezer; commercial phase-change packs near 4–6 °C exist for this reason (many are blends rather than single compounds). Dry ice in a closed vehicle is a genuine hazard because the carbon dioxide gas it releases can build up and displace oxygen. This sheet is the chapter's one deliberate near-boundary case: the 3 °C refrigerator is only about 3 °C below tetradecane's melting point, so re-solidifying works but is slow, and real clinics condition such packs overnight and check that they are fully solid before use. Keep all reasoning qualitative; the only calculation is cost. If students ask why the plateau is not exactly doubled, the reason is that part of each run is spent warming the packs and the cooler from 3 °C to the melting point.

Scaffold offered to students: The flat step is the design

Think of the heating curve from class. While a pure solid melts at a steady pressure, its temperature stays flat at the melting point even though energy keeps flowing in. A phase-change pack is that flat step put to work. For each option ask: where is its flat step, and is that temperature between 2 °C and 8 °C? Then ask: can the clinic make it solid again (is the fridge or freezer colder than its melting point)?

Extension: Design for a colder job

Some vaccines must be shipped frozen, far below the 2–8 °C range, and some lab samples must stay below –60 °C. Explain which of the four materials could serve a shipment that must stay below –60 °C, what new safety constraints the clinic would have to add, and why that material cannot simply be refrozen in an ordinary freezer. Then explain why a pack that sublimates instead of melting is a problem in a closed van, using the particle model of a gas.