Testing Your Hypothesis by Boiling Water Below Its Boiling Temperature

Purpose

To have students boil water below its typical boiling temperature by reducing the pressure above the surface of the liquid

Overview

Groups discuss ways to reduce the boiling temperature of water and present their best idea. After discussing each idea, groups select an approach, write a procedure, and follow it. Students find that water can boil well below its typical boiling temperature. They try to make sense of their observations and discuss their conclusions in their groups. Next, the teacher gives the students a phase diagram for water without telling them what it is. The groups study it and write a caption for it based on what they think it shows. Through a discussion, the students learn about phase diagrams and use them to better understand their previous work with pressure and changes of state. Finally, the students hypothesize about the effects of different elevations and weather conditions on the boiling point of water.

Key Concept

Water boils when its vapor pressure equals atmospheric pressure. As a result, water's boiling temperature is pressure, rather than temperature, dependent.

Context for This Activity

Mars has such low atmospheric pressure that any water at the surface would boil away. In this activity, students see that they can get water to boil below its "typical" boiling temperature when they drop the pressure in a closed container. By extrapolating the pattern between boiling temperature and pressure, they realize that even water near its freezing point has enough kinetic energy to boil if the pressure is low enough.

Skills

- *Predicting* the outcome of an experiment
- *Developing* a hypothesis
- *Writing* a procedure to test a hypothesis
- *Controlling* variables
- *Conducting* an experiment
- *Using* a phase change diagram
- *Collecting*, *recording*, and *graphing* data
- *Drawing* conclusions and *communicating* them to others

Common Misconceptions

- Boiling is a process that is controlled solely by the heat source.
- Pressure has no bearing on water's boiling temperature.

Materials

Heat source, 500- or 1,000-milliliter round-bottomed, thick-walled (for example, Florence) flask, three-hole stopper, plastic tubing, thermometer, 100 cc or larger air piston (syringe), ring stand or tripod, ring clamps, thermometer clamp, stirring rod, wire gauze (burners only), graph paper, goggles, appropriate safety equipment.

Preparation

- Plan how to present the initial problem and the best way to develop a procedure.
- Insert thermometers in the rubber stoppers.
- Set out the necessary equipment for each group. Make sure the glassware is heavy-duty enough to withstand considerable pressure.
- Discuss safety procedures related to heat sources, thermometers, glassware, pressurized containers, and hot water.

Time: 2–3 class periods

Background

In Activity 3, students raised the boiling temperature of water by increasing the pressure above the water. To vaporize in the pressurized container, the water molecules needed to increase their kinetic energy. This increase in kinetic energy translated into a higher boiling temperature. Activity 5 is a natural extension of this earlier work. In this activity, students find ways to *reduce* the temperature of the water-to-vapor plateau. By challenging students to reduce water's boiling temperature, they must apply their understanding to a related, but new, situation. Their hypotheses will reveal how well they understand the relationship between pressure and boiling temperature.

Just how do you reduce water's boiling temperature? You can do this by reducing the pressure above the water. With a reduced pressure, the water molecules need less kinetic energy to vaporize than they do in an open container. This decrease in kinetic energy translates into a lower boiling temperature.

Whether water exists as a solid, liquid, or gas depends on its temperature *and* the pressure of the surrounding environment. Change the temperature or pressure, and water may undergo a phase change. We are familiar with how water responds to changes in temperature—at sea level, it typically freezes at 0 degrees Celsius and boils at 100 degrees Celsius. However, we are less familiar with how water responds to changes in pressure (recall Figure 4.1).

Researchers have measured the phase changes of water over a wide variety of temperatures and pressures. The resulting graph is called a *phase diagram* (Figure 5.1).

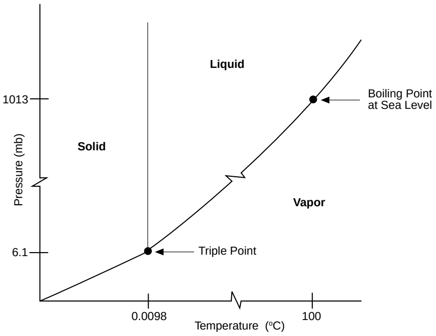


Figure 5.1. A phase diagram shows the equilibria among the three phases of water. At the triple point, the vapor pressure of ice, water, and water vapor are equal.

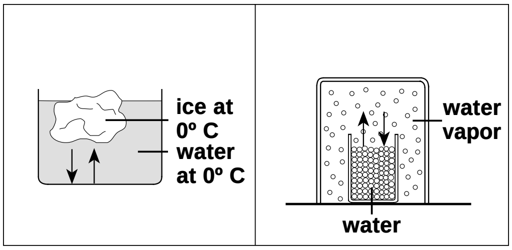


Figure 5.2. Water is in equilibrium with ice when it freezes at the same rate that the ice melts (a). It is in equilibrium with vapor when it evaporates at the same rate that the vapor condenses (b).

Every substance has its own unique phase diagram. At a boundary line between two phases, two phases are in *equilibrium* with one another—that is, the rate of molecules leaving a particular phase equals the number returning (Figure 5.2). We refer to the inclination of a molecule to change phase and establish an equilibrium as its *vapor pressure*. Vapor pressure increases with increasing temperatures. At higher temperatures, a particle's kinetic energy is higher, and, with more energy available at higher temperatures, it is easier for particles to change phase. Even solids such as ice have a vapor pressure and can *sublimate* directly to the vapor phase.

If two phases are not in equilibrium, molecules will change from one phase to the other until an equilibrium is established. The water evaporating out of a lake in the desert is trying to establish an equilibrium with the dry desert air. In the case of a puddle, the water disappears completely before an equilibrium is established. Each temperature-pressure combination has its own equilibrium point. If you connect these many equilibrium points, you will have drawn the boundary lines on the phase diagram.

All three boundary lines meet at a point called the *triple point*. At this temperature and pressure, all three phases are in equilibrium with one another. In other words, at the triple point, vapor sublimates to ice and condenses to liquid, liquid evaporates to vapor and freezes to ice, and ice melts to liquid and sublimates to vapor all at the same rate. A minuscule change in either temperature or pressure will move the phase changes away from the triple point. Away from the boundary lines, water exists in a single phase over a particular range of temperatures and pressures.

Because a phase diagram shows so clearly how water changes phase in relation to pressure and temperature levels, it is the key to helping students understand the current situation with liquid water on Mars. In fact, a phase diagram contains the essence of this entire module!

On the phase diagram, notice that below 6.1 millibars, liquid water cannot exist, irrespective of the temperature. Water's vapor pressure is just too high to remain a liquid below this level. When atmospheric pressure falls below 6.1 millibars, water can only exist as ice or vapor, depending on the temperature. This fact is significant in our study of Mars because the atmospheric pressure at the Martian surface hovers just above 6.1 millibars. Any water that might form on a warm afternoon from melting ice would quickly disappear in the desiccated Martian atmosphere. If the vapor pressure of the warmed water exceeded atmospheric pressure, it would boil. If, instead, its vapor pressure stayed below atmospheric pressure, the water would evaporate. The temperature and pressure combinations on Mars make liquid water theoretically possible on an occasional basis. However, the desiccated atmosphere and the short-term nature of the appropriate temperature-pressure conditions make the existence of significant amounts of water on the Martian surface impossible (Figure 5.3).

On Earth, propane, butane, dry ice, ether, and freon are familiar materials whose vapor pressure is considerably higher than Earth's atmospheric pressure. Toy stores often sell freon-filled "perpetual drinking birds" and globes containing freon that can boil when held in one's hand. Bring these or a butane lighter into class and discuss what is happening inside. On Mars, water would behave the way freon and butane behave on Earth.

Something to be alert to when discussing weather-related pressure changes is the fact that humid air weighs *less* than dry air. This is because water vapor (H_2O) weighs less than gaseous nitrogen (N_2). Because liquid water weighs more than air, students invariably say that humid air weighs more than dry air. This response reveals that they make no distinction between liquid and gaseous water, even though we teach about states of matter. Consider addressing this common misconception during the activity. So, there are actually two reasons why low pressures are associated with rainy weather—a humid air mass weighs less than a dry air mass, and a low pressure system rises to a lower altitude than a high-pressure system (that is, it is not as tall).

Use the phase diagram to answer questions about cooking modifications, the boiling of eggs, and water sterilization. Whenever the pressure changes, there is a corresponding change in water's boiling temperature. People living at high altitudes use pressure cookers, cook foods longer, or modify their recipes to compensate for the lower boiling temperatures. In fact, Galileo used differences in boiling temperature to calculate elevation. Students might try to predict the weather or measure elevations using water's boiling temperature.

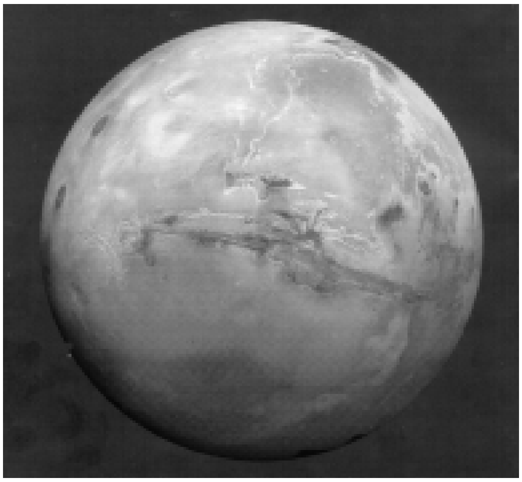


Figure 5.3. This image of Mars shows that the Martian surface is currently dry.

Preassessment

(a) *Students Take a Position and Become Aware of Their Preconceptions:* Ask students:

- How low can air pressure on Earth be lowered?
- What happens when one lowers the air pressure over some liquid water?

(b) *Students Expose Their Beliefs:* Have each student write down his or her prediction, sign his or her name, and hand it in to the teacher.

Procedure to Test Students' Preconceived Ideas

1. At the end of Activity 3, each group developed a hypothesis about the relationship between pressure and water's boiling temperature. For this lab, ask students groups to suggest procedures to *reduce* the boiling temperature of water.
2. Have each group present its best idea for how to reduce the boiling temperature of water and explain how its approach works. List the ideas on the board, and have the class identify the ones that achieve the objective and are testable in the classroom.

   If students suggest some feasible, nonpressure-related ideas, decide whether you want the groups that came up with them to test their procedures. Doing so maintains student ownership of the problem but risks extending the time required to complete the unit. Record any unused hypotheses for future projects.

3. Depending on time, equipment, and the nature of the suggested procedures, decide which approach below best fits your situation:

   - Have each group select a feasible idea, write a procedure, and follow it.
   - As a class, select a feasible idea, write a procedure together, and have each group follow it.
   - Write a procedure as a class, and then perform it as a demonstration (see Figure 5.4).

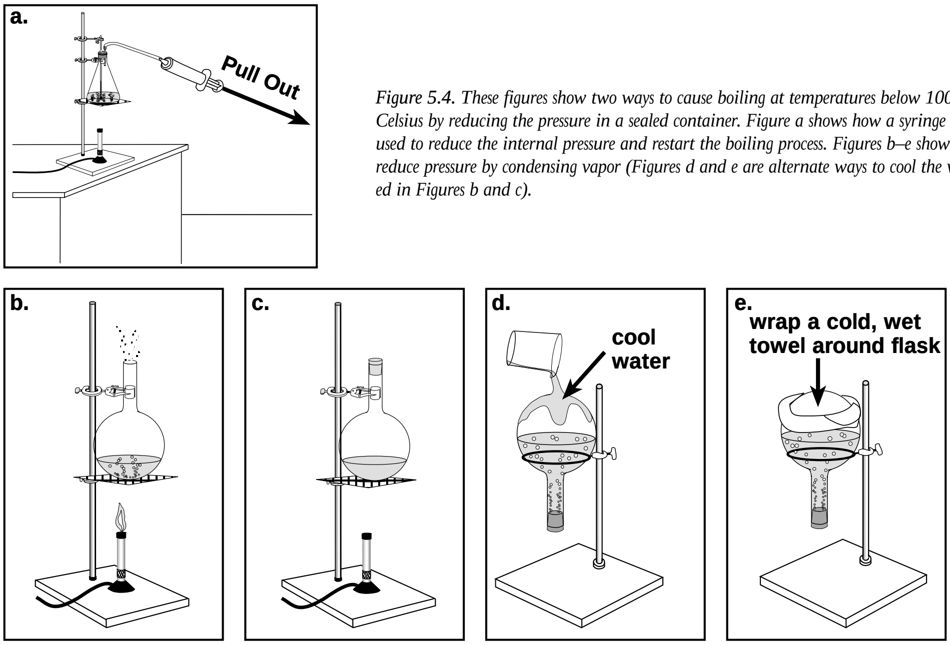


Figure 5.4. These figures show two ways to cause boiling at temperatures below 100 degrees Celsius by reducing the pressure in a sealed container. Figure a shows how a syringe can be used to reduce the internal pressure and restart the boiling process. Figures b–e show how to reduce pressure by condensing vapor (Figures d and e are alternate ways to cool the water heated in Figures b and c).

Writing a procedure as a class enables you to discuss the elements of a complete procedure and to highlight safety concerns. If groups each write their own procedures, you may want to check the procedures for dangerous practices before having students begin. Writing the procedure can also be assigned as homework and discussed at the start of the next class, either in groups or as a class. The appeal of a demonstration is its efficiency. However, research shows that students retain ideas best when they play an active role. A demonstration robs students of the direct involvement so crucial to experiencing and understanding an activity.

4. After groups complete the procedure, have them summarize their observations.

5. Have each student explain in his or her own way how water can boil by lowering the temperature of the flask.

   This step is vital in helping students resolve any conflicts between their preconceptions and observations. By making sense of the observations, students are forced to confront their earlier thinking and to accommodate a new concept.

6. Have students share their explanations in their groups.

7. Have groups summarize their conclusions and share them in a class discussion.

8. Without introducing it, distribute the two phase diagrams of water to each group. Have each group write a caption for the diagram based on what they think it shows.

9. Have groups share their captions in a class discussion.

10. Ask groups to explain how this diagram can be used to explain what happened in this activity and in Activities 1, 2, and 3.

11. Have students hypothesize about the effects of different elevations and weather conditions on the boiling point of water. Ask how they might test their hypotheses.

    Have students test their hypotheses by boiling water under different weather conditions and/or by contacting schools at very different elevations and comparing boiling temperatures.

Questions to Probe Students' Observations

1. How did you lower the boiling temperature of water?

2. What was the temperature of the water when it boiled?

3. Why did your approach enable water to boil below its typical boiling temperature?

Analysis Questions

This series of questions probes students' assumptions and understanding of boiling. Use them as the basis of a discussion, for group work, or for homework.

1. Use the phase diagram to explain why, under the same weather conditions, it is harder to make hard-boiled eggs in Denver, known as the "mile-high city," than in Miami, a sea-level city.

2. On rainy days, water's boiling temperature is several degrees lower than it is on dry days. Also, water at sea level boils at a higher temperature than water at higher elevations. Why does boiling temperature vary?

3. How could you use boiling temperature to predict weather or determine elevation?

4. How might recipes need to be modified for mountain cooking?

5. Why is it hard to sterilize drinking water by boiling it at a higher elevation?

6. Will water always boil at the same temperature in your kitchen? Why or why not?

7. How could you get water to boil at its freezing temperature?

   Lower the pressure to the triple point.

8. What do you think water would look like at the triple point?

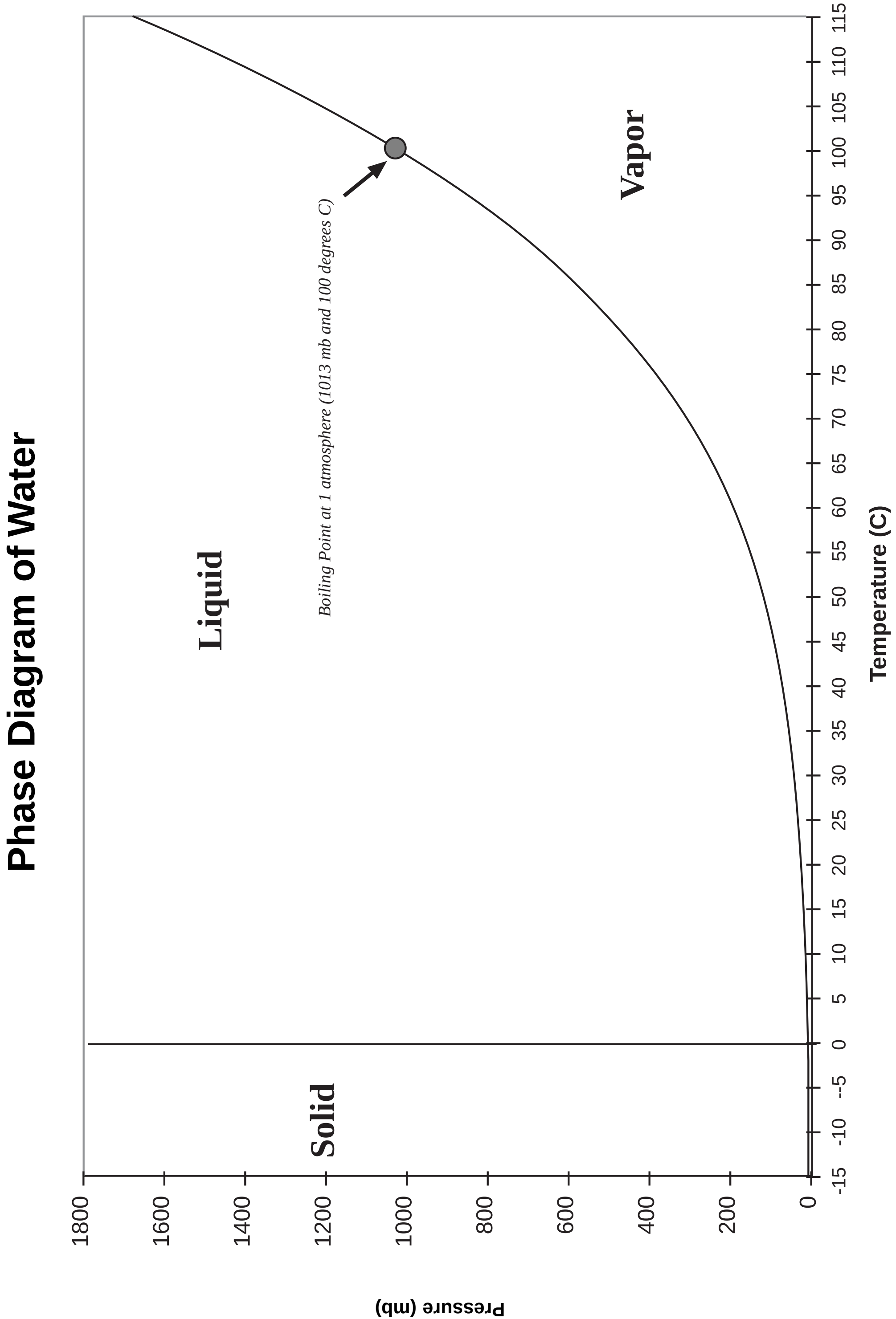
   Water can change phase only after crossing a boundary line. Therefore, it would remain in its current phase until it crossed a boundary line. However, the three phases are in equilibrium at the triple point. As a result, the water would change phase in order to establish an equilibrium between all three phases over time.

9. Why does water not boil at room temperature? What stops it from turning into a vapor?

10. Suppose you are on a climbing expedition to the top of Mount Everest. Near the top you decide to pause and boil tea for lunch. What can you predict about the process of boiling here? Would the tea burn your mouth?

11. Write a paragraph comparing how you answered the preassessment question with how you would answer it now.

12. At the start of this unit, you were asked to write down how hot could you heat water given unlimited time and heating equipment. How would you respond to this question now?



Phase Diagram of Water

Detail of the Phase Diagram of Water from –1 C to 2 C