A2 Storing heat – From heat store to molten salt

Enough apparatus and materials are supplied to allow eight groups of students to conduct the experiments simultaneously. When all the subexperiments are conducted in the suggested sequence, they form a basis for a learning unit on heat, heat storage, temperature, phase transition (states of matter), heat of fusion, and latent heat. These instructions provide explanatory notes and ideas for further study.

1 Main question

Many technical processes – and especially those related to renewable energy sources – produce heat, which is often discharged unused into the environment. An important question for the future, therefore, is how this heat can be stored and used.
The suggested experiments demonstrate that heat can be stored and how it can be stored, including over longer periods of time. In the simplest case, water is used. A more effective storage medium is molten salt, which can discharge large amounts of heat as it hardens (crystallizes). The experiments use commercially available heat packs filled with a sodium salt of acetic acid.
Conducting these experiments teaches students that heat that cannot be used at the time it is produced does not necessarily have to be wasted through temperature equalization with the environment, but can also be used later on. They come to understand the principles behind heat accumulators (e.g., water heaters, seasonal heat stores) and (chemical) latent heat stores that work with molten salts. They learn the methodology for systematically taking and interpreting single and comparative measurements.

2 Integrating the experiment into the teaching context

2.1 Basic principles

Although everyday experience has already taught students at a very young age about the transitions between solid, liquid, and gas – water being the prime example – they are not always aware that every transition is associated with energy transfer. The experiments can be used to build on this students' prior practical knowledge and develop a deeper understanding of the fact that the heat of fusion (and of evaporation) can also be used to store energy.
For further study, the topic can be examined at the particle level, at which heat is interpreted as motion and entropy plays a role in a material's energy content.

2.2 Relevance to the curriculum

States of matter and transitions are topics suitable for students aged 13 and up. A differentiated consideration of energy transfer begins early on, but the more detailed technical background comes later.
Although the topic is appropriate for both physics and chemistry classes, it offers content that is fundamentally cross-disciplinary. Practically speaking, the experiments can be used to teach both subjects, but they can also be included in teaching projects that deal comprehensively with the technical side of heat storage.
The core concept is the possibility of using heat by employing suitable materials to store it. In technical terms, the experiments focus on the concept of states of matter, along with their transitions and the associated energy transfer.

Topics and terms: crystallization, crystallization heat, crystallize, energy transfer, entropy, entropy effect, heat, heat capacity, heat insulation, heat of evaporation, heat of fusion, heat store, insulation, latent heat store, lattice binding energy, molten salt, particle model of heat, phase transitions, sodium acetate, states of matter (solid, liquid, gas), supercooling, temperature, temperature variation

2.3 Skills

The students will ...

- learn about the transition between liquid and solid states of matter as a source of heat release.
- recognize the possibility of storing the heat produced for later use.
- come to understand that all transitions between states of matter are associated with energy transfers.

2.4 Explaining the experiment in the teaching context

It is recommended that the experiments be used in pairs:

- The first pair deals with the possibility of using water to store heat.
- The second pair uses a commercially available heat pack, or rather its contents (a sodium salt of acetic acid), to demonstrate the energy transfer of transitions between states of matter (in this case, crystallization).

2.4.1 Subexperiment 1: Water as a heat store – Not only the tea gets cold

Due to its high heat capacity, water is an excellent medium for storing heat. But without insulation, water continually releases this heat into the environment until its temperature has equalized with the ambient temperature. Students should measure the temperature variation of water starting from approx. 60°C, enter the measured value in a table, and prepare a graph (temperature over time). The finished graphs are a good illustration of how the water temperature drops.

2.4.2 Subexperiment 2: Water as an effective heat store – Water can stay hot longer if …

For the heat stored in water to remain usable over a longer period of time, the vessel in which it is stored must be insulated as well as possible. Students should repeat subexperiment 1 using various commonly available materials. The temperature variation then indicates the quality of the heat insulation and the practical storage options.

If the material chosen insulates well, the temperature drops more slowly than it does without insulation.

2.4.3 Subexperiment 3: Heat for cold fingers – Is the heat pack a heat store?

The basis for first experiment on the heat of fusion and crystallization is the phenomenon by which heat packs with liquid contents heat up during crystallization and release heat over a longer period of time at a constant temperature. Students know from everyday experience (candle wax) that a solid requires additional energy (in the form of heat) to melt. The reverse, however – that heat is released during the hardening process (also called solidification or crystallization) – may be surprising. Heat packs are especially suitable for demonstrating this effect, because the liquid is a supercooled molten mass that crystallizes only after a metal disk is bent. (Bending causes crystallization seeds to form, similar to scraping with a glass rod – see subexperiment 4.)
This experiment can be repeated as often as desired by placing the heat pack in extremely hot water (approx. 90°C) for about 10 minutes or until the crystals have completely melted. (It is recommended that the teacher do this using an electric kettle during the preparation or follow-up period for the experiment.)

2.4.4 Subexperiment 4: How the heat pack stores heat – A salt that changes between solid and liquid states

To examine the processes in more detail, a heat pack is cut open. Some of the contents are then transferred to a test tube, melted, and caused to crystallize again after cooling by scraping with a glass rod. The temperature is monitored throughout the entire process.
The experiment demonstrates that solidification always occurs at the same temperature (approx. 50°C to 58°C, depending on the type of heat pack), which corresponds to the solid's melting point. (Actually, the values measured in student experiments are often lower due to heat losses.)
This experiment can be repeated only to a limited extent, because a little water is lost each time the substance is heated, thus altering the composition of molten mass and solid until no more clear liquid can be formed.
Note: It is recommended that the teacher cut open a hardened heat pack and distribute the salt to the students. The remaining salt can be preserved in a tightly sealed container and used for experiments with other classes. (If necessary, occasionally add a few drops of water to compensate for losses through evaporation.) Since the box contains nine heat packs, this will ensure that there will always be enough packs for eight groups of students.

2.4.5 Background information on heat packs

The solid material is generally sodium acetate trihydrate, which has a melting point of 58°C. (In heat packs commercially available today, the water content has apparently been changed because of the risk of burning, with the result that the melting point is often only about 50°C.) Whereas most other salts tend toward spontaneous seed formation and crystallization (and therefore are not as easily supercooled in a molten mass), this salt remains liquid for a very long period of time, even at lower temperatures. If we do not get a reading of exactly 58°C for our experiment, it has to do with the measurement conditions or the composition of the heat pack.

A typical measurement curve for the heat pack looks as follows:

T [°C]

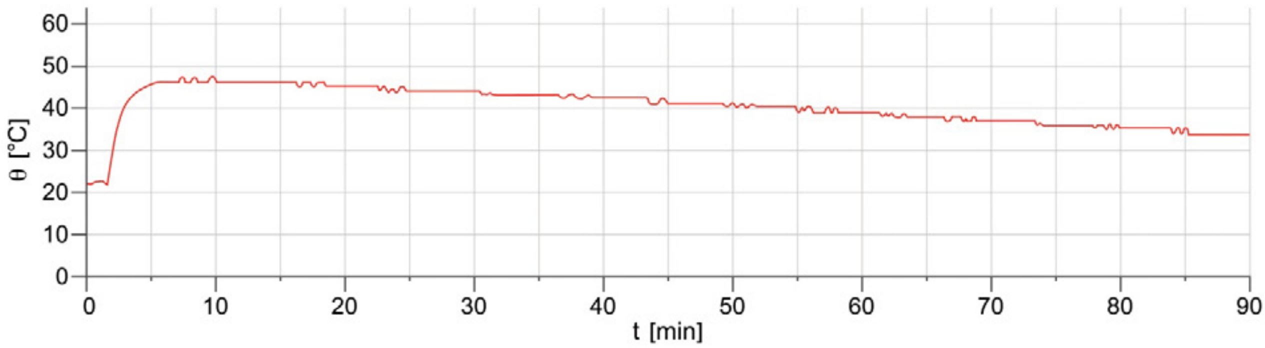

Fig. 1: Temperature curve of a heat pack.

From a physicochemical point of view, the explanation of energy transfers and heat release is slightly more complicated. There is said to be an entropy effect, because the particles are more highly organized in the solid than in the molten state. However, this perspective has limited significance for classes of 13-to-16-year-olds.
It is also interesting to answer the question why crystallization is triggered by bending a metal disk or by scraping the mass with a glass rod. Students will easily understand crystallization on tiny foreign bodies that serve as crystallization seeds, upon which the first atoms of the hardening substance grow. (This effect is often used in metal casting.) However, crystallization is also possible without crystallization seeds. What happens when the metal disk is bent? A prevalent “explanation” states that nanocrystals of salt deposited on the metal act as seeds to start the crystallization process when the disk is bent. This explanation is contradicted by the fact that scraping with a previously unused glass rod free of nanocrystals (see subexperiment 4) also triggers crystallization. If we apply the findings gained in the field of materials science when metals harden to the triggering of crystallization of molten salt, we come up with a different explanation: The shock waves generated by the bending or scraping cause some ions to come so close to each other that they form conglomerates (or “energy centers”) that then act as crystallization seeds.

Important note:
Start of crystallization:
In subexperiment 3 (heat packs), students should make sure they do not bend the metal disk so far that it breaks. In an intact heat pack, it is sufficient to carefully bend the metal disk just far enough to hear or feel a snap to trigger the crystallization.

The heat pack is already hardened:
Even before being used the first time, the heat packs might not be in the liquid state due to pressure, impacts from other objects, or vibrations during transport. In this case, it is best for teachers to regenerate them in an electric kettle, as described in Section 4.5. Afterwards, they should work correctly again.

2.5 Experimental variations

- All experiments can be conducted individually and in small groups. Temperature variations should be measured in teams of at least two students so that the measured values can be read and recorded separately.
- To obtain an accurate, reproducible reading in subexperiment 3, it is recommended that students work on an insulated surface (e.g., corrugated cardboard), that the heat packs be wrapped around the thermometer's probe, and, if possible, that they be secured with rubber bands (or string).
- If your school has enough test tubes and stoppers on hand, at the end of subexperiment 4, the students could seal the test tube containing the hardened sodium acetate with a stopper. Stored in this manner, the sodium acetate can be used repeatedly.
- Perform subexperiments 1 and 3 as per the instructions. Subexperiment 2 can also be elaborated by the students themselves and then conducted. This procedure gives the students an excellent opportunity to deliberately use and apply scientific methods.
  To ensure that the test tube containing hot water in subexperiment 2 is well insulated, the students must test several different insulating materials. When the test tube is wrapped in a woolen cloth, the temperature drops only 3 degrees less over a 20-minute period than it does without any insulation (see table).

	Starting temperature	**After 3 min.**	**After 6 min.**	**After 9 min.**	**After 12 min.**	**After 15 min.**	**After 18 min.**
Water in the test tube	46.5°C	41.4°C	37.6°C	35.1°C	32.5°C	30.3°C	28.5°C
With woolen cloth	47.4°C	43.5°C	40.5°C	37.9°C	35.5°C	33.5°C	31.6°C

- So that students can better understand the absorption of heat during the melting process, they can measure the temperature variation when heating a mixture of water and ice: as long as there is any ice remaining, the temperature of the mixture stays at 0°C. Another suitable demonstration experiment would be the boiling and evaporation of water. In this case, the temperature of the liquid remains at 100°C until the very end (or slightly lower, depending on altitude and air pressure).
- For older students and higher grades, heat can also be explained on the particle level.
- Be sure to discuss the technical and practical applications of long-term heat storage. For example, today's modern office buildings are already being heated by means of seasonal heat stores: In summer, the sun heats water stored in well-insulated underground gravel-water pits. In winter, this water then releases heat into the heating systems.
  Salts other than sodium acetate can be used to store heat in other temperature ranges. Currently, salt mixtures with melting points of up to approx. 800°C are being used. The energy is often fed back into a technical process – for example, to preheat a material prior to a chemical reaction. Solar thermal power plants such as Andasol in southern Spain also use molten salt storage. With a mixture of potassium and sodium nitrate that melts at 400°C, the plant can also run at full power for 7 hours after the sun goes down.

3 Additional information on the experiment

You will find additional media for preparing or for further study of this experiment on the Siemens Stiftung Media Portal
https://medienportal.siemens-stiftung.org

4 Notes on conducting the subexperiments

4.1 Facilities

No special facilities are necessary.

4.2 Time required

	Preparation and execution
Subexperiment 1	20 – 30 min., preparation 5 min.
Subexperiment 2	Depending on learning group and variation, from 20 min. to one teaching period
Subexperiment 3	10 min. incl. preparation
Subexperiment 4	15 min. incl. preparation

4.3 Safety aspects

The students may conduct the experiments only in the presence and under the supervision of the teacher. The teacher is to point out to the students that the provided materials may be used only according to the respective instructions.
For these experiments, watch out for the following potential dangers and make your students aware of them:

- Make sure that no damage can occur to water-sensitive materials and apparatus.
- Working with a flame can result in burns or fires. Before a lighter is used for the first time, the teacher must check that it is working properly and, above all, adjust the flame height.
- Working with hot water (subexperiments 1 and 2) can result in scalding.
- The boiling of water to regenerate the heat packs (subexperiment 3) is too hazardous to be performed at the student workstation in a normal classroom. Therefore, the teacher should regenerate the heat packs during the preparation or follow-up to subexperiment 3 (regenerate all heat packs simultaneously).
- Heat packs should be cut open only under the supervision of a teacher and preferably by the teacher. However, sodium acetate trihydrate and anhydrous sodium acetate are not considered hazardous.
- When working with molten salt, students must wear safety goggles. If the 16 pairs of safety goggles in the box are not enough, additional pairs may need to be provided by the school.

4.4 Apparatus and materials

Required materials that are not supplied:
If the teacher wishes to regenerate the heat packs during class, boiling water is required. A large electric kettle with an enclosed heating element is preferred. The heat packs are placed in the kettle, the water is brought to a boil, and the heat packs are left in the hot water for approx. 10 minutes.
Each group will also require either a watch with a second hand or a stopwatch and one lighter (if possible, a gas igniter) or matches.
Insulation materials must be available for subexperiments 2 and 3, such as a woolen glove or scarf, corrugated cardboard, styrofoam, etc.
If the experiment was already conducted once before, use the salt from the heat pack that was previously cut open.

Supplied:
Enough apparatus and materials are supplied to allow **eight** groups of students to conduct the experiments at the same time.
Safety-relevant materials and apparatus must be tested for proper functioning before being handed out to the students.
The following materials included in the kit are needed for **one** group of students:

Material	Quantity
Digital thermometer*	1x
Glass rod	1x
Heat pack (with molten salt)	1x
Plant clip (as test tube holder)	1x
Rubber band	2x
Safety goggles	1x**
Syringe (conical tip), 5 ml (as pipette)	1x
Tea light	1x
Teaspoon	1x
Test tube, glass, 13 cm	2x
Test tube clamp, wooden	1x

*Remove the plastic sleeve before the first use. Press the “on/off” button to turn on the thermometer. After completing the experiment, turn off the thermometer again (press “on/off” again). Press the “°C/°F” button to switch between the Celsius and Fahrenheit temperature scales.
**A total of 16 pairs of safety goggles are supplied for all students in all groups. If more than 16 students participate in the experiments, additional pairs may need to be provided by the school.
Note: A heat pack must be cut open the first time subexperiment 4 is conducted, meaning that one heat pack is “used up.” As a replacement, the box contains an additional (ninth) heat pack. The contents of the open heat pack must be saved (see Section 2.4.4) so that no additional heat pack will need to be “used up” when the experiment is conducted with other groups of students.

Fig. 2: Apparatus and materials supplied for one group of students.

4.5 Cleanup, disposal, and recycling

All apparatus and nearly all materials from the kit can be reused. Therefore, after the students have completed the respective experiment, they should put the apparatus and materials back in the appropriate boxes and return them to the kit. This practice will ensure that you and your colleagues will find everything again quickly the next time the kit is used.
Apparatus that become dirty during the experiment, such as cups, bowls, spoons, and test tubes, should be cleaned before being returned to the kit. We recommend that you have the students do this immediately after they have completed the experiment.
Also make sure that the apparatus are in working order for the next time. For example, recharge used accumulators immediately (It makes sense to charge the accumulators even if they will not be used for an extended period.).
Materials that cannot be reused, such as used pH test strips and filter paper, should be disposed of properly.
The waste that accumulates during this experiment can be disposed of in the regular trash or poured down the sink.
Note on regenerating the heat pack: This is a fairly long process: Once they are immersed in boiling water, it takes 10 to 15 minutes for all the salt to melt. Afterwards, the heat pack must be cooled to room temperature, which can take 30 minutes or more, depending on the ambient temperature. Do not try to speed up the cooling process using cold water, because this often interferes with supercooling and the heat pack immediately hardens.