Section 11.5

The Formula for a Hydrate

Objectives

- **Explain** what a hydrate is and how its name reflects its composition.
- **Determine** the formula for a hydrate from laboratory data.

Vocabulary

hydrate

Have you ever watched crystals slowly form from a water solution? Sometimes water molecules adhere to the ions as the solid forms. These water molecules become part of the crystal and are called water of hydration. Solids in which water molecules are trapped are called hydrates. A **hydrate** is a compound that has a specific number of water molecules bound to its atoms. **Figure 11-12** shows examples of a common gemstone called opal, which is composed of silicon dioxide (SiO_2). The unusual coloring is the result of the presence of water in the mineral.

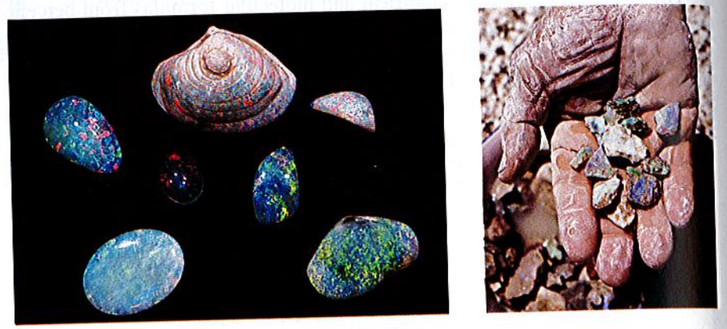

Figure 11-12

The presence of water and various mineral impurities account for the variety of different colored opals. Further changes in color occur when opals are allowed to dry out.

Naming Hydrates

In the formula for a hydrate, the number of water molecules associated with each formula unit of the compound is written following a dot: for example, $Na_2CO_3 \cdot 10H_2O$. This compound is called sodium carbonate decahydrate. In the word *decahydrate*, the prefix *deca-* means ten and the root word *hydrate* refers to water. Decahydrate means that ten molecules of water are associated with one formula unit of compound. The mass of water associated with a formula unit must be included in molar mass calculations. Hydrates are found with a variety of numbers of water molecules. **Table 11-1** lists some common hydrates.

Table 11-1

Formulas for Hydrates

Prefix	Molecules H_2O	Formula	Name
Mono-	1	$(NH_4)_2C_2O_4 \cdot H_2O$	Ammonium oxalate monohydrate
Di-	2	$CaCl_2 \cdot 2H_2O$	Calcium chloride dihydrate
Tri-	3	$NaC_2H_3O_2 \cdot 3H_2O$	Sodium acetate trihydrate
Tetra-	4	$FePO_4 \cdot 4H_2O$	Iron(III) phosphate tetrahydrate
Penta-	5	$CuSO_4 \cdot 5H_2O$	Copper(II) sulfate pentahydrate
Hexa-	6	$CoCl_2 \cdot 6H_2O$	Cobalt(II) chloride hexahydrate
Hepta-	7	$MgSO_4 \cdot 7H_2O$	Magnesium sulfate heptahydrate
Octa-	8	$Ba(OH)_2 \cdot 8H_2O$	Barium hydroxide octahydrate
Deca-	10	$Na_2CO_3 \cdot 10H_2O$	Sodium carbonate decahydrate

Analyzing a Hydrate

To analyze hydrates, you must drive off the water of hydration. Often this is done by heating the compound. The substance remaining after heating is anhydrous, or "without water." For example, hydrated cobalt(II) chloride is a pink solid that turns a deep blue when the water of hydration is driven off and anhydrous cobalt(II) chloride is produced. See **Figure 11-13.**

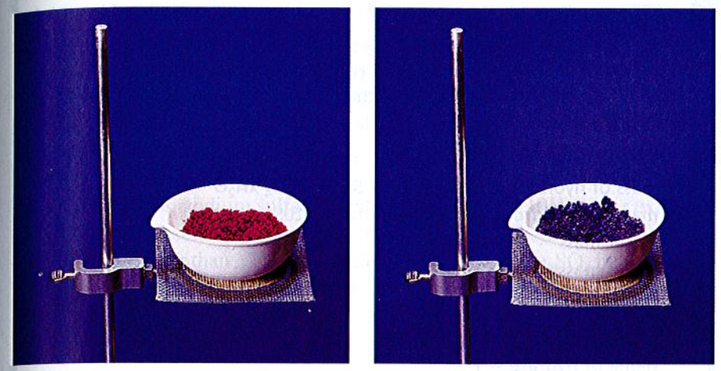

Figure 11-13

Hydrated $CoCl_2$, shown on the left, is pink. Its anhydrous form, on the right, is blue. The transition from pink to blue was accomplished by heating the hydrate until all water of hydration was removed.

Formula for a hydrate How can you determine the formula for a hydrate? You must find the number of moles of water associated with one mole of the hydrate. Suppose you have a 5.00-g sample of a hydrate of barium chloride. You know that the formula is $BaCl_2 \cdot xH_2O$. You must determine x, the coefficient of H_2O in the hydrate formula that indicates the number of moles of water associated with one mole of $BaCl_2$. To find x, you would heat the sample of the hydrate to drive off the water of hydration. After heating, the dried substance, which is anhydrous $BaCl_2$, has a mass of 4.26 g. The mass of the water of hydration is the difference between the mass of the hydrate (5.00 g) and the mass of the anhydrous compound (4.26 g).

$$5.00 \text{ g } BaCl_2 \text{ hydrate} - 4.26 \text{ g anhydrous } BaCl_2 = 0.74 \text{ g } H_2O$$

You now know the masses of $BaCl_2$ and H_2O in the sample. You can convert these masses to moles using the molar masses. The molar mass of $BaCl_2$ is 208.23 g/mol and the molar mass of H_2O is 18.02 g/mol.

	$BaCl_2$
g	4.26
g/mol	208.23
mol	0.0205

	H_2O
g	0.74
g/mol	18.02
mol	0.041

Now that the moles of $BaCl_2$ and H_2O have been determined, you can calculate the ratio of moles of H_2O to moles of $BaCl_2$ which is x, the coefficient that precedes H_2O in the formula for the hydrate.

$$x = \frac{\text{moles } H_2O}{\text{moles } BaCl_2} = \frac{0.041 \text{ mol } H_2O}{0.0205 \text{ mol } BaCl_2} = \frac{2.0 \text{ mol } H_2O}{1.00 \text{ mol } BaCl_2} = \frac{2}{1}$$

The ratio of moles of H_2O to moles of $BaCl_2$ is 2:1, so two moles of water are associated with one mole of barium chloride. The value of the coefficient x is 2 and the formula for the hydrate is $BaCl_2 \cdot 2H_2O$. What is the name of the hydrate? The **CHEMLAB** at the end of this chapter will give you experience determining the formula of a hydrate.

Heating blue anhydrous copper sulfate drives off the water of hydration and converts it to white anhydrous copper sulfate. How could you convert anhydrous copper sulfate to its blue hydrated form?

EXAMPLE PROBLEM 11-14

Determining the Formula for a Hydrate

A mass of 2.50 g of blue, hydrated copper sulfate ($CuSO_4 \cdot xH_2O$) is placed in a crucible and heated. After heating, 1.59 g white anhydrous copper sulfate ($CuSO_4$) remains. What is the formula for the hydrate? Name the hydrate.

1. Analyze the Problem

You are given a mass of hydrated copper sulfate. The mass after heating is the mass of the anhydrous compound. You know the formula for the compound except for *x*, the number of moles of water of hydration.

Known

mass of hydrated compound = 2.50 g $CuSO_4 \cdot xH_2O$
mass of anhydrous compound = 1.59 g $CuSO_4$
molar mass = 18.02 g/mol H_2O
molar mass = 159.6 g/mol $CuSO_4$

Unknown

formula for hydrate = ?
name of hydrate = ?

2. Solve for the Unknown

Subtract the mass of the anhydrous copper sulfate from the mass of the hydrated copper sulfate to determine the mass of water lost.

mass of hydrated copper sulfate	2.50 g
mass of anhydrous copper sulfate	−1.59 g
mass of water lost	0.91 g

Calculate the number of moles of H_2O and anhydrous $CuSO_4$ using the conversion factor that relates moles and mass based on the molar mass.

$$1.59 \text{ g } \cancel{CuSO_4} \times \frac{1 \text{ mol } CuSO_4}{159.6 \text{ g } \cancel{CuSO_4}} = 0.00996 \text{ mol } CuSO_4$$

$$0.91 \text{ g } \cancel{H_2O} \times \frac{1 \text{ mol } H_2O}{18.02 \text{ g } \cancel{H_2O}} = 0.050 \text{ mol } H_2O$$

Determine the value of *x*.

$$x = \frac{\text{moles } H_2O}{\text{moles } CuSO_4}$$

$$x = \frac{0.050 \text{ mol } H_2O}{0.00996 \text{ mol } CuSO_4} = \frac{5.0 \text{ mol } H_2O}{1.00 \text{ mol } CuSO_4} = 5$$

The ratio of H_2O to $CuSO_4$ is 5 : 1, so the formula for the hydrate is $CuSO_4 \cdot 5H_2O$, copper(II) sulfate pentahydrate.

3. Evaluate the Answer

Copper(II) sulfate pentahydrate is listed as a hydrate in **Table 11-1.**

PRACTICE PROBLEMS

63. A hydrate is found to have the following percent composition: 48.8% $MgSO_4$ and 51.2% H_2O. What is the formula and name for this hydrate?

64. **Figure 11-13** shows a common hydrate of cobalt(II) chloride. If 11.75 g of this hydrate is heated, 9.25 g of anhydrous cobalt chloride remains. What is the formula and name for this hydrate?

Practice! For more practice calculating the formula for a hydrate, go to **Supplemental Practice Problems** in Appendix A.

Uses of hydrates The ability of the anhydrous form of a hydrate to absorb water into its crystal structure has some important applications. Anhydrous calcium chloride and calcium sulfate are used as desiccants or drying agents in the laboratory because they can absorb water from the air or from their liquid surroundings. For example, calcium sulfate is often added to solvents such as ethanol and ethyl ether to keep them free of water. Anhydrous calcium chloride is placed in the bottom of tightly sealed containers called desiccators. The calcium chloride absorbs moisture from the air inside the desiccator, thus creating a dry atmosphere in which other substances can be placed to be kept dry. Calcium chloride forms a monohydrate, a dihydrate, and a hexahydrate. Electronic and optical equipment, particularly that transported overseas by ship, is packaged with packets of desiccants that absorb water from the air and prevent moisture from interfering with sensitive circuitry. Some of these uses are illustrated in **Figure 11-14**.

Some hydrates, sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$) for example, are used to store solar energy. When the Sun's energy heats the hydrate to a temperature greater than 32°C, the single formula unit of Na_2SO_4 in the hydrate dissolves in the 10 moles of water of hydration. In the process, energy is absorbed by the hydrate. This solar energy, stored in the solution of the hydrate, is released when the temperature decreases and the hydrate crystallizes again.

Figure 11-14

Calcium sulfate is not soluble in ethanol so it remains on the bottom of the ethanol bottle and absorbs any water dissolved in the ethanol. Calcium chloride, in the bottom of the desiccator, keeps the air inside the desiccator dry. Porous packets of desiccants can be packaged with materials that need to be kept moisture free.

Section 11.5 Assessment

65. What is a hydrate? What does its name indicate about its composition?

66. Describe the experimental procedure for determining the formula for a hydrate. Explain the reason for each step.

67. Name the compound having the formula $SrCl_2 \cdot 6H_2O$.

68. **Thinking Critically** Explain how the hydrate illustrated in **Figure 11-13** might be used as a means of roughly determining the probability of rain.

69. **Sequencing** Arrange these hydrates in order of increasing percent water content: $MgSO_4 \cdot 7H_2O$, $Ba(OH)_2 \cdot 8H_2O$, $CoCl_2 \cdot 6H_2O$.

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