Thermochemistry

Massachusetts Insight
Workshop
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Dr. John Gelder (Emeritius)
Department of Chemistry
Oklahoma State University

Lisa McGaw (Emeritus)
AP Chemistry Teacher (Texas),
2-year College (Oklahoma)
And 4-year University (Oklahoma)

Welcome to Advance Kentucky Student Session on Thermochemistry

▶ We will begin this afternoon with some vocabulary and some questions to gain some idea of your intuition about heat, mass and change in temperature (ΔT).

▶ Heat is measured in units of joules (J) or kilojoules (kJ). Heat is one of two ways energy is transferred.

▶ Mass is measured in unit of grams.

▶ Temperature is measured in units of degrees Celsius (˚C). Temperature is a measure of the average kinetic energy of a sample of matter.

Heat, mass, and change in temperature Slide 1

1. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.
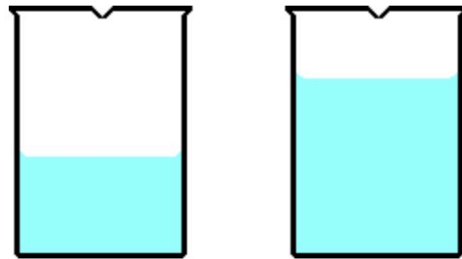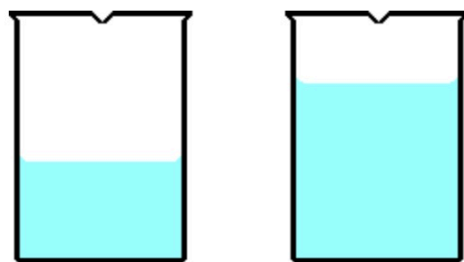

The beaker on the left has 25 mLs of water and the beaker on the right has 50 mLs of water. Both have the same initial temperature. If the same amount of heat is added to both beakers, using a bunsen burner, does the beaker on the right or the beaker on the left have the higher final temperature?

right or left

Heat, mass, and change in temperature Slide 2

1. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.

The beaker on the left has 25 mLs of water and the beaker on the right has 50 mLs of water. Both have the same initial temperature. If the same amount of heat is added to both beakers, using a bunsen burner, does the beaker on the right or the beaker on the left have the higher final temperature?
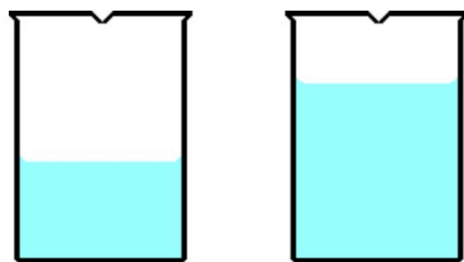
Left   right or left

In this experiment q (amount of heat) is constant. What is the relationship between mass and change in temperature?

Heat, mass, and change in temperature Slide 3

1. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.

The beaker on the left has 25 mLs of water and the beaker on the right has 50 mLs of water. Both have the same initial temperature. If the same amount of heat is added to both beakers, using a bunsen burner, does the beaker on the right or the beaker on the left have the higher final temperature?
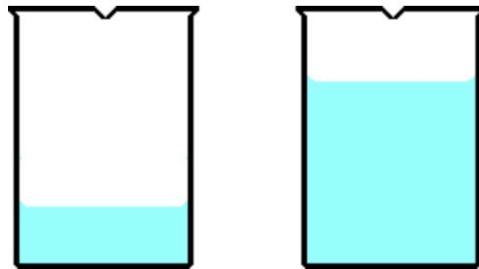
LEFT   right or left

In this experiment q (amount of heat) is constant. What is the relationship between mass and change in temperature?

$$\Delta T \propto 1/mass$$

Heat, mass, and change in temperature Slide 4

2. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.
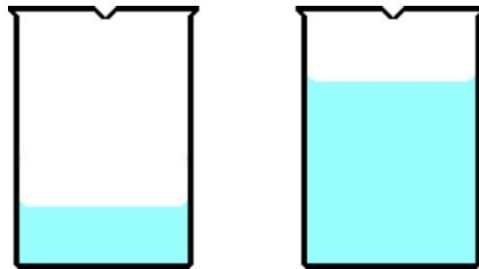

If the final temperature of the water in both beakers is identical, is the greater amount of heat added to the beaker on the right or the beaker on the left?

[   ] **right or left**

Heat, mass, and change in temperature
Slide 5

2. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.

If the final temperature of the water in both beakers is identical, is the greater amount of heat added to the beaker on the right or the beaker on the left?

RIGHT right or left

In this experiment ΔT (change in temperature) is constant.
What is the relationship between heat and mass?

Heat, mass, and change in temperature Slide 6

2. Consider the two beakers containing water, both at the same initial temperature, say 25 degrees Celsius.

If the final temperature of the water in both beakers is identical, is the greater amount of heat added to the beaker on the right or the beaker on the left?
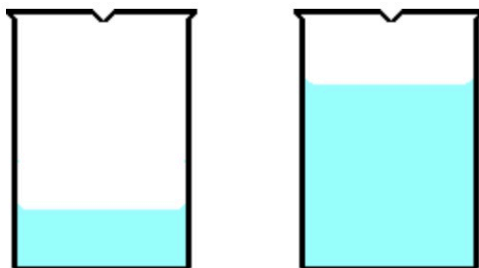
RIGHT right or left

In this experiment ΔT (change in temperature) is constant.
What is the relationship between heat and mass?
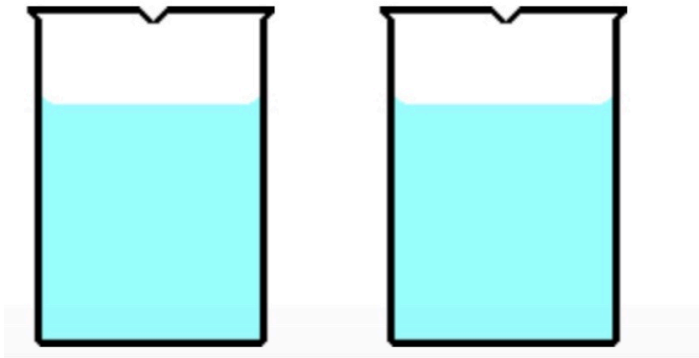
$q \propto$ mass

Heat, mass, and change in temperature Slide 7

- In the two experiments we have considered we know the following relationships between heat, mass and change in temperature

- Experiment #1 : **$\Delta T \propto 1/\text{mass}$ (at constant heat (q))**

- Experiment #2 : **$q \propto \text{mass}$ (at constant change in temperature)**

Heat, mass, and change in temperature Slide 8

3. Consider two beakers each with the same volume of water at the same initial temperature, $25°C$.

If twice the heat was added to the beaker on the right compared to the beaker on the left, does the beaker on the right or on the left have the highest final temperature?

Right or left

Heat, mass, and change in temperature Slide 9

3. Consider two beakers each with the same volume of water at the same initial temperature, 25°C.
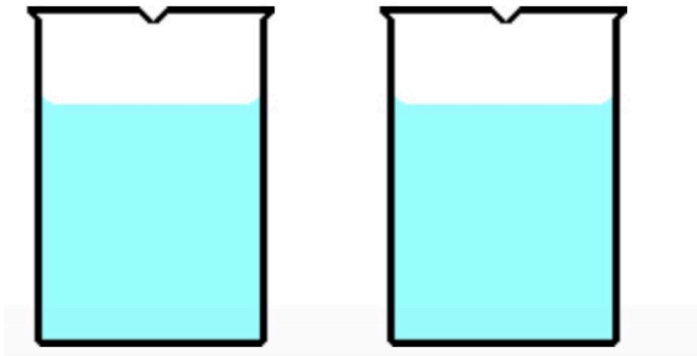

If twice the heat was added to the beaker on the right compared to the beaker on the left, does the beaker on the right or on the left have the highest final temperature?

| RIGHT | Right or left

In this experiment mass is constant. What is the relationship between heat and ΔT?

Heat, mass, and change in temperature
Slide 9

3. Consider two beakers each with the same volume of water at the same initial temperature,25°C.

If twice the heat was added to the beaker on the right compared to the beaker on the left, does the beaker on the right or on the left have the highest final temperature?
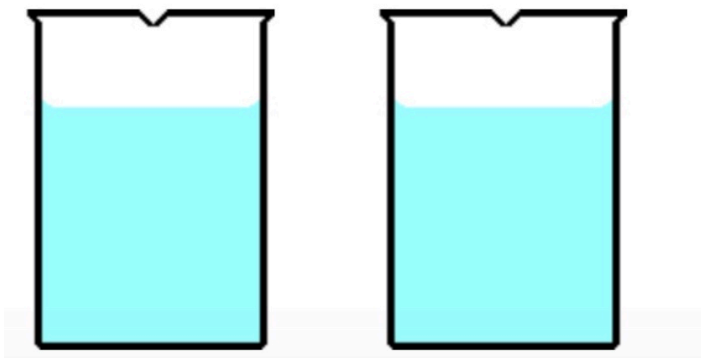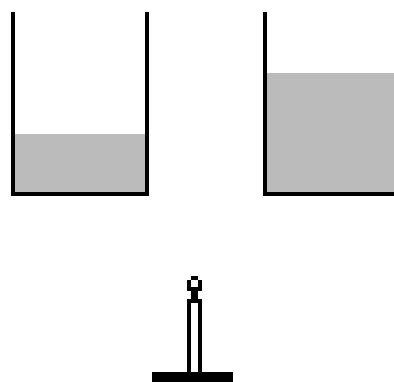
RIGHT   Right or left

In this experiment mass is constant. What is the relationship between heat and ΔT?

q α ΔT

Introduction to Thermodynamics

DCI15.1.   Two containers of water are at 20 ˚C initially. One contains 50 mLs and the other 100 mLs. They are each heated with the same source of heat for the same amount of time. If the final temperature of the 50 mLs sample is 50 ˚C what would be the final temperature of the 100 mLs sample?

A.   50 ˚C

B.   80 ˚C

C.   25 ˚C

D.   100 ˚C

E.   35 ˚C

DCI15.1.   Two containers of water are at 20 ˚C initially. One contains 50 mLs and the other 100 mLs. They are each heated with the same source of heat for the same amount of time. If the final temperature of the 50 mLs sample is 50 ˚C what would be the final temperature of the 100 mLs sample?

A.   50 ˚C

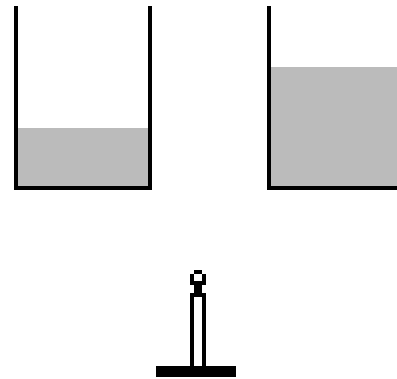B.   80 ˚C

C.   25 ˚C

D.   100 ˚C

E.   35 ˚C

Same amount of heat to both beakers, but different mass. ΔT = 30˚ for beaker on the left, so ΔT is half or 15˚.

Mass α 1/ΔT

Introduction to Thermodynamics

Two containers each have 50 mLs of water at 20 ˚C initially. They are each heated with the same source of heat. One is heated for ten minutes and the other for five minutes. If the container that was heated for five minutes has a final temperature 30 ˚C what would be the final temperature of the other sample?

A.   35 ˚C

B.   40 ˚C

C.   60 ˚C

D.   25 ˚C

E.   30 ˚C
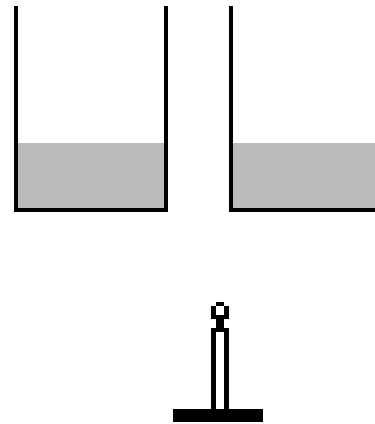
Introduction to Thermodynamics

Two containers each have 50 mLs of water at 20 ˚C initially. They are each heated with the same source of heat. One is heated for ten minutes and the other for five minutes. If the container that was heated for five minutes has a final temperature 30 ˚C what would be the final temperature of the other sample?
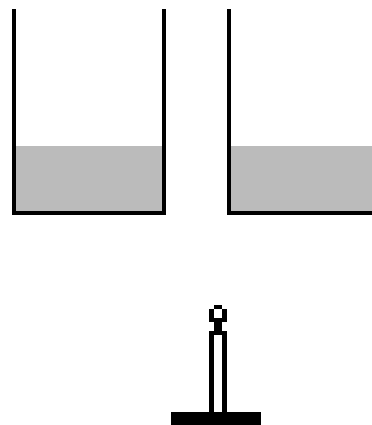
A.   35 ˚C

B.   40 ˚C

C.   60 ˚C

D.   25 ˚C

E.   30 ˚C

Both beakers contain the same amount of water. Twice the heat to one. ΔT is 10˚ for smaller amount of heat, than $\Delta T = 20$˚ for larger amount.

$$Q(heat) \ \alpha \ \Delta T$$

Introduction to Thermodynamics

Two containers of water are at 20 ˚C initially. One contains 50 g of water and is heated by a source for a specified time to a final temperature of 30 ˚C. The second container has an unknown amount of water and is heated with the same source to 30 ˚C. However, it takes twice as long to get to this final temperature. How much water is in this container?

A.   100 g

B.   25 g

C.   30 g

D.   50 g

E.   75 g

Introduction to Thermodynamics

Two containers of water are at 20 ˚C initially. One contains 50 g of water and is heated by a source for a specified time to a final temperature of 30 ˚C. The second container has an unknown amount of water and is heated with the same source to 30 ˚C. However, it takes twice as long to get to this final temperature. How much water is in this container?
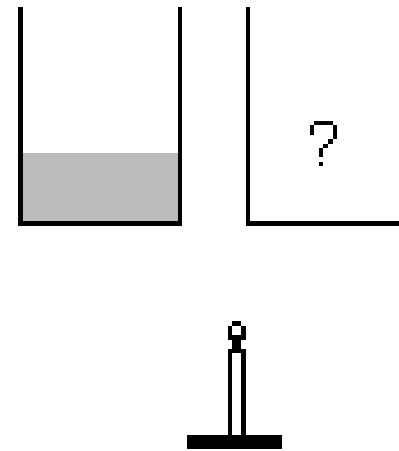
A.   **100 g**

B.   25 g

C.   30 g

D.   50 g

E.   75 g

Twice the heat is added to one beaker to reach the same final temperature (ΔT). So the beaker must have twice the mass.

Q(heat) α Mass

Introduction to Thermodynamics

So we have established the following relationships;

$$\text{Mass } \alpha \text{ } 1/\Delta T \qquad \text{at constant q}$$
$$\text{q(heat) } \alpha \text{ } \Delta T \qquad \text{at constant mass}$$
$$\text{q(heat) } \alpha \text{ mass} \qquad \text{at constant } \Delta T$$

So

$$\text{q(heat) } \alpha \text{ mass} \cdot \Delta T$$

Heat is directly proportional to the mass times the change in temperature.

Introduction to Thermodynamics

50 mLs of water at 80 ˚C is added to 50 mLs of water at 20 ˚C. What would be the final temperature?

A.   60 ˚C
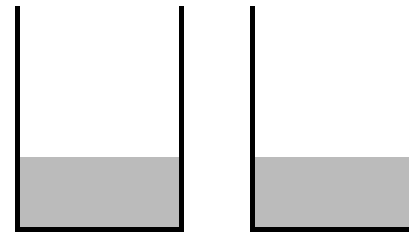
B.   40 ˚C

C.   30 ˚C

D.   20 ˚C

E.   50 ˚C

Introduction to Thermodynamics

50 mLs of water at 80 ˚C is added to 50 mLs of water at 20 ˚C. What would be the final temperature?

A. 60 ˚C

B. 40 ˚C

C. 30 ˚C

D. 20 ˚C

E. 50 ˚C

Introduction to Thermodynamics

50 mLs of water at 80 ˚C is added to 50 mLs of water at 20 ˚C. What would be the final temperature?

A. 60 ˚C

B. 40 ˚C

C. 30 ˚C

D. 20 ˚C

E. 50 ˚C

$$q_{hot\ water} + q_{cold\ water} = 0$$

$$q_{hot\ water} = -q_{cold\ water}$$

$$mass_{hot\ water} \cdot \Delta T_{hot\ water} = -mass_{cold\ water} \cdot \Delta T_{cold\ water}$$

$$50.\ g \cdot \Delta T_{hot\ water} = -50.\ g \cdot \Delta T_{cold\ water}$$

$$50.\ g \cdot (T_{final} - 80.0°) = -50.\ g \cdot (T_{final} - 20.0°)$$

$$2T_{final} = 100° \quad T_{final} = 50°$$

Introduction to Thermodynamics

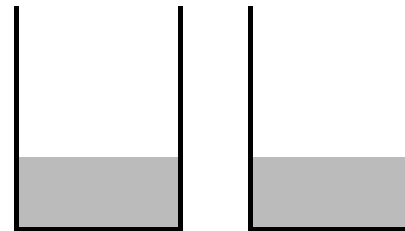50 mLs of water at 80 ˚C is added to 100 mLs of water at 20 ˚C. What would be the final temperature?

A.   70 ˚C

B.   40 ˚C

C.   30 ˚C

D.   60 ˚C

E.   50 ˚C

Introduction to Thermodynamics

50 mLs of water at 80 ˚C is added to 100 mLs of water at 20 ˚C. What would be the final temperature?
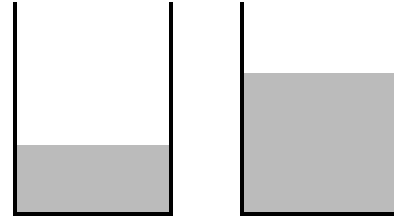
A.   70 ˚C

B.   40 ˚C

C.   30 ˚C

D.   60 ˚C

E.   50 ˚C

Introduction to Thermodynamics

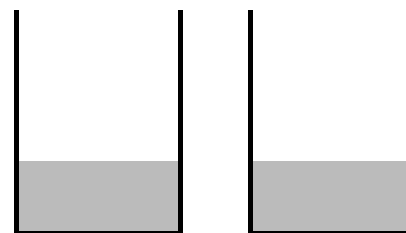50 mLs of water at 80 ˚C is added to 100 mLs of water at 20 ˚C. What would be the final temperature?

A.   70 ˚C

B.   40 ˚C

C.   30 ˚C

D.   60 ˚C

E.   50 ˚C

$$q_{hot\ water} = -q_{cold\ water}$$
$$mass_{hot\ water} \cdot \Delta T_{hot\ water} = -mass_{cold\ water} \cdot \Delta T_{cold\ water}$$
$$50.\ g \cdot \Delta T_{hot\ water} = -100.\ g \cdot \Delta T_{cold\ water}$$
$$50.\ g \cdot (T_{final} - 80.0˚) = -100.\ g \cdot (T_{final} - 20.0˚)$$
$$(T_{final} - 80.0˚) = -2 \cdot (T_{final} - 20.0˚)$$
$$3T_{final} = 120˚ \quad T_{final} = 40˚$$

Introduction to Thermodynamics

50 g of water at 80 ˚C is added to 50 g of ethyl alcohol at 20 ˚C. What would be the approximate final temperature?

A.   60 ˚C
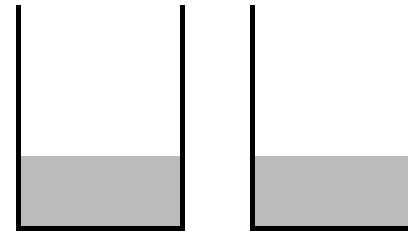
B.   40 ˚C

C.   30 ˚C

D.   20 ˚C

E.   50 ˚C

Introduction to Thermodynamics

50 g of water at 80 ˚C is added to 50 g of ethyl alcohol at 20 ˚C. What would be the approximate final temperature?

A.   60 ˚C

B.   40 ˚C

C.   30 ˚C

D.   20 ˚C

E.   50 ˚C
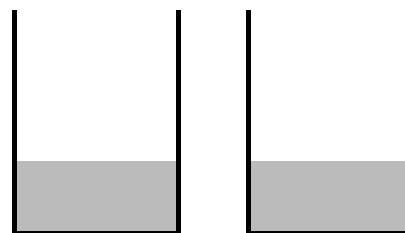
TWO DIFFERENT SUBSTANCES!

Experimentally the final temperature is determined to be close to 60˚.

Introduction to Thermodynamics

q(heat) α mass · ΔT

How do we make this an equality?

We must introduce a constant….in this case the constant is called the specific heat, SH,

q(heat) = mass · SH · ΔT

Specific heat is the amount of heat required to raise the temperature of 1 gram of a substance 1 ˚C.

Introduction to Thermodynamics

Specific Heats of Substances

Compound	Specific Heat (J $°C^{-1}g^{-1}$)
$H_2O(l)$	4.184
$H_2O(s)$	2.03
$Al(s)$	0.89
$C(s)$	0.71
$Fe(s)$	0.45
$Hg(l)$	0.14
$O_2(g)$	0.917
CH_3CH_2OH	2.46

Introduction to Thermodynamics

Specific Heats of Substances

Exp	Heat Added (J)	Mass (g)	T_i (°C)	T_f (°C)		
1	1000	10.0	20.0	43.9		
2	2000	10.0	20.0	67.8		
3	3000	10.0	20.0	91.7		
4	1000	20.0	20.0			
5	1700	45.0	25.0			

Note: All five experiments use the same substance.

Introduction to Thermodynamics

Specific Heats of Substances

Exp	Heat Added (J)	Mass (g)	T_i (°C)	T_f (°C)	ΔT (°C)	Constant
1	1000	10.0	20.0	43.9	23.9	4.184
2	2000	10.0	20.0	67.8	47.8	4.184
3	3000	10.0	20.0	91.7	71.7	4.184
4	1000	20.0	20.0	32.0	12.0	4.184
5	1700	45.0	25.0			4.184

Note: All five experiments use the same substance.

Introduction to Thermodynamics

Specific Heats of Substances

Exp	Heat Added (J)	Mass (g)	T_i (˚C)	T_f (˚C)	ΔT (˚C)	Constant
1	1000	10.0	20.0	43.9	23.9	4.184
2	2000	10.0	20.0	67.8	47.8	4.184
3	3000	10.0	20.0	91.7	71.7	4.184
4	1000	20.0	20.0	32.0	12.0	4.184
5	1700	45.0	25.0	34.0	9.0	4.184

Note: All five experiments use the same substance.

Heat, mass, and change in temperature
Slide 9

Heat, mass, and change in temperature Slide 10

- In the three experiments we have considered we know the following relationships between heat, mass and change in temperature:
- Experiment #1 :
- Experiment #2 :
- Experiment #3 :

Heat, mass, and change in temperature Slide 12

- **In the three experiments we have considered we know:**
- **Experiment #1 :**
- **Experiment #2 :**
- **Experiment #3 :**

With these three experiments we can see a connection between heat, mass and change in temperature.

Heat, mass, and change in temperature Slide 10

▶ **In the three experiments we have considered we know the following relationships between heat, mass and change in temperature:**

▶ **Experiment #1 : $\Delta T \; \alpha \; 1/mass$ (at constant heat (q))**

▶ **Experiment #2 : $q \; \alpha \; mass$ (at constant change in temperature)**

▶ **Experiment #3 : $q \; \alpha \; \Delta T$ (at constant mass)**

Heat, mass, and change in temperature Slide 11

- In the two experiments we have considered we know:

- Experiment #1 : $\Delta T \, \alpha \, 1/mass$ (at constant heat (q))

- Experiment #2 : $q \, \alpha$ mass (at constant change in temperature)

- Experiment #3 : $q \, \alpha \, \Delta T$ (at constant mass)

With these three experiments we can see a connection between heat, mass and change in temperature.

Heat, mass, and change in temperature
Slide 12

- In the two experiments we have considered we know:

- Experiment #1 : $\Delta T \propto$ 1/mass (at constant heat (q))

- Experiment #2 : q $\propto$ mass (at constant change in temperature)

- Experiment #3 : q $\propto \Delta T$ (at constant mass)

With these three experiments we can see a connection between heat, mass and change in temperature.

$$q \propto mass \cdot \Delta T$$

Heat, mass, change in temperature and specific heat Slide 13

► **In the two experiments we have considered we know:**

► **Experiment #1 : $\Delta T \; \alpha \; 1/$mass (at constant heat (q))**

► **Experiment #2 : q α mass (at constant ΔT)**

► **Experiment #3 : q $\alpha \; \Delta T$ (at constant mass)**

With these three experiments we can see a connection between heat, mass and change in temperature.

$$q \; \alpha \; \text{mass} \cdot \Delta T$$

$$q = \text{mass} \cdot c \cdot \Delta T$$

$$c \text{ has units of joules} \cdot g^{-1} \cdot {}^{\circ}C^{-1}$$

Heat, mass, change in temperature and specific heat Slide 14

Very important relationship

$$q = mass \cdot c \cdot \Delta T$$

c has units of joules $\cdot$ g^{-1} $\cdot$ °C^{-1}

DANGER!!

We must be very careful using this relationship!

Calculates the magnitude of the heat released or absorbed but not the sign of q.

Heat, mass, change in temperature and specific heat Slide 14

Using

$$q = mass \cdot c \cdot \Delta T$$

To calculate the magnitude of the heat released or absorbed but not the sign of q.

For example, an exothermic reaction in water will cause the aqueous solution to increase in temperature so T_{final} is larger than $T_{initial}$ and ΔT would be a positive number. The mass of the solution and the specific heat of the solution are also positive, so using the equation $q = mass \cdot c \cdot \Delta T$ to calculate q yields a positive value for q! For exothermic reactions q must be negative.

Heat, mass, change in temperature and specific heat Slide 16

First Law of Thermodynamics

Experiments that we do in AP chemistry.

Mix hot and cold water

Add a hot piece of metal to water at room temperature

Add an ionic solid to water

Mix a strong acid with a strong base

Mix a strong acid with a reactive metal

Heat, mass, change in temperature and specific heat Slide 17

First Law of Thermodynamics

Experiments that we do in AP chemistry.

    Mix hot and cold water;

    Add a hot piece of metal to water at room temperature;

    Add an ionic solid to water;

    Mix a strong acid with a strong base ;

    Mix a strong acid with a reactive metal;
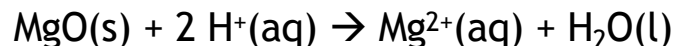
$q_{hot\ water} = -q_{cold\ water}$

$q_{hot\ metal} = -q_{cold\ water}$

$q_{dissolution} = -q_{solution}$

$q_{neutralization} = -q_{solution}$

$q_{reaction} = -q_{solution}$

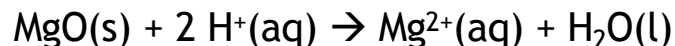$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

3. A student was assigned the task of determining the enthalpy change for the reaction between solid MgO and aqueous HCl represented by the net-ionic equation above. The student uses a polystyrene cup calorimeter and performs four trials. Data for each trial are shown in the table below.

Trial	Volume of 1.0 M HCl (mL)	Mass of MgO(s) Added (g)	Initial Temperature of Solution (°C)	Final Temperature of Solution (°C)
1	100.0	0.25	25.5	26.5
2	100.0	0.50	25.0	29.1
3	100.0	0.25	26.0	28.1
4	100.0	0.50	24.1	28.1

(a) Which is the limiting reagent in all four trials, HCl or MgO? Justify your answer.

(b) The data in one of the trials is inconsistent with the data in the other three trials. Identify the trial with inconsistent data and draw a line through the data from that trial in the table above. Explain how you identified the inconsistent data.

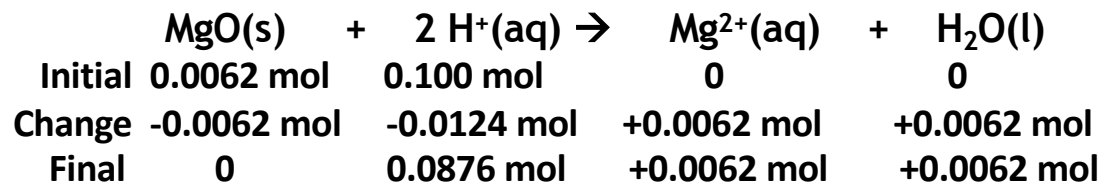$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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1	100.0	0.25	25.5	26.5
2	100.0	0.50	25.0	29.1
3	100.0	0.25	26.0	28.1
4	100.0	0.50	24.1	28.1

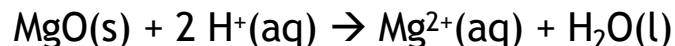(a) Which is the limiting reagent in all four trials, HCl or MgO? Justify your answer.

n_{HCl} = 0.100 L · 1.0 mol HCl/1 L = 0.10 mol H^+
n_{MgO} = 0.25 g MgO · 1 mol MgO/40.3 g MgO = 0.0062 mol MgO

	MgO(s)	+ 2 H⁺(aq) →	Mg²⁺(aq)	+ H₂O(l)
Initial	0.0062 mol	0.100 mol	0	0
Change	-0.0062 mol	-0.0124 mol	+0.0062 mol	+0.0062 mol
Final	0	0.0876 mol	+0.0062 mol	+0.0062 mol

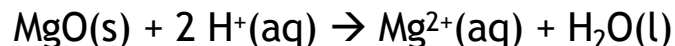$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

3. A student was assigned the task of determining the enthalpy change for the reaction between solid MgO and aqueous HCl represented by the net-ionic equation above. The student uses a polystyrene cup calorimeter and performs four trials. Data for each trial are shown in the table below.

Trial	Volume of 1.0 M HCl (mL)	Mass of MgO(s) Added (g)	Initial Temperature of Solution (°C)	Final Temperature of Solution (°C)
1	100.0	0.25	25.5	26.5
2	100.0	0.50	25.0	29.1
3	100.0	0.25	26.0	28.1
4	100.0	0.50	24.1	28.1

(b) The data in one of the trials is inconsistent with the data in the other three trials. Identify the trial with inconsistent data and draw a line through the data from that trial in the table above. Explain how you identified the inconsistent data.

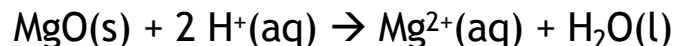$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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(b) The data in one of the trials is inconsistent with the data in the other three trials. Identify the trial with inconsistent data and draw a line through the data from that trial in the table above. Explain how you identified the inconsistent data.

Compare the ΔT for the different masses of the limiting reagent MgO added to the aqueous HCl solution. Trial 1 for 0.25 g MgO ΔT = 1 ˚C : Trial 2 for 0.50 g MgO ΔT = 4 ˚C : Trial 3 for 0.25 g MgO ΔT = 2.1 ˚C : Trial 4 for 0.50 g MgO ΔT = 4 ˚C

$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

3. A student was assigned the task of determining the enthalpy change for the reaction between solid MgO and aqueous HCl represented by the net-ionic equation above. The student uses a polystyrene cup calorimeter and performs four trials. Data for each trial are shown in the table below.
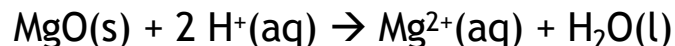
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4	100.0	0.50	24.1	28.1

For parts (c) and (d), use the data from one of the other three trials (i.e., not from the trial you identified in part (b) above). Assume the calorimeter has a negligible heat capacity and that the specific heat of the contents of the calorimeter is 4.18 J/(g˚C). Assume that the density of the HCl(aq) is 1.0 g/mL.

(c) Calculate the magnitude of q, the thermal energy change, when the MgO was added to the 1.0 M HCl(aq). Include units with your answer.

(d) Determine the student's experimental value of $\Delta H°$ for the reaction between MgO and HCl in units of kJ/mol_{rxn}.

$$MgO(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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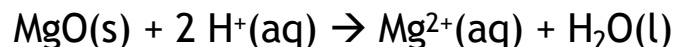
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(c) Calculate the magnitude of q, the thermal energy change, when the MgO was added to the 1.0 M HCl(aq). Include units with your answer.

$$q_{rxn} = -q_{solution} = -(mass \cdot c \cdot \Delta T)_{solution}$$

$$MgO(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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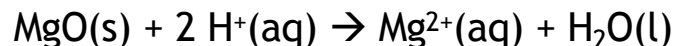
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(c) Calculate the magnitude of q, the thermal energy change, when the MgO was added to the 1.0 M HCl(aq). Include units with your answer.

(Using Trial 2 data) q_{rxn} = -$q_{solution}$ = -(mass·c·ΔT)$_{solution}$ = -(100.5 g·4.18 J g^{-1}°C^{-1}·(29.1 °C – 25.0 °C))$_{solution}$

$$q_{rxn} = -1.72 \times 10^3 \text{ J}$$

$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

3. A student was assigned the task of determining the enthalpy change for the reaction between solid MgO and aqueous HCl represented by the net-ionic equation above. The student uses a polystyrene cup calorimeter and performs four trials. Data for each trial are shown in the table below.
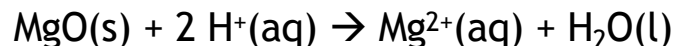
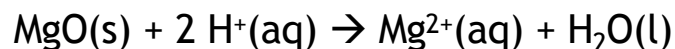| Trial	Volume of 1.0 M HCl (mL)	Mass of MgO(s) Added (g)	Initial Temperature of Solution (°C)	Final Temperature of Solution (°C)
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(c) Calculate the magnitude of q, the thermal energy change, when the MgO was added to the 1.0 M HCl(aq). Include units with your answer.

(Using Trial 2 data) $q_{rxn} = -q_{solution} = -(mass \cdot c \cdot \Delta T)_{solution} = -(100.5 \text{ g} \cdot 4.18 \text{ J g}^{-1} °C^{-1} \cdot (29.1 °C - 25.0 °C))_{solution}$

$$q_{rxn} = -1.72 \times 10^3 \text{ J}$$

(d) Determine the student's experimental value of $\Delta H°$ for the reaction between MgO and HCl in units of kJ/mol$_{rxn}$.

$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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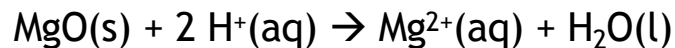| Trial	Volume of 1.0 M HCl (mL)	Mass of MgO(s) Added (g)	Initial Temperature of Solution (˚C)	Final Temperature of Solution (˚C)
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(c) Calculate the magnitude of q, the thermal energy change, when the MgO was added to the 1.0 M HCl(aq). Include units with your answer.

(Using Trial 2 data) q_{rxn} = -$q_{solution}$ = -(mass·c·ΔT)$_{solution}$ = -(100.5 g·4.18 J g^{-1}˚C^{-1}·(29.1 ˚C – 25.0 ˚C))$_{solution}$

q_{rxn} = -1.72 x 10^3 J

(d) Determine the student's experimental value of ΔH˚ for the reaction between MgO and HCl in units of kJ/mol$_{rxn}$.

(Using Trial 2 data) ΔH$_{rxn}$ = q_{rxn} /mol$_{rxn}$

$$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

3. A student was assigned the task of determining the enthalpy change for the reaction between solid MgO and aqueous HCl represented by the net-ionic equation above. The student uses a polystyrene cup calorimeter and performs four trials. Data for each trial are shown in the table below.

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(Using Trial 2 data) $q_{rxn} = -q_{solution} = -(mass \cdot c \cdot \Delta T)_{solution} = -(100.5\ g \cdot 4.18\ J\ g^{-1}\ ˚C^{-1} \cdot (29.1\ ˚C - 25.0\ ˚C))_{solution}$

$$q_{rxn} = -1.72 \times 10^3\ J$$

(d) Determine the student's experimental value of $\Delta H˚$ for the reaction between MgO and HCl in units of kJ/mol$_{rxn}$.

(Using Trial 2 data) $\Delta H_{rxn} = q_{rxn}/mol_{rxn} = -1.72 \times 10^3\ J/0.0124\ mol_{MgO}\ (1\ mol_{MgO}/1\ mol_{rxn})$

$$\Delta H_{rxn} = -1.39 \times 10^5\ J/mol_{rxn} = -1.39 \times 10^2\ kJ/mol_{rxn}$$

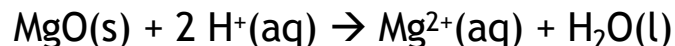$MgO(s) + 2 H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$

(e) Enthalpies of formation for substances involved in the reaction are shown in the table below. Using the information in the table, determine the accepted value of $\Delta H°$ for the reaction between MgO(s) and HCl(aq).

Substance	$\Delta H°_f$(kJ/mol)
MgO(s)	–602
$H_2O(l)$	–286
$H^+(aq)$	0
$Mg^{2+}(aq)$	–467

AP Chemistry Exam Equations for Thermochemistry

THERMODYNAMICS / ELECTROCHEMISTRY

$$q = mc\Delta T$$

$$\Delta S° = \sum S° \text{ products} - \sum S° \text{ reactants}$$

$$\Delta H° = \sum \Delta H_f° \text{ products} - \sum \Delta H_f° \text{ reactants}$$

$$\Delta G° = \sum \Delta G_f° \text{ products} - \sum \Delta G_f° \text{ reactants}$$

$$\Delta G° = \Delta H° - T\Delta S°$$

$$= -RT \ln K$$

$$= -nFE°$$

$$I = \frac{q}{t}$$

$$E_{cell} = E_{cell}° - \frac{RT}{nF} \ln Q$$

$$MgO(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

(e) Enthalpies of formation for substances involved in the reaction are shown in the table below. Using the information in the table, determine the accepted value of $\Delta H°$ for the reaction between $MgO(s)$ and $HCl(aq)$.
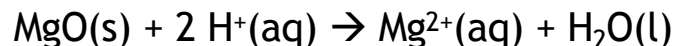
Substance	$\Delta H°_f$(kJ/mol)
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$H_2O(l)$	–286
$H^+(aq)$	0
$Mg^{2+}(aq)$	–467

$$\Delta H°_{rxn} = \Sigma\ (\Delta H°_f(products)) - \Sigma\ (\Delta H°_f(reactants))$$

$$MgO(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

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MgO(s)	–602
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H^+(aq)	0
Mg^{2+}(aq)	–467

$$\Delta H°_{rxn} = \Sigma\ (\Delta H°_f(\text{products})) - \Sigma\ (\Delta H°_f(\text{reactants}))$$

$$\Delta H°_{rxn} = 1\cdot\Delta H°_f(Mg^{2+}(aq)) + 1\cdot\Delta H°_f(H_2O(l)) - (1\cdot\Delta H°_f(MgO(s)) + 2\cdot\Delta H°_f(H^+(aq))$$

$$\Delta H°_{rxn} = 1\cdot(-467\ \text{kJ/mol}\ Mg^{2+}(aq)) + 1\cdot(-286\ \text{kJ/mol}\ H_2O(l)) - (1\cdot(-602\ \text{kJ/mol}\ H^+(aq))$$

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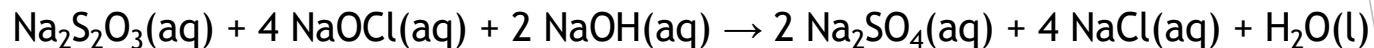| Substance	ΔH°_f(kJ/mol)
MgO(s)	–602
H_2O(l)	–286
H^+(aq)	0
Mg^{2+}(aq)	–467

$$\Delta H^\circ_{rxn} = \Sigma\ (\Delta H^\circ_f(products)) - \Sigma\ (\Delta H^\circ_f(reactants))$$

$$\Delta H^\circ_{rxn} = 1 \cdot \Delta H^\circ_f(Mg^{2+}(aq)) + 1 \cdot \Delta H^\circ_f(H_2O(l)) - (1 \cdot \Delta H^\circ_f(MgO(s)) + 2 \cdot \Delta H^\circ_f(H^+(aq))$$

$$\Delta H^\circ_{rxn} = 1 \cdot (-467\ kJ/mol\ Mg^{2+}(aq)) + 1 \cdot (-286\ kJ/mol\ H_2O(l)) - (1 \cdot (-602\ kJ/mol\ H^+(aq))$$

$$\Delta H^\circ_{rxn} = 1\ mol\ Mg^{2+}(aq)/1\ mol_{rxn} \cdot (-467\ kJ/mol\ Mg^{2+}(aq)) + 1\ mol\ H_2O(l)/1\ mol_{rxn} \cdot (-286\ kJ/mol\ H_2O(l)) - (1\ mol\ H^+(aq)/1\ mol_{rxn} \cdot (-602\ kJ/mol\ H^+(aq))$$

$$MgO(s) + 2\ H^+(aq) \rightarrow Mg^{2+}(aq) + H_2O(l)$$

(e) Enthalpies of formation for substances involved in the reaction are shown in the table below. Using the information in the table, determine the accepted value of ΔH° for the reaction between MgO(s) and HCl(aq).

Substance	ΔH°_f (kJ/mol)
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$H^+(aq)$	0
$Mg^{2+}(aq)$	–467

$$\Delta H^\circ_{rxn} = \Sigma\ (\Delta H^\circ_f(\text{products})) - \Sigma\ (\Delta H^\circ_f(\text{reactants}))$$

ΔH°_{rxn} = 1 mol $Mg^{2+}(aq)$/1 mol $_{rxn}$·(-467 kJ/mol $Mg^{2+}(aq)$) + 1 mol $H_2O(l)$/1 mol $_{rxn}$·(-286 kJ/mol $H_2O(l)$) – (1 mol $H^+(aq)$/1 mol $_{rxn}$·(-602 kJ/mol $H^+(aq)$))

ΔH°_{rxn} = ~~1 mol $Mg^{2+}(aq)$~~/1 mol $_{rxn}$·(-467 kJ/~~mol $Mg^{2+}(aq)$~~) + ~~1 mol $H_2O(l)$~~/1 mol $_{rxn}$·(-286 kJ/~~mol $H_2O(l)$~~) – (~~1 mol $H^+(aq)$~~/1 mol $_{rxn}$·(-602 kJ/~~mol $H^+(aq)$~~))

$$\Delta H^\circ_{rxn} = -151\ \text{kJ/1 mol}_{rxn}$$

2018 AP Chemistry Exam Question 1 Slide 1

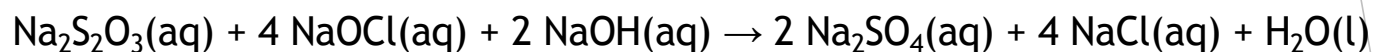$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$
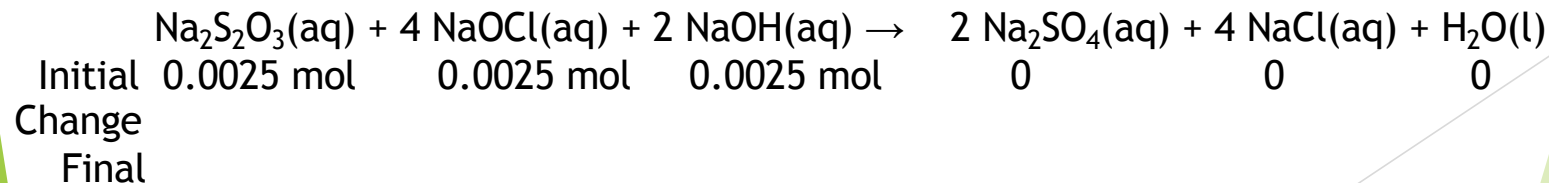
1. A student performs an experiment to determine the value of the enthalpy change, $\Delta H°_{rxn}$, for the oxidation-reduction reaction represented by the balanced equation above.

In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (M)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	5
$NaOCl(aq)$	0.500	5
$NaOH(aq)$	0.500	5

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

1. A student performs an experiment to determine the value of the enthalpy change, $\Delta H°_{rxn}$, for the oxidation-reduction reaction represented by the balanced equation above.

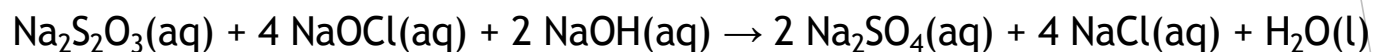In the experiment, the student uses the solutions shown in the table below.

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$NaOCl(aq)$	0.500	5
$NaOH(aq)$	0.500	5

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

$n_{Na2S2O3} = n_{NaOCl} = n_{NaOH} = 0.0050\ L \cdot 0.500\ mol/Liter = 0.0025\ mol$

	$Na_2S_2O_3(aq)$ +	4 NaOCl(aq) +	2 NaOH(aq) $\rightarrow$	2 $Na_2SO_4(aq)$ +	4 NaCl(aq) +	$H_2O(l)$
Initial	0.0025 mol	0.0025 mol	0.0025 mol	0	0	0
Change						
Final						

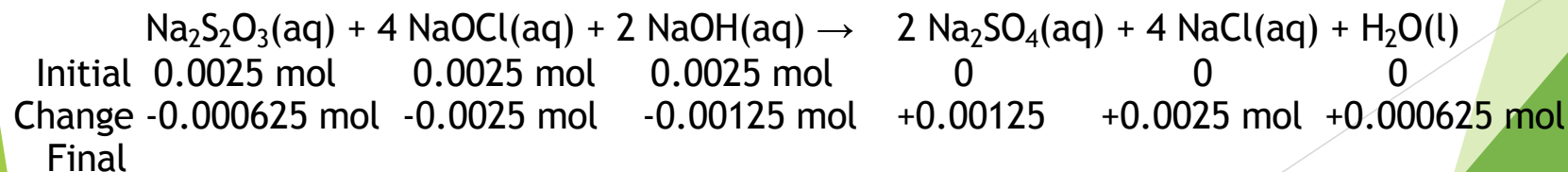$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$

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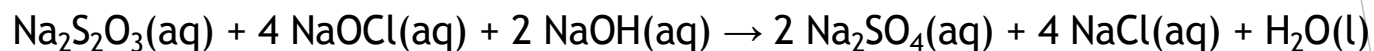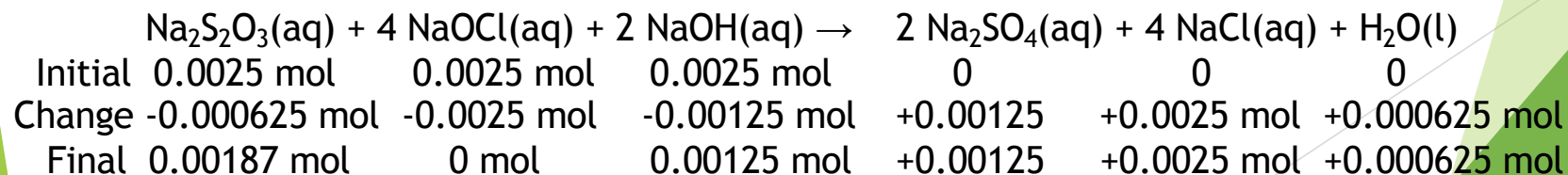In the experiment, the student uses the solutions shown in the table below.

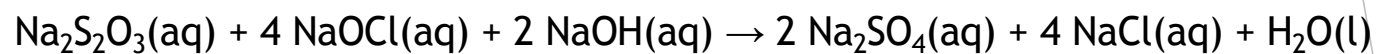| Solution	Concentration (M)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	5
$NaOCl(aq)$	0.500	5
$NaOH(aq)$	0.500	5

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

$n_{Na2S2O3} = n_{NaOCl} = n_{NaOH} = 0.0050\ L \cdot 0.500\ mol/Liter = 0.0025\ mol$

	$Na_2S_2O_3(aq)$	+ 4 $NaOCl(aq)$	+ 2 $NaOH(aq) \rightarrow$	2 $Na_2SO_4(aq)$	+ 4 $NaCl(aq)$	+ $H_2O(l)$
Initial	0.0025 mol	0.0025 mol	0.0025 mol	0	0	0
Change	-0.000625 mol	-0.0025 mol	-0.00125 mol	+0.00125	+0.0025 mol	+0.000625 mol
Final						

$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

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In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (M)	Volume (mL)
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$n_{Na2S2O3} = n_{NaOCl} = n_{NaOH} = 0.0050\ L \cdot 0.500\ mol/Liter = 0.0025\ mol$

	$Na_2S_2O_3(aq)$	+ 4 $NaOCl(aq)$	+ 2 $NaOH(aq)$ $\rightarrow$	2 $Na_2SO_4(aq)$	+ 4 $NaCl(aq)$	+ $H_2O(l)$
Initial	0.0025 mol	0.0025 mol	0.0025 mol	0	0	0
Change	-0.000625 mol	-0.0025 mol	-0.00125 mol	+0.00125	+0.0025 mol	+0.000625 mol
Final	0.00187 mol	0 mol	0.00125 mol	+0.00125	+0.0025 mol	+0.000625 mol

NaOCl is the limiting reagent

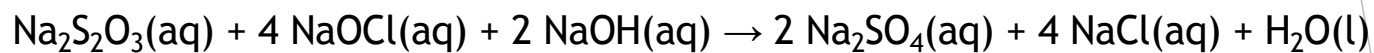$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

The solutions, all originally at 20.0 ˚C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.
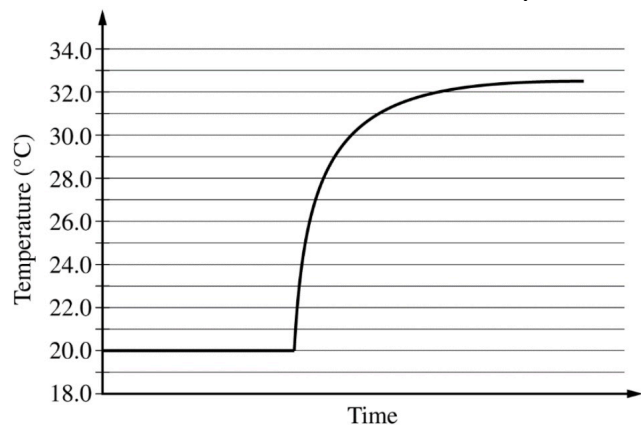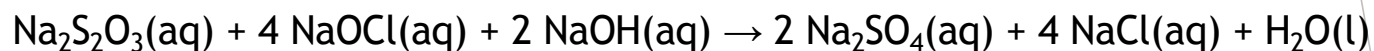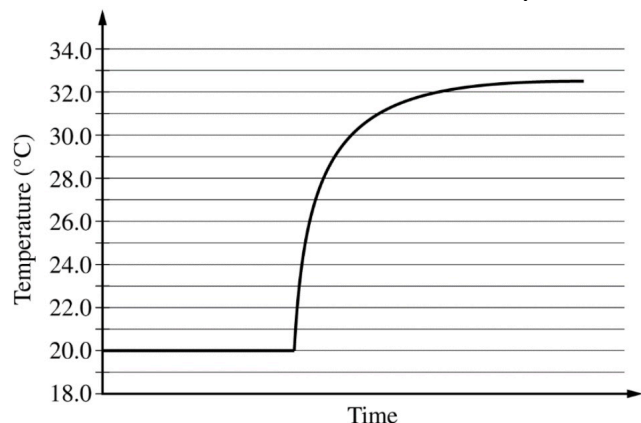

(d) According to the graph, what is the temperature change of the reaction mixture?

$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

The solutions, all originally at 20.0 °C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

(d) According to the graph, what is the temperature change of the reaction mixture?

$$\Delta T = 32.5\ °C - 20.0\ °C = 12.5\ °C$$

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

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(d) According to the graph, what is the temperature change of the reaction mixture?
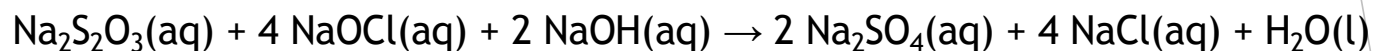
$$\Delta T = 32.5\ ˚C - 20.0\ ˚C = 12.5\ ˚C$$

(e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
  (i) Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·˚C) and that the heat absorbed by the calorimeter is negligible.

$$q_{rxn} = -q_{solution} = -(mass \cdot c \cdot \Delta T)_{solution}$$
$$q_{rxn} = -(15.0\ g \cdot 3.94\ J/(g\cdot˚C) \cdot 12.5\ ˚C)_{solution}$$
$$q_{rxn} = -739\ J$$

$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

The solutions, all originally at 20.0 ˚C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

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(e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
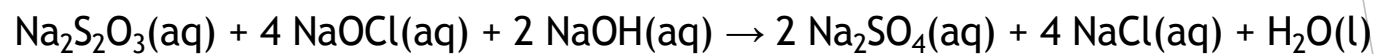   (i) Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·˚C) and that the heat absorbed by the calorimeter is negligible.

$$q_{rxn} = -q_{solution} = -(mass·c·\Delta T)_{solution}$$
$$q_{rxn} = -(15.0\ g · 3.94\ J/(g·˚C) ·12.5\ ˚C)_{solution}$$
$$q_{rxn} = -739\ J$$

(ii) Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, $\Delta H°_{rxn}$, in kJ/mol$_{rxn}$. Include the appropriate algebraic sign with your answer.

$$\Delta H_{rxn} = q_{rxn}/mol_{rxn} = -739\ J/0.0025\ mol_{NaOCl}\ (4\ mol_{NaOCl}/1\ mol_{rxn})$$
$$\Delta H_{rxn} = -1.18 \times 10^6\ J/mol_{rxn} = -1.18 \times 10^3\ kJ/mol_{rxn}$$

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

The solutions, all originally at 20.0 °C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

(g) Write the balanced net ionic equation for the given reaction.

$$Na_2S_2O_3(aq) + 4\ NaOCl(aq) + 2\ NaOH(aq) \rightarrow 2\ Na_2SO_4(aq) + 4\ NaCl(aq) + H_2O(l)$$

The solutions, all originally at 20.0 ˚C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.
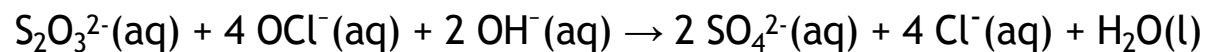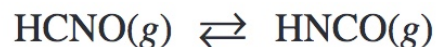
(g) Write the balanced net ionic equation for the given reaction.

$$S_2O_3^{2-}(aq) + 4\ OCl^-(aq) + 2\ OH^-(aq) \rightarrow 2\ SO_4^{2-}(aq) + 4\ Cl^-(aq) + H_2O(l)$$

$$HCNO(g) \rightleftarrows HNCO(g)$$

fulminic acid   *isocyanic acid*

Fulminic Acid	Isocyanic Acid
H—C≡N—Ö:	H—N̈=C=Ö:

(b) Using the Lewis electron-dot diagrams of fulminic acid and isocyanic acid shown in the boxes above and the table of average bond enthalpies below, determine the value of' ΔH° for the reaction of HCNO(g) to form HNCO(g).

Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)
N–O	201	C=N	615	H–C	413
C=O	745	C≡N	891	H–N	391

AP Chemistry Exam Equations for Thermochemistry

THERMODYNAMICS / ELECTROCHEMISTRY

$$q = mc\Delta T$$

$$\Delta S^\circ = \sum S^\circ \text{ products} - \sum S^\circ \text{ reactants}$$

$$\Delta H^\circ = \sum \Delta H_f^\circ \text{ products} - \sum \Delta H_f^\circ \text{ reactants}$$

$$\Delta G^\circ = \sum \Delta G_f^\circ \text{ products} - \sum \Delta G_f^\circ \text{ reactants}$$

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$
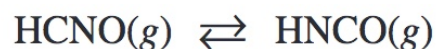
$$= -RT \ln K$$

$$= -nFE^\circ$$

$$I = \frac{q}{t}$$

$$E_{cell} = E_{cell}^\circ - \frac{RT}{nF} \ln Q$$

Mathematical Equations NOT on AP Chemistry Exam Equations Pages

$\Delta H^\circ_{rxn} = \Sigma$ (Bond Energy(reactants)) – Σ (Bond Energy(products))

$$HCNO(g) \rightleftarrows HNCO(g)$$

fulminic acid   isocyanic acid

Fulminic Acid	Isocyanic Acid
H—C≡N—Ö:	H—N̈=C=Ö:

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$\Delta H°_{rxn}$ = Σ (Bond Energy(reactants)) – Σ (Bond Energy(products))

2017 AP Chemistry Exam Question 2 Slide 2

$$HCNO(g) \rightleftarrows HNCO(g)$$

fulminic acid   isocyanic acid

Fulminic Acid	Isocyanic Acid
H—C≡N—Ö:	H—N̈=C=Ö:

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N–O	201		C=N	615		H–C	413
C=O	745		C≡N	891		H–N	391

$$\Delta H°_{rxn} = \Sigma \text{ (Bond Energy(reactants))} - \Sigma \text{ (Bond Energy(products))}$$
$$\Delta H°_{rxn} = BE(H\text{-}C) + BE(C\equiv N) + BE(N\text{-}O) - (BE(H\text{-}N) + BE(N=C) + BE(C=O))$$
$$\Delta H°_{rxn} = 413 \text{ kJ/mol} + 891 \text{ kJ/mol} + 201 \text{ kJ/mol} - (391 \text{ kJ/mol} + 615 \text{ kJ/mol} + 745 \text{ kJ/mol})$$
$$\Delta H°_{rxn} = -246 \text{ kJ/mol}_{rxn}$$