**Activity 9.1 A Quick Review of Energy Transformations**

Review Chapter 8 and pages 160–162 of Chapter 9 in *Biology,* 7th edition. Then complete the discussion by supplying or choosing the appropriate terms.

To maintain life, organisms must be able to convert energy from one form to another. For example, in the process of photosynthesis, algae, plants, and photosynthetic prokaryotes use the energy from sunlight to convert carbon dioxide and water to glucose and oxygen (a waste product).

The summary reaction for photosynthesis can be written as

6 CO2  6 H2O  C6H12O6  6 O2

This type of reaction is an oxidation-reduction (or redox) reaction. This reaction is also [***anabolic***/**catabolic**] and [***endergonic***/**exergonic**].

In redox reactions, **electrons** (and associated H ions) are transferred from one compound or element to another. If one compound or element loses **electrons** and becomes oxidized, another must gain **electrons** and become reduced. For example, in photosynthesis, water becomes [***oxidized***/**reduced**] (to O2) and the **electrons**
(and associated H ions) it “loses” in the process [**oxidize**/***reduce***]CO2 to glucose.

[***Anabolic***/**Catabolic**] reactions “build” more complex molecules from simpler ones. To do this they require energy input. Reactions that require the input of energy are termed [***endergonic***/**exergonic**] reactions.

The reactions involved in aerobic respiration are also redox reactions:

C6H12O6  6 O2  6 CO2  6 H2O

In this set of reactions, however, more complex molecules are “broken down” into simpler ones. Glucose is broken down or becomes [***oxidized/*reduced**] (to CO2), and the oxygen becomes [**oxidized/*reduced***] (to water).

[**Anabolic**/***Catabolic***] reactions break down more complex molecules into simpler ones and in the process release energy. Reactions that release energy that can be used to do work are [**endergonic**/***exergonic***]**.** Therefore, aerobic respiration is a(n) [**anabolic**/***catabolic***] process and is [**endergonic**/***exergonic***]**.**

[**Endergonic**/***Exergonic***] reactions are also said to be spontaneous reactions**.** Does this mean that if we don’t keep glucose in tightly sealed containers it will spontaneously interact with atmospheric oxygen and turn into carbon dioxide and water? The answer is obviously no.

Spontaneous reactions rarely occur “spontaneously” because all chemical reactions, even those that release energy, require some addition of energy—the energy of activation— before they can occur. One way of supplying this energy is to add heat. An example is heating a marshmallow over a flame or campfire. When enough heat is added to reach (or overcome) the activation energy, the sugar in the marshmallow reacts by oxidizing. (Burning is a form of oxidation.) The marshmallow will continue to burn even if you remove it from the campfire. As the marshmallow burns, carbon dioxide and water are formed as products of the reaction, and the energy that was stored in the bonds of the sugar is released as heat.

If our cells used heat to overcome activation energies in metabolism, they would probably burn up like the marshmallow did. Instead, living systems use protein catalysts or enzymes to lower the energy of activation without adding heat. In addition, the metabolic breakdown of sugars is carried out in a controlled series of reactions. At each step or reaction in the sequence, a small amount of the total energy is released. Some of this energy is still lost as heat. The rest is converted to other forms that can be used in the cell to drive or fuel coupled endergonic reactions or to make ATP.

**Activity 9.2 Modeling Cellular Respiration: How can Cells Convert the Energy in Glucose to ATP?**

Using your textbook, lecture notes, and the materials available in class (or those you devise at home), model both fermentation (an anaerobic process) and cellular respiration (an aerobic process) as they occur in a plant or animal cell. Each model should include a dynamic (working or active) representation of the events that occur in glycolysis.

**Building the Model**

* Use chalk on a tabletop or a marker on a large sheet of paper to draw the cell membrane and the mitochondrial membranes.
* Use playdough or cutout pieces of paper to represent the molecules, ions, and membrane transporters or pumps.
* Use the pieces you assembled to model the processes of fermentation and aerobic respiration. Develop a dynamic (claymation-type) model that allows you to manipulate or move glucose and its breakdown products through the various steps of both fermentation and aerobic respiration.
* When you feel you have developed a good working model, demonstrate and explain it to another student.

Be sure your model of **fermentation** includes and explains the actions and roles of the following:

glycolysis

cytoplasm

electrons

protons

glucose

NAD

NADH

ADP

 P i

ATP

pyruvate

ethyl alcohol (or lactic acid)

substrate-level phosphorylation

Be sure your model of **cellular respiration** includes and explains the actions and roles of the following:

glucose

oxygen

carbon dioxide

pyruvate

acetyl CoA

NAD

NADH

FAD

FADH2

ADP

 P i

ATP

water

electron transport chain

mitochondria

inner mitochondrial membrane

outer mitochondrial membrane

H

electrons (*e*)

chemiosmosis

ATP synthase (proton pumps)

cristae

proton gradients

oxidative phosphorylation

substrate-level phosphorylation

oxidative phosphorylation

**Use your models to answer the questions.**

1. The summary formula for cellular respiration is

C6H12O6  6 O2  6 CO2  6 H2O  Energy

|  |  |
| --- | --- |
| a. Where is each of the reactants used in the overall process?  | b. Where is each of the products produced in the overall process? |
|  C6H12O6  6 O2  6 CO2  6 H2O  Energy |
| Glycolysis | Oxidative phosphorylation | Pyruvate  Acetyl CoA and Krebs cycle | Oxidative phosphorylation | ATP/glucose Glycolysis (2), Krebs (2 GTP), oxidative phosphorylation(up to 34) |

2. In cellular respiration, the oxidation of glucose is carried out in a controlled series of reactions. At each step or reaction in the sequence, a small amount of the total energy is released. Some of this energy is lost as heat. The rest is converted to other forms that can be used by the cell to drive or fuel coupled endergonic reactions or to make ATP.

|  |  |  |
| --- | --- | --- |
| a. What is/are the overall function(s) of glycolysis? | b. What is/are the overall function(s) of the Krebs cycle?  | c. What is/are the overall function(s) of oxidative phosphorylation? |
| Oxidation of glucose to 2 pyruvate. Generates 2 ATP and 2 NADH per glucose. | Oxidation of pyruvate/acetyl CoA to carbon dioxide. Generates 2 GTP, 6 NADH, and 2 FADH2 per glucose. | Oxidation of NADH and FADH2to H2O (and NAD or FAD). Generates H ion concentration gradient and therefore ATP. |

|  |  |  |  |
| --- | --- | --- | --- |
| 3. Are the compounds listed here *used* or *produced* in: | Glycolysis? | The Krebs cycle? | Oxidative phosphorylation? |
| Glucose | Used |  |  |
| O2 |  |  | Used |
| CO2 |  | Produced |  |
| H2O |  |  | Produced |
| ATP | Produced | Produced(GTP) | Produced |
| ADP  P i | Produced & used | Used | Used |
| NADH | Produced | Produced | Used |
| NAD | Used | Used | Produced |

4. The cell’s supply of ADP, P i, and NAD is finite (limited). What happens to cellular respiration when all of the cell’s NAD has been converted to NADH?

If NAD is unavailable, the cell is unable to conduct any processes that involve the conversion of NAD to NADH. Because both glycolysis and the Krebs cycle produce NADH, both of these processes shut down when there is no available.NAD.

5. If the Krebs cycle does not require oxygen, why does cellular respiration stop after glycolysis when no oxygen is present?

When no oxygen is present, oxidative phosphorylation cannot occur. As a result, the NADH produced in glycolysis and the Krebs cycle cannot be oxidized to NAD. When no NAD is available, pyruvate cannot be converted to the acetyl CoA that is required for the Krebs cycle.

6. Many organisms can withstand periods of oxygen debt (anaerobic conditions). Yeast undergoing oxygen debt converts pyruvic acid to ethanol and carbon dioxide. Animals undergoing oxygen debt convert pyruvic acid to lactic acid. Pyruvic acid is fairly nontoxic in even high concentrations. Both ethanol and lactic acid are toxic in even moderate concentrations. Explain why this conversion occurs in organisms.

As noted in question 4, when no NAD is available, even glycolysis stops. No ATP will be produced and the cell (or organism) will die. The conversion of pyruvic acid (pyruvate) to lactic acid (or ethanol) requires the input of NADH and generates NAD. This process, called fermentation, allows the cell to continue getting at least 2 ATP per glucose.

7. How efficient is fermentation? How efficient is cellular respiration? Remember that efficiency is the amount of useful energy (as ATP) gained during the process divided by the total amount of energy available in glucose. Use 686 kcal as the total energy available in 1 mol of glucose and 8 kcal as the energy available in 1 mol of ATP.

|  |  |
| --- | --- |
| Efficiency of fermentation | Efficiency of aerobic respiration |
| 8 kcal/mole of ATP x 2 ATP  16 kcal16 kcal/2 moles of ATP  2.3%686 kcal/mole of glucose | 8 kcal/mole of ATP x 38 ATP (maximum)  304 kcal304 kcal/38 moles of ATP  44.3%686 kcal/mole of glucose |

8. a. Why can’t cells store large quantities of ATP? (*Hint:* Consider both the chemical stability of the molecule and the cell’s osmotic potential.)

ATP is highly reactive at normal body temperatures and therefore difficult for cells to store for any period of time. (In the lab, ATP is usually stored at very low temperatures, for example, at –20°C.) In addition, ATP is a relatively small molecule. As a result, if cells could store high concentrations of ATP, their osmotic potential would change. This is also why cells don’t store glucose. The cells would become hypertonic to the fluid around them and could pick up enough water to burst.

b. Given that cells can’t store ATP for long periods of time, how do they store energy?

Instead of storing ATP, cells tend to store energy as fats, oils, or starches. These are very large molecules and, as a result, do not have as great an effect on osmotic potential.

9. To make a 5 *M* solution of hydrochloric acid, we add 400 ml of 12.5 *M* hydrochloric acid to 600 ml of distilled water. Before we add the acid, however, we place the flask containing the distilled water into the sink because this solution can heat up so rapidly that the flask breaks. How is this reaction similar to what happens in chemiosmosis? How is it different?

|  |  |
| --- | --- |
| Similarities | Differences |
| In both processes, as we add the acid to the water, we are generating a difference in concentration between the two, or a H ion gradient. As the H ions flow down this gradient (that is, mix with the water), they release energy in the form of heat. | Chemiosmosis also sets up a H ion concentration gradient; however, the energy release is controlled as the H ions pass through the ATP synthase molecules and ATP is generated. Some energy is lost as heat, but much of it is captured in the chemical bonds of ATP. |

10. If it takes 1,000 g of glucose to grow 10 g of an anaerobic bacterium, how many grams of glucose would it take to grow 10 g of that same bacterium if it was respiring aerobically? Estimate your answer. For example, if it takes *X* amount of glucose to grow 10 g of anaerobic bacteria, what factor would you have to multiply or divide *X* by to
grow 10 g of the same bacteria aerobically? Explain how you arrived at your answer.

Aerobic respiration can produce a maximum of 38 ATP per glucose molecule. Anaerobic respiration can produce 2 ATP per glucose molecule. As a result, aerobic respiration is about 19 times more efficient. Therefore, you would need 19 times less glucose if respiring aerobically: 1,000 g of glucose divided by 19 equals approximately 50 g of glucose required if respiration is aerobic.

11. Mitochondria isolated from liver cells can be used to study the rate of electron transport in response to a variety of chemicals. The rate of electron transport is measured as the rate of disappearance of O2 from the solution using an oxygen-sensitive electrode.

How can we justify using the disappearance of oxygen from the solution as a measure of electron transport?

Use the balanced equation for aerobic respiration:

C6H12O6  6 O2  6 CO2  6 H2O  Energy

If the final energy produced is 38 ATP, then for every 6 oxygen molecules consumed (or 6 moles of oxygen consumed), we expect 38 molecules of ATP (or moles of ATP) to be produced.

12. Humans oxidize glucose in the presence of oxygen. For each mole of glucose oxidized, about 686 kcal of energy is released. This is true whether the mole of glucose is oxidized in human cells or burned in the air. A calorie is the amount of energy required to raise the temperature of 1 g of water by 1°C; 686 kcal  686,000 cal. The average human requires about 2,000 kcal of energy per day, which is equivalent to about 3 mol of glucose per day. Given this, why don’t humans spontaneously combust?

As noted in question 9, during cellular respiration, the energy from the oxidation of glucose is not released all at once (as it is in burning). Instead, each of the reactions in glycolysis, the Krebs cycle, and electron transport releases a small amount of the energy stored in the molecules. Much of this energy is captured as NADH, FADH2, ATP, or GTP. Some is lost as heat; however, the heat loss also occurs at each step and not all at once.