ATP and Cellular Respiration NOTES

ATP AND ENERGY:

- Living things need continuous input of ENERGY to sustain life
- ENERGY is defined as the capacity of a system to perform work or an action.
- Living organisms obtain energy via the interdependent processes of PHOTOSYNTHESIS AND CELLULAR RESPIRATION.

- What form of “energy” do the cells of living things actually USE?
- ENERGY STORED IN THE CHEMICAL BONDS OF SPECIFIC MOLECULES, PRIMARILY ATP
- What is ATP? ADENOSINE TRIPHOSPHATE
- The energy stored in ATP is located within the chemical bond between the 2nd and 3rd phosphate of the ATP molecule
CELLULAR RESPIRATION IN DETAIL:

The three steps of Cellular Respiration are

1. **Glycolysis**, occurs in the **cytoplasm**
2. **Pyruvate oxidation and the citric acid cycle**, occurs in the **mitochondrial inner compartment**
3. The **electron transport chain**, located in the **mitochondrial inner membrane**.

**STEP 1: Glycolysis**

Glycolysis occurs in the cytoplasm. In glycolysis, glucose, a six-carbon sugar, is converted into 2 molecules of pyruvate, a 3-carbon sugar. The energy released as covalent bonds are broken by this conversion is captured to produce 2 molecules of ATP from 2 ADP and 2 free phosphate groups (2 P); as well as 2 molecules of NADH from 2 NAD⁺. Two free hydrogen ions (H⁺) are also released.

Thus the net ATP yield (the ATP “profit”) of glycolysis is 2 ATP. The NADH yield of glycolysis is 2 NADH.

NADH is an alternate energy storage molecule that carries 2 electrons (2 e⁻; represented in blue) and one hydrogen ion (H⁺) to the electron transport chain (see step 3).

**STEP 2: Pyruvate oxidation and the citric acid cycle**

The 2 pyruvate molecules produced by glycolysis are then transported from the cytoplasm to the mitochondrial inner compartment, where pyruvate oxidation and the citric acid cycle (also known as the Krebs cycle) take place.

During pyruvate oxidation, each molecule of pyruvate is attached to a large organic molecule called coenzyme A to create Acetyl coenzyme A (acetyl-coA). In the process one molecule of CO₂ is released as well as one hydrogen ion (H⁺). The energy released as covalent bonds are broken by this conversion is captured to produce 1 molecule of NADH from 2 NAD⁺.

Since each molecule of glucose yields 2 pyruvate, the net yields of pyruvate oxidation are: a) 2 acetyl-CoA, b) 2 CO₂ molecules, c) 2 NADH, and d) 2 H⁺ per molecule of glucose.

NADH is an alternate energy storage molecule that carries 2 electrons (2 e⁻; represented in blue) and one hydrogen ion (H⁺) to the electron transport chain (see step 3).
Each acetyl-coA molecule then enters the citric acid cycle (the Krebs cycle). From each molecule of acetyl-CoA the citric acid cycle releases 2 \( CO_2 \). The energy released as each carbon-to-carbon covalent bond is broken is captured to produce:

a) 3 molecules of NADH from 3 NAD\(^+\) (3 free hydrogen ions \( (H^+) \) are also released)
b) 1 molecule of ATP from 1 ADP and 1 free phosphate group \( (P) \)
c) 1 molecule of FADH\(_2\) from FAD

Since each molecule of glucose yields 2 molecules of acetyl-CoA, the cycle occurs twice, making the net yields of the citric acid cycle

a) 4 \( CO_2 \)
b) 6 NADH and 6 \( H^+ \)
c) 2 ATP
d) 2 FADH\(_2\)

per molecule of glucose.

NADH and FADH\(_2\) are alternate energy storage molecules that carry 2 electrons (2 e\(^-\); represented in blue) and one (NADH) or two (FADH\(_2\)) hydrogen ions \( (H^+) \) to the electron transport chain (see step 3).

**STEP 3: The Electron Transport Chain**

The electron transport chain is made up of a series of proteins located within the mitochondrial inner membrane. NADH and FADH\(_2\) deliver their high-energy electrons to the electron transport chain and pass the electrons into the chain. These high energy electrons are then passed through the proteins of the chain.
and their energy is harvested to drive active transport of hydrogen ions (H\(^+\)) from the mitochondrial inner compartment, where hydrogen ion (H\(^+\)) concentration is LOW, into the mitochondrial outer compartment where hydrogen ion (H\(^+\)) concentration is HIGH.

At the end of the electron transport chain, the now energy-depleted electrons (e\(^-\)) are “accepted” by oxygen (O\(_2\)), which then forms a covalent bond with remaining hydrogen ions (H\(^+\)) to make water. Thus, oxygen (O\(_2\)) is called the “final electron acceptor” of cellular respiration.

During chemiosmosis, the highly concentrated hydrogen ions (H\(^+\)) from the mitochondrial outer compartment pass through the ATP synthase protein, a transport protein located within the mitochondrial inner membrane, as they passively diffuse back into the mitochondrial inner compartment. The energy of motion as these hydrogen ions (H\(^+\)) pass through ATP synthase is captured to produce ATP from ADP and free phosphate groups (P). The maximum theoretical ATP yield of the electron transport chain per molecule of glucose is about 28 ATP.

**PLEASE NOTE:** Different sources differ in their calculations of maximum theoretical ATP yield from the electron transport chain. These estimates vary from as little as about 28 ATP to as much as about 32 ATP per molecule of glucose. For our purposes, we will use the minimum estimate of about 28 ATP, as shown in your textbook.

Thus, the maximum theoretical ATP yield of cellular respiration per molecule of glucose is about 32 ATP

\[ 2 \text{ ATP from glycolysis} \]
\[ 2 \text{ ATP from the citric acid cycle} \]
\[ + \text{ about 28 ATP from the electron transport chain} \]
\[ = \text{ maximum about 32 ATP yield per molecule of glucose} \]

The balanced chemical equation for cellular respiration is:

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{energy in the form of about 32 ATP and heat} \]

(glucose)
Many known poisons exert their toxic effects by interfering with cellular respiration, and in particular by interfering with the function of the electron transport chain of the mitochondrial inner membrane.

For example, **ROtenone**, an insecticide/pesticide, binds to the electron (e⁻) carrier of the first protein of the electron transport chain, preventing the transport of electrons (e⁻) along the electron transport chain, and thereby preventing the creation of the proton gradient (H⁺ gradient) that powers the generation of ATP. Without the creation of the proton gradient (H⁺ gradient), ATP synthase cannot generate any ATP.

Similarly, **Cyanide** and **Carbon Monoxide** bind to the last protein of the electron transport chain, and prevent it from transferring the de-energized electrons (e⁻) to oxygen gas (O₂), the final electron acceptor of the electron transport chain. Therefore, the flow of electrons along the electron transport chain becomes blocked, preventing the creation of the proton gradient (H⁺ gradient) that powers the generation of ATP. Again, without the creation of the proton gradient (H⁺ gradient), ATP synthase cannot generate any ATP.

Other poisons such as **Dinitrophenol (DNP)** are known as “uncouplers”. Such poisons allow the protons (H⁺ ions) to travel across the mitochondrial inner membrane **without** passing through ATP synthase. Thus the cell continues to burn food energy, consume oxygen, and generate heat as it creates the proton gradient (H⁺ gradient), but the protons (H⁺ ions) immediately diffuse back across the mitochondrial inner membrane along the concentration gradient. Since they are not traveling through ATP synthase, however, no ATP is generated.

**Oligomycin**, a topical medication used to treat fungal infections of the skin, directly interferes with ATP synthase. It blocks the passage of protons (H⁺ ions) through ATP synthase thereby preventing the synthesis of ATP. The medicine can be safely used on the skin because the layer of dead skin cells we have acts as a protective barrier that prevents the oligomycin from entering our live cells.