

Example question: Redox reactions - solution

In this example question, we will compare the energy obtained by aerobic oxidation of glucose ($C_6H_{12}O_6$) and nitrification ($NH_4^+ \rightarrow NO_3^-$). In both processes, microorganisms use molecular oxygen (O_2) dissolved in water as an electron acceptor.

1) Pick up a pair of half reactions from Table 14.2 of the EOC textbook for each process. Combine the half reactions to write up the overall reaction for each process and calculate the $\Delta_r G^0(W)$ values.

Answer)

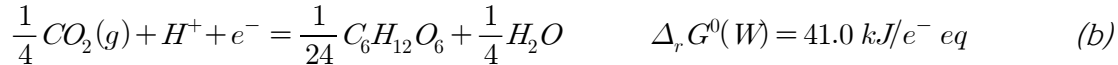
It is convenient to convert the half reactions in an electron-equivalent form.

Aerobic glucose oxidation:

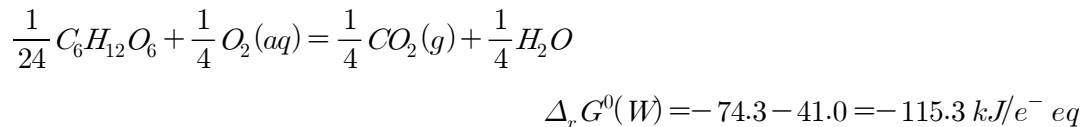
Use (1b) and convert:



Use (12) and convert:



Overall reaction, (a) - (b):



Nitrification:

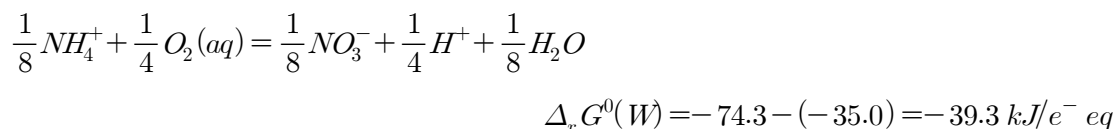
reduction half reaction is given above:



Use (5) and convert:



Overall reaction, (a) - (c):



- 2) From the E_H^0 values of the half reactions, obtain the standard free energy change ($\Delta_r G^0$) of the half reactions. From the $\Delta_r G^0$ values for half reactions, calculate the standard free energy change of the two overall reactions.

Answer)

Aerobic glucose oxidation:

i) oxygen reduction half reaction

$$\Delta_r G^0 = -nFE_H^0 = -1 \cdot 96.5 \text{ kJ/mole} - V \cdot 1.19 \text{ V} = -114.8 \text{ kJ/e}^- \text{ eq}$$

ii) glucose oxidation half reaction

$$\Delta_r G^0 = -nFE_H^0 = -1 \cdot 96.5 \text{ kJ/mole} - V \cdot (-0.01 \text{ V}) = 1.0 \text{ kJ/e}^- \text{ eq}$$

iii) overall reaction:

$$\Delta_r G^0 = -114.8 - 1.0 = -115.8 \text{ kJ/e}^- \text{ eq}$$

Nitrification:

i) oxygen reduction half reaction: $\Delta_r G^0 = -114.8 \text{ kJ/e}^- \text{ eq}$

ii) ammonium oxidation half reaction

$$\Delta_r G^0 = -nFE_H^0 = -1 \cdot 96.5 \text{ kJ/mole} - V \cdot 0.88 \text{ V} = -84.9 \text{ kJ/e}^- \text{ eq}$$

iii) overall reaction:

$$\Delta_r G^0 = -114.8 - (-84.9) = -29.9 \text{ kJ/e}^- \text{ eq}$$

- 3) Assume you added 90 mg/L glucose and 14 mg-N/L NH_4^+ into water at 25°C and pH=7.0. You maintained the dissolved oxygen (DO) concentration in the water as 8 mg/L and inoculated a group microorganisms that mediate the two reactions. Calculate the $\Delta_r G$ values for both reactions. Assume the partial pressure of CO_2 as 3.0×10^{-4} atm and NO_3^- -N concentration of 0.1 mM.

(Hint: assume molarity (M) equals activity for dissolved constituents. For gas constituents, use partial pressure as activity. Assume activity of water as 1.)

Answer)

Convert concentrations of all water constituents in molarity (M).

Glucose MW = 180 g/mole

$$\text{glucose: } \frac{90 \text{ mg/L}}{180 \text{ g/mole}} \times 10^{-3} \text{ g/mg} = 5.0 \times 10^{-4} \text{ M}$$

$$NH_4^+: \frac{14 \text{ mg} - N/L}{14 \text{ g/mole}} \times 10^{-3} \text{ g/mg} = 1.0 \times 10^{-3} \text{ M}$$

$$O_2: \frac{8 \text{ mg/L}}{32 \text{ g/mole}} \times 10^{-3} \text{ g/mg} = 2.5 \times 10^{-4} \text{ M}$$

$$\Delta G_r = \Delta_r G^0 + RT \ln Q_r$$

glucose aerobic oxidation:

$$Q_r = \frac{\{CO_2\}^{1/4}}{\{C_6H_{12}O_6\}^{1/24} \{O_2\}^{1/4}} = \frac{P_{CO_2}^{1/4}}{[C_6H_{12}O_6]^{1/24} [O_2]^{1/4}} = \frac{(3.0 \times 10^{-4})^{1/4}}{(5.0 \times 10^{-4})^{1/24} (2.5 \times 10^{-4})^{1/4}}$$

$$= 1.437$$

$$\Delta G_r = \Delta_r G^0 + RT \ln Q_r = -115.8 \text{ kJ/mole} + (8.314 \times 10^{-3} \text{ kJ/K-mole}) \cdot 298 \text{ K} \cdot \ln 1.437$$

$$= -114.9 \text{ kJ/e}^- \text{ eq}$$

Nitrification:

$$Q_r = \frac{\{NO_3^-\}^{1/8} \{H^+\}^{1/4}}{\{NH_4^+\}^{1/8} \{O_2\}^{1/4}} = \frac{[NO_3^-]^{1/8} [H^+]^{1/4}}{[NH_4^+]^{1/8} [O_2]^{1/4}} = \frac{(10^{-4})^{1/8} (10^{-7.0})^{1/4}}{(1.0 \times 10^{-3})^{1/8} (2.5 \times 10^{-4})^{1/4}}$$

$$= 0.1062$$

$$\Delta G_r = \Delta_r G^0 + RT \ln Q_r = -29.9 \text{ kJ/mole} + (8.314 \times 10^{-3} \text{ kJ/K-mole}) \cdot 298 \text{ K} \cdot \ln 0.1062$$

$$= -35.5 \text{ kJ/e}^- \text{ eq}$$

4) In the condition given in 3), which process is more competitive, glucose oxidation or nitrification? Can you guess how the glucose and ammonium concentration will change over time?

Answer)

As glucose oxidation gives more energy than nitrification, glucose oxidation is more competitive. Therefore, glucose concentration will decrease first while nitrification does not occur significantly at the beginning of incubation. Later, as glucose is consumed, nitrification will get more and more competitive, because glucose oxidizing microorganisms will suffer from limited availability of glucose. In the sense of thermodynamics, Q_r for glucose oxidation reaction will go up as glucose concentration decreases, resulting in reduced ΔG_r . Therefore, ammonium concentration will decrease once glucose is consumed substantially.