

# 23 Metals and Metallurgy

## Visualizing Concepts

23.1 The diagram indicates that the roasting of ZnS is exothermic. The roasting reaction, once under way, will increase the temperature of the oven. The thermodynamic characteristics of the reaction do not affect its rate. Although heating will decrease the value of the equilibrium constant for an exothermic reaction, it is required so that the roasting reaction occurs at a practical rate.

23.3 *Analyze/Plan.* See the discussion of metallic bonding and physical properties in Section 23.5. Consider the electron configurations of Zr, Mo and Cd.

*Solve.* Zr:  $[\text{Kr}]5s^25d^2$ ; Mo:  $[\text{Kr}]5s^14d^5$ ; Cd:  $[\text{Kr}]5s^24d^{10}$

The chemical equation that represents formation of gaseous elements is  $M(s) \rightarrow M(g)$ , where  $M(s)$  represents the metal in its standard state and  $M(g)$  is the gaseous metal. In order for this change to occur, metal-metal bonds in the solid must be broken as the atoms move apart to enter the gas phase. The stronger the metal-metal bonding of the element, the greater the magnitude of  $\Delta H_f^\circ$ . The metals shown in the diagram have valence orbitals that are less than half full and the number of valence electrons increases from Rb to Zr. The metal-metal bonding band contains progressively more electrons, the strength of metallic bonding increases, and  $\Delta H_f^\circ$  increases.

Molybdenum, with valence orbitals that are exactly half-full, has a full bonding band and an empty valence band. It has stronger metal-metal bonding than Zr, and thus a larger enthalpy of formation of the gaseous form.

Cadmium atoms have filled valence orbitals, resulting in filled bonding and anti-bonding bands. Metal-metal bonding in Cd is weaker than that in Zr, so the standard enthalpy of formation of  $\text{Cd}(g)$  is smaller than that of Zr.

23.5 Periodic properties are explained in terms of effective nuclear charge,  $Z_{\text{eff}}$ . Moving from left to right in a period,  $Z_{\text{eff}}$  increases because the increase in  $Z$  is not offset by a significant increase in shielding. Increasing  $Z_{\text{eff}}$  leads to increasing ionization energy and electronegativity, but decreasing atomic radius.

The chart shows a general decrease in magnitude of the property from K to Ge, so the property must be atomic radius.

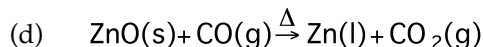
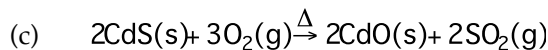
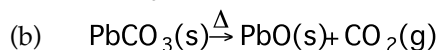
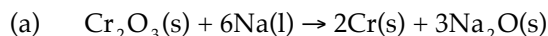
## Metallurgy

23.7 *Analyze/Plan.* Use Table 23.1 and other information in Section 23.1-23.4 to find important natural sources of Al and Fe. Use the rules for assigning oxidation numbers in Section 4.4 to determine the oxidation state of the metal in each natural source.

*Solve.* Important sources of iron are **hematite** ( $\text{Fe}_2\text{O}_3$ ) and **magnetite** ( $\text{Fe}_3\text{O}_4$ ). Principle mineral sources of aluminum are corundum ( $\text{Al}_2\text{O}_3$ ) and Gibbsite ( $\text{Al}(\text{OH})_3$ ). Gibbsite is one component of **bauxite rock**, the major industrial source of new Al. In ores, iron is present as the +3 ion, or in both the +2 and +3 states, as in magnetite. Aluminum is always present in the +3 oxidation state.

23.9 An ore consists of a little bit of the stuff we want, (chalcopyrite,  $\text{CuFeS}_2$ ) and lots of other junk (gangue).

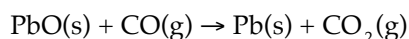
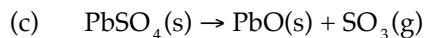
23.11 *Analyze/Plan.* Use principles of writing and balancing chemical equations from Chapter 3 to complete and balance the given reactions. The  $\Delta$  above each arrow indicates that the reactions take place at elevated temperature. Information in Section 23.2 on *pyrometallurgy* will probably be useful. *Solve.*



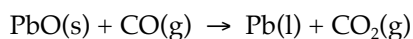
23.13 *Analyze/Plan.* Use information on *pyrometallurgy* in Section 23.2, along with principles of writing and balancing equations to provide the requested information. *Solve.*



(b)  $\text{CO}(\text{g})$  provides a reducing environment for the transformation of  $\text{Pb}^{2+}$  to Pb.



23.15 *Analyze/Plan.* Use Hess's law to calculate  $\Delta H^\circ$  from  $\Delta H_f^\circ$  for the reactants and products, and then  $\Delta G^\circ$  from  $\Delta G_f^\circ$  and  $\Delta S^\circ$  from  $S^\circ$  values. Use Pb(s) values for Pb(l) (approximate). *Solve.*



$$\Delta H^\circ = \Delta H_f^\circ \text{Pb}(\text{l}) + \Delta H_f^\circ \text{CO}_2(\text{g}) - \Delta H_f^\circ \text{PbO}(\text{s}) - \Delta H_f^\circ \text{CO}(\text{g})$$

$$= 0 + (-393.5) - (-217.3) = (-110.5) = -65.7 \text{ kJ}$$

$$\Delta G^\circ = \Delta G_f^\circ \text{Pb}(\text{l}) + \Delta G_f^\circ \text{CO}_2(\text{g}) - \Delta G_f^\circ \text{PbO}(\text{s}) - \Delta G_f^\circ \text{CO}(\text{g})$$

$$= 0 + (-394.4) - (-187.9) - (-137.2) = -69.3 \text{ kJ}$$

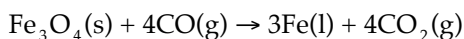
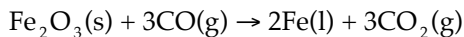
$$\Delta S^\circ = S^\circ \text{Pb}(\text{l}) + S^\circ \text{CO}_2(\text{g}) - S^\circ \text{PbO}(\text{s}) - S^\circ \text{CO}(\text{g})$$

$$= 68.85 + 213.6 - 68.70 - 197.9 = 15.85 = 15.9 \text{ J/K}$$

$\Delta G^\circ$  is negative; the reaction is spontaneous at  $25^\circ\text{C}$  and standard conditions.  $\Delta H^\circ$  is negative; the reaction is exothermic. (We anticipate that  $\Delta H_f^\circ$  for Pb(l) is positive, so the magnitude of  $\Delta H_f^\circ$  for the reaction is a bit overestimated. The reaction is probably still exothermic.)

- 23.17 *Analyze/Plan.* Use information on *pyrometallurgy* in Section 23.2, along with principles of writing and balancing equations to provide the requested information. *Solve.*

The major reducing agent is CO, formed by partial oxidation of the coke (C) with which the furnace is charged.

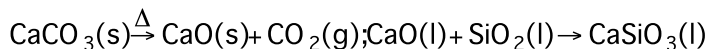


- 23.19 *Analyze/Plan.* Use information on *pyrometallurgy* in Section 23.2, along with principles of writing and balancing equations to provide the requested information. *Solve.*

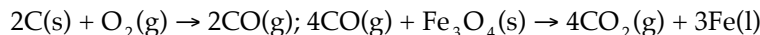
- (a) *Air* serves primarily to oxidize coke (C) to CO, the main reducing agent in the blast furnace. This exothermic reaction also provides heat for the furnace.



- (b) *Limestone*,  $\text{CaCO}_3$ , is the source of basic oxide for slag formation.



- (c) *Coke* is the fuel for the blast furnace, and the source of CO, the major reducing agent in the furnace.



- (d) *Water* acts as a source of hydrogen, and as a means of controlling temperature. (See Equation [23.8].)  $\text{C}(\text{s}) + \text{H}_2\text{O}(\text{g}) \rightarrow \text{CO}(\text{g}) + \text{H}_2(\text{g}) \quad \Delta H = +131 \text{ kJ}$

- 23.21 *Analyze/Plan.* Use information on the *electrometallurgy* of Cu as a model for describing how electrometallurgy can be employed to purify pure Co. Compare the ease of oxidation and reduction of cobalt with that of water. *Solve.*

Cobalt could be purified by constructing an electrolysis cell in which the crude metal was the anode and a thin sheet of pure cobalt was the cathode. The electrolysis solution is aqueous with a soluble cobalt salt such as  $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$  serving as the electrolyte. (Other soluble salts with anions that do not participate in the cell reactions could be used.) Anode reaction:  $\text{Co}(\text{s}) \rightarrow \text{Co}^{2+}(\text{aq}) + 2\text{e}^-$ ; cathode reaction:  $\text{Co}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Co}(\text{s})$ . Although  $E^\circ$  for reduction of  $\text{Co}^{2+}(\text{aq})$  is slightly negative ( $-0.277 \text{ V}$ ), it is less than the standard reduction potential for  $\text{H}_2\text{O}(\text{l})$ ,  $-0.83 \text{ V}$ .

## Metals and Alloys

- 23.23 *Analyze/Plan.* Compare the bonding characteristics of metallic sodium and ionic sodium chloride and use them to explain the difference in malleability. *Solve.*

Sodium is metallic; each atom is bonded to many nearest neighbor atoms by metallic bonding involving just one electron per atom, and delocalized over the entire three-dimensional structure. When sodium metal is distorted, each atom continues to have bonding interactions with many nearest neighbors. In NaCl the ionic forces are strong, and the arrangement of ions in the solid is very regular. When subjected to physical stress, the three-dimensional lattice tends to cleave along the very regular lattice planes, rather than undergo the large distortions characteristic of metals.

- 23.25 *Analyze/Plan.* Apply the description of the electron-sea model of metallic bonding given in Section 23.5 to the conductivity of metals. *Solve.*

In the electron-sea model for metallic bonding, valence electrons move about the three-dimensional metallic lattice, while the metal atoms maintain regular lattice positions.

Under the influence of an applied potential the electrons can move throughout the structure, giving rise to high electrical conductivity. The mobility of the electrons facilitates the transfer of kinetic energy and leads to high thermal conductivity.

- 23.27 *Analyze/Plan.* Consider trends in atomic mass and volume of the elements listed to explain the variation in density. *Solve.*

Moving left to right in the period, atomic mass and  $Z_{\text{eff}}$  increase. The increase in  $Z_{\text{eff}}$  leads to smaller bonding atomic radii and thus atomic volume. Mass increases, volume decreases, and density increases in the series.

The variation in densities reflects shorter metal-metal bond distances. These shorter distances suggest that the extent of metal-metal bonding increases in the series. This is consistent with greater occupancy of the bonding band as the number of valence electrons increases up to 6. The strength of metal-metal bonds in the series is probably the most important factor influencing the increase in density.

- 23.29 *Analyze/Plan.* Consider the definition of ductility, as well as the discussion of metallic bonding in Section 23.5. *Solve.*

Ductility is the property related to the ease with which a solid can be drawn into a wire. Basically, the softer the solid the more ductile it is. The more rigid the solid, the less ductile it is. For metals, ductility decreases as the strength of metal-metal bonding increases, producing a stiffer lattice less susceptible to distortion.

- (a) Ag is more ductile. Mo, with 6 valence electrons, has a filled bonding band, strong metal-metal interactions, and a rigid lattice. This predicts high hardness and low ductility. Ag, with 12 valence electrons, has filled antibonding as well as bonding bands. Bonding is weaker than in Mo, and Ag is more ductile.
- (b) Zn is more ductile. Si is a covalent-network solid with all valence electrons localized in bonds between Si atoms. Covalent-network substances are high-melting, hard, and not particularly ductile.

- 23.31 *Analyze/Plan.* Recall the diamond and closest-packed structures described in Section 11.7. Use these structures to draw conclusions about Sn–Sn distance and electrical conductivity in the two allotropes. *Solve.*

White tin, with a characteristic metallic structure, is expected to be more metallic in character. The white allotropic form has the properties of a metal, including high electrical conductivity, because the valence electrons are shared with 12 nearest neighbors rather than being localized in four bonds to nearest neighbors as in gray tin. Gray tin, on the other hand, has the diamond structure characteristic of other Group IV semiconductors.

The Sn–Sn distance should be longer in white tin; there are only four valence electrons from each atom, and 12 nearest neighbors. The **average** tin–tin bond order can, therefore, be only about 1/3, whereas in gray tin the bond order is one. Gray tin, with the higher bond order, has a shorter Sn–Sn distance, 2.81 Å. The bond length in white tin, with the lower bond order, is 3.02 Å.

- 23.33 *Analyze/Plan.* Use information in Section 23.6 to define *alloy*, and compare the various types of alloys. *Solve.*

An *alloy* contains atoms of more than one element and has the properties of a metal. *Solution alloys* are homogeneous mixtures with different kinds of atoms dispersed randomly and uniformly. In *heterogeneous alloys* the components (elements or compounds) are not evenly dispersed and their properties depend not only on composition but methods of preparation. In an *intermetallic compound* the component elements have interacted to form a compound substance, for example,  $\text{Cu}_3\text{As}$ . As with more familiar compounds, these are homogeneous and have definite composition and properties.

- 23.35 *Analyze/Plan.* Consider the descriptions of various alloy types in Section 23.6. *Solve.*

- $\text{Fe}_{0.97}\text{Si}_{0.03}$ ; interstitial alloy. The radii of Fe and Si are substantially different, so Si could fit in “holes” in the Fe lattice. Also, the small amount of Si relative to Fe is characteristic of an interstitial alloy.
- $\text{Fe}_{0.60}\text{Ni}_{0.40}$ ; substitutional alloy. The two metals have very similar atomic radii and are present in similar amounts.
- $\text{Cu}_3\text{Au}$ , intermetallic compound. The two elements are present in stoichiometric amounts.

## Transition Metals

- 23.37 *Analyze/Plan.* Consider the definitions of the properties listed (Chapter 7 and Chapter 23) and whether they refer to single, isolated atoms or bulk material. *Solve.*

Of the properties listed, (b) the first ionization energy and (f) electron affinity are characteristic of isolated atoms. Electrical conductivity (a), atomic radius (c), melting point (d), and heat of vaporization (e) are properties of the bulk metal. Although it seems that atomic radius would be a property of isolated atoms, it can only be measured in bulk samples.

- 23.39 *Analyze/Plan.* Examine the electron configurations,  $Z$  and  $Z_{\text{eff}}$  of the two elements to account for their similar atomic radii.

*Solve.* Zr:  $[\text{Kr}]5s^24d^2$ ,  $Z = 40$ ; Hf:  $[\text{Xe}]6s^24f^{14}5d^2$ ,  $Z = 72$

Moving down a family of the periodic chart, atomic size increases because the valence electrons are in a higher principle quantum level (and thus further from the nucleus) and are more effectively shielded from the nuclear charge by a larger core electron cloud. However, the build-up in  $Z$  that accompanies the filling of the 4f orbitals causes the valence electrons in Hf to experience a much greater relative nuclear charge than those in La, its neighbor to the left. This increase in  $Z$  offsets the usual effect of the increase in  $n$  value of the valence electrons and the radii of Zr and Hf atoms are similar.

23.41 *Analyze/Plan.* Use Figure 23.22 to determine the highest oxidation state of each metal. Write formulas of the metal fluorides, given that fluoride ion is  $F^-$ . *Solve.*

- (a)  $ScF_3$                       (b)  $CoF$                       (c)  $ZnF_2$   
 (d)  $MoF_6$  (The oxidation states of Mo are similar to those of Cr.)

23.43 *Analyze/Plan.* Consider the electron configurations of Cr and Al to rationally observed oxidation states. *Solve.*

Chromium,  $[Ar]4s^13d^5$ , has six valence-shell electrons, some or all of which can be involved in bonding, leading to multiple stable oxidation states. By contrast, aluminum,  $[Ne]3s^23p^1$ , has only three valence electrons which are all lost or shared during bonding, producing the +3 state exclusively.

23.45 *Analyze/Plan.* Write electron configurations for the neutral elements and their positive ions recalling that valence electrons are last in order of descending  $n$ -value. *Solve.*

- (a)  $Cr^{3+}: [Ar]3d^3$                       (b)  $Au^{3+}: [Xe]4f^{14}5d^8$                       (c)  $Ru^{2+}: [Kr]4d^6$   
 (d)  $Cu^+: [Ar]3d^{10}$                       (e)  $Mn^{4+}: [Ar]3d^3$                       (f)  $Ir^+: [Xe]4f^{14}5d^8$

23.47 *Analyze/Plan.* Oxidation is loss of electrons. Which periodic trend determines how tightly a valence electron is held in a particular atom or ion? *Solve.*

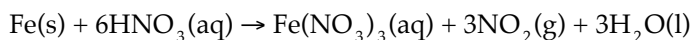
Ease of oxidation decreases from left to right across a period (owing to increasing effective nuclear charge);  $Ti^{2+}$  should be more easily oxidized than  $Ni^{2+}$ .

23.49 *Analyze/Plan.* Consider Equation [23.26] regarding the oxidation states of iron. *Solve.*  $Fe^{2+}$  is a reducing agent that is readily oxidized to  $Fe^{3+}$  in the presence of  $O_2$  from air.

23.51 *Analyze/Plan.* Consider information on the descriptive chemistry of iron in Section 23.8. *Solve.*

- (a)  $Fe(s) + 2HCl(aq) \rightarrow FeCl_2(aq) + H_2(g)$   
 (b)  $Fe(s) + 4HNO_3(aq) \rightarrow Fe(NO_3)_3(aq) + NO(g) + 2H_2O(l)$

(See net ionic equation, Equation [23.28].) In concentrated nitric acid, the reaction can produce  $NO_2(g)$  according to the reaction:



23.53 *Analyze/Plan.* Consider the definitions of paramagnetic and diamagnetic. *Solve.*

The unpaired electrons in a *paramagnetic* material cause it to be weakly attracted into a magnetic field. A *diamagnetic* material, where all electrons are paired, is very weakly repelled by a magnetic field.

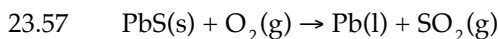
23.55 *Analyze/Plan.* Consider Figure 23.23 and the accompanying descriptions in Section 23.7 regarding *ferromagnetic*, *ferrimagnetic*, and *antiferromagnetic* materials. *Solve.*

- (a) Ferromagnetic, ferrimagnetic and antiferromagnetic materials all have atoms or ions with unpaired electrons. Furthermore, the spins of these electrons are influenced by (coupled with) the electron spins at neighboring atoms or ions. In *ferromagnetic* materials, coupled electron spins are aligned in the same direction. In *antiferromagnetic* materials, coupled spins are aligned in opposite directions

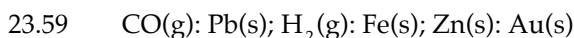
and the opposing spins exactly cancel. In ferrimagnetic materials coupled spins are aligned in opposite directions (like antiferromagnets) but the opposing spins do not cancel.

- (b) Permanent magnets have a permanent magnetic moment resulting from a net electron spin in the material. Ferromagnetic and ferrimagnetic materials have net spin (electrons with the same spins aligned, spin not canceled or only partially canceled by electrons with opposite spins) and can be used to make permanent magnets. Antiferromagnetic materials have no net electron spin, because coupled electrons have spins that exactly cancel. They cannot be used to make permanent magnets.

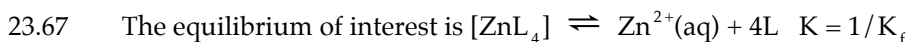
### Additional Exercises



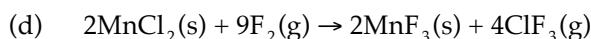
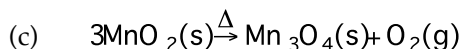
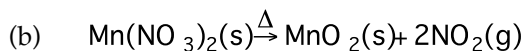
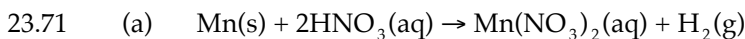
Regardless of the metal of interest,  $\text{SO}_2(\text{g})$  is a product of roasting sulfide ores. In an oxygen rich environment,  $\text{SO}_2(\text{g})$  is oxidized to  $\text{SO}_3(\text{g})$ , which dissolves in  $\text{H}_2\text{O(l)}$  to form sulfuric acid,  $\text{H}_2\text{SO}_4(\text{aq})$ . Because of its corrosive nature,  $\text{SO}_2(\text{g})$  is a dangerous environmental pollutant (Section 18.4) and cannot be freely released into the atmosphere. A sulfuric acid plant near a roasting plant would provide a means for disposing of  $\text{SO}_2(\text{g})$  that would also generate a profit.



- 23.62 Follow the logic in Sample Exercise 23.2. The standard reduction potential for  $\text{Te}^{4+}$ , 0.57 V, is more positive than that of  $\text{Cu}^{2+}$ , 0.34 V. This means the  $\text{Te}^{4+}$  is "easier" to reduce than  $\text{Cu}^{2+}$ , but Te is harder to oxidize and less active than Cu. During electrorefining, while Cu is oxidized from the crude anode, Te will not be oxidized. It is likely to accumulate along with other impurities less active than Cu, in the so-called anode sludge.



Since  $\text{Zn}(\text{H}_2\text{O})_4^{2+}$  is  $\text{Zn}^{2+}(\text{aq})$ , its reduction potential is -0.763 V. As the stability ( $K_f$ ) of the complexes increases, K decreases. Since  $E^\circ$  is directly proportional to  $\log K$  (Equation [20.16]),  $E^\circ$  values for the complexes will become more negative as  $K_f$  increases.



- 23.73 (a) insulator (b) semiconductor (c) metallic conductor  
 (d) metallic conductor (e) insulator (f) metallic conductor

## Integrative Exercises

23.74 (a) Calculate mass  $\text{Cu}_2\text{S}$  and  $\text{FeS}$ , then mass  $\text{SO}_2$  from each.

$$3.3 \times 10^6 \text{ kg sample} \times 0.27 = 8.91 \times 10^5 = 8.9 \times 10^5 \text{ kg} = 8.9 \times 10^8 \text{ g Cu}_2\text{S}$$

$$3.3 \times 10^6 \text{ kg sample} \times 0.13 = 4.29 \times 10^5 = 4.3 \times 10^5 \text{ kg} = 4.3 \times 10^8 \text{ g FeS}$$

$$8.91 \times 10^8 \text{ g Cu}_2\text{S} \times \frac{1 \text{ mol Cu}_2\text{S}}{1591 \text{ g Cu}_2\text{S}} \times \frac{1 \text{ mol SO}_2}{1 \text{ mol Cu}_2\text{S}} \times \frac{6407 \text{ g SO}_2}{1 \text{ mol SO}_2} = 3.588 \times 10^8 \\ = 3.6 \times 10^8 \text{ g SO}_2$$

$$4.29 \times 10^8 \text{ g FeS} \times \frac{1 \text{ mol FeS}}{87.9 \text{ g FeS}} \times \frac{1 \text{ mol SO}_2}{1 \text{ mol FeS}} \times \frac{6407 \text{ g SO}_2}{1 \text{ mol SO}_2} = 3.127 \times 10^8 \text{ g} \\ = 3.1 \times 10^8 \text{ g SO}_2$$

$$\text{g SO}_2 = 3.588 \times 10^8 + 3.127 \times 10^8 = 6.715 \times 10^8 = 6.7 \times 10^8 \text{ g SO}_2$$

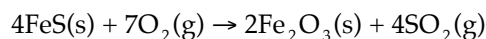
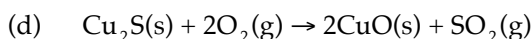
(b) Calculate mol Cu, mol Fe and mole ratio Cu: Fe.

$$8.91 \times 10^8 \text{ g Cu}_2\text{S} \times \frac{1 \text{ mol Cu}_2\text{S}}{1591 \text{ g Cu}_2\text{S}} \times \frac{2 \text{ mol Cu}}{1 \text{ mol Cu}_2\text{S}} = 1.12 \times 10^7 = 1.1 \times 10^7 \text{ mol Cu}$$

$$4.29 \times 10^8 \text{ g FeS} \times \frac{1 \text{ mol FeS}}{87.9 \text{ g FeS}} \times \frac{1 \text{ mol Fe}}{1 \text{ mol FeS}} = 4.88 \times 10^6 = 4.9 \times 10^6 \text{ mol Fe}$$

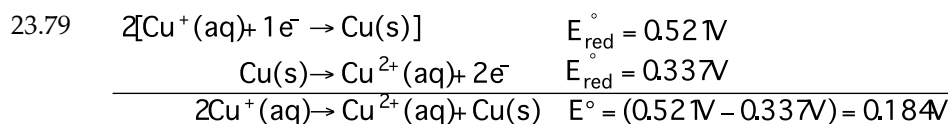
$$1.12 \times 10^7 \text{ mol Cu} / 4.88 \times 10^6 \text{ mol Fe} = 2.3 \text{ mol Cu/mol Fe}$$

(c) The oxidizing environment of the converter is likely to produce  $\text{CuO}$  and  $\text{Fe}_2\text{O}_3$ .



23.76 The first equation indicates that one mole  $\text{Ni}^{2+}$  is formed from passage of two moles of electrons, and the second equation indicates the same thing. Thus, the simple ratio (1 mol  $\text{Ni}^{2+}/2\text{F}$ ).

$$67\text{A} \times 11.0 \text{ hr} \times \frac{3600 \text{ s}}{1 \text{ hr}} \times \frac{1 \text{ C}}{1 \text{ A} \cdot \text{s}} \times \frac{1 \text{ F}}{96,500} \times \frac{1 \text{ mol Ni}^{2+}}{2 \text{ F}} \times \frac{587 \text{ g Ni}^{2+}}{1 \text{ mol Ni}^{2+}} \\ \times \frac{0.90 \text{ g Ni actual}}{1.00 \text{ g Ni theoretical}} = 7.3 \times 10^2 \text{ g Ni}^{2+} \text{(aq)}$$



Rearrange Equation [20.16] for equilibrium conditions. At equilibrium,  $Q = K$  and  $E = 0$ ;

$$\log K = \frac{nE^\circ}{0.0592}; n = 2 \quad \log K = \frac{2(0.184)}{0.0592} = 6.216 \approx 6.22; K = 1.6 \times 10^6$$

23.82 (a) The standard reduction potential for  $\text{H}_2\text{O}(\text{l})$  is much greater than that of  $\text{Mg}^{2+}(\text{aq})$  ( $-0.83 \text{ V}$  vs.  $-2.37 \text{ V}$ ). In aqueous solution,  $\text{H}_2\text{O}(\text{l})$  would be preferentially reduced and no  $\text{Mg}(\text{s})$  would be obtained.

$$\begin{aligned} \text{(b)} \quad 97,000 \text{ A} \times 24 \text{ hr} \times \frac{3600 \text{ s}}{1 \text{ hr}} \times \frac{1 \text{ C}}{1 \text{ A} \cdot \text{s}} \times \frac{1 \text{ F}}{96,500} \times \frac{1 \text{ mol Mg}}{2 \text{ F}} \times \frac{2431 \text{ g Mg}}{1 \text{ mol Mg}} \times 0.96 \\ = 1.0 \times 10^6 \text{ g Mg} = 1.0 \times 10^3 \text{ kg Mg} \end{aligned}$$

23.85 Density is the mass of the unit cell contents divided by the unit cell volume [(edge length)<sup>3</sup>]. Refer to Figure 23.17 to determining the number of Ni atoms and  $\text{Ni}_3\text{Al}$  units in each unit cell. Use Figure 11.34 and Table 11.6 for more details.

Ni: There are 4 Ni atoms in each face-centered cubic unit cell ( $8 \times 1/8$  at the corners,  $6 \times 1/2$  on the face-centers).

$$\text{density} = \frac{4 \text{ Ni atoms}}{(3.53 \text{ \AA})^3} \times \frac{58693 \text{ g Ni}}{6.022 \times 10^{23} \text{ Ni atoms}} \times \left( \frac{\text{\AA}}{1 \times 10^{-8} \text{ cm}} \right)^3 = 8.86 \text{ g/cm}^3$$

$\text{Ni}_3\text{Al}$ : There is 1  $\text{Ni}_3\text{Al}$  unit in each cubic unit cell. According to Figure 23.17(b), Ni is at the face-centers ( $6 \times 1/2 = 3 \text{ Ni atoms}$ ) and Al is at the corners ( $8 \times 1/8 = 1 \text{ Al atom}$ ); the stoichiometry is correct.

$$\text{density} = \frac{1 \text{ Ni}_3\text{Al unit}}{(3.56 \text{ \AA})^3} \times \frac{20306 \text{ g Ni}_3\text{Al}}{6.022 \times 10^{23} \text{ Ni atoms}} \times \left( \frac{\text{\AA}}{1 \times 10^{-8} \text{ cm}} \right)^3 = 7.47 \text{ g/cm}^3$$

The density of the  $\text{Ni}_3\text{Al}$  alloy (intermetallic compound) is ~85% of the density of pure Ni. The sizes of the two unit cells are very similar. In  $\text{Ni}_3\text{Al}$ , one out of every four Ni atoms is replaced with an Al atom. The mass of an Al atom is (~27 amu) is about half that of a Ni atom (~59 amu); the mass of the unit cell contents of  $\text{Ni}_3\text{Al}$  is ~7/8 (87.5%) that of Ni, and the densities show the same relationship.