TOPIC 6:
ELECTROCHEMISTRY

Topic 6: Electrochemistry

C12-6-01 Develop an activity series experimentally.

C12-6-02 Predict the spontaneity of reactions using an activity series.

C12-6-03 Outline the historical development of voltaic (galvanic) cells.
Include: contributions of Luigi Galvani and Alessandro Volta

C12-6-04 Explain the operation of a voltaic (galvanic) cell at the visual, particulate, and symbolic levels.
Include: writing half-cell reactions, the overall reaction, and shorthand (line) notation

C12-6-05 Construct a functioning voltaic (galvanic) cell and measure its potential.

C12-6-06 Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07 Calculate standard cell potentials, given standard electrode potentials.

C12-6-08 Predict the spontaneity of reactions using standard electrode potentials.

C12-6-09 Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10 Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.
Include: a molten ionic compound and an aqueous ionic compound

C12-6-11 Describe practical uses of electrolytic cells.
Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

C12-6-12 Solve problems related to electrolytic cells, using Faraday's law.

Suggested Time: 14 hours

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-01: Develop an activity series experimentally.

C12-6-02: Predict the spontaneity of reactions using an activity series.

(2 hours)

SLO: C12-6-01
SLO: C12-6-02

SUGGESTIONS FOR INSTRUCTION

Entry-Level Knowledge

In Topic 1: Reactions in Aqueous Solutions, students were introduced to oxidation and reduction reactions. Given an oxidation-reduction reaction, students should now be able to identify the oxidation numbers of all the elements in a given reaction, the element being oxidized, the element being reduced, and the oxidizing and reducing agents. Students should also be able to balance oxidation-reduction reactions and have a good understanding of the concept of the conservation of electrons. If students are not able to perform these tasks adequately, they will have difficulty understanding electrochemistry. Review redox information from Topic 1, as necessary.

If students were asked to research practical applications of oxidation-reduction in Topic 1 (C12-1-12), give them time to present their findings in Topic 6.

TEACHER NOTES

Standard Reduction Potentials

Many chemistry texts use the SI system to present tables of Standard Reduction Potentials in which the half-reaction at the top of the tables is the lithium ion being reduced to the lithium atom, with the fluorine reduction half-reaction placed at the bottom of the tables.

The tendency for a substance to gain electrons is referred to as its *reduction potential* (E^0). Because each reduction must be coupled with an oxidation, scientists decided on a standard substance against which they could measure reduction potential. Hydrogen was chosen; thus, the hydrogen half-reaction shows up in all Standard Reduction Potentials tables as 0 volts. The rest of the table is experimentally determined by reacting substances with hydrogen at concentrations of 1 mol/L at standard temperature and pressure.

General Learning Outcome Connections

GLO B3: Identify the factors that affect health, and explain the relationships among personal habits, lifestyle choices, and human health, both individual and social.

GLO B5: Identify and demonstrate actions that promote a sustainable environment, society, and economy, both locally and globally.

GLO C1: Recognize safety symbols and practices related to scientific and technological activities and to their daily lives, and apply this knowledge in appropriate situations.

GLO C2: Demonstrate appropriate scientific inquiry skills when seeking answers to questions.

GLO C5: Demonstrate curiosity, skepticism, creativity, open-mindedness, accuracy, precision, honesty, and persistence, and appreciate their importance as scientific and technological habits of mind.

SKILLS AND ATTITUDES OUTCOMES

C12-0-S1: Demonstrate work habits that ensure personal safety and the safety of others, as well as consideration for the environment.

Include: knowledge and use of relevant safety precautions, Workplace Hazardous Materials Information System (WHMIS), and emergency equipment

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

What to Remember When Using a Table of Standard Reduction Potentials

1. Electrode potentials depend on the concentration of the reactants and products, not on the quantity. This means that stoichiometric coefficients do not alter the voltage of a half-reaction.

   Examples:

   $Ag^+ + e^- \longrightarrow Ag_{(s)}$ $E^0 = 0.80$ V

   $2Ag^+ + 2e^- \longrightarrow 2Ag(s)$ $E^0 = 0.80$ V

2. Half-reactions are listed as reductions.

3. Half-reactions can occur in either direction. Reversing the direction makes the reaction an oxidation and reverses the sign of E^0.

4. A positive value for E^0 means that the substance is easily reduced. The more positive the value is, the easier it is to reduce. Conversely, the more negative a number is, the easier it is to oxidize.

5. A negative value for E^0 means that the substance is not easily reduced. The more negative the value is, the more likely it is to be oxidized.

6. A substance with a more positive value for E^0 will oxidize a substance that is less positive on the Standard Reduction Potentials table. In other words, a substance on the reactant side of any half-reaction can oxidize a substance that is on the product side of a more negative E^0 half-reaction.

Note:

- Depending on which resources you use, **electrode potentials** tables may be listed as oxidation potentials and may list all the reactions as oxidation half-reactions. Also, some tables list more positive values for E^0 at the top, while others list more negative values at the top. This document uses **reduction potentials**, with more positive values for E^0 at the top. See Appendix 6.1: Activity Series: Lab Activity.
- Remember that –1.0 V is more positive than –2.0 V, and +1.0 V is more negative than +2.0 V.

Representations of Electrochemistry

Electrochemistry is ideally suited to discussions about what is occurring in the visual, particulate, and symbolic modes of representation. Current research shows that students gain a better understanding of chemical processes when these modes of representation are discussed and illustrated. Once students have experienced visual (macroscopic) changes in the laboratory, ask them to draw and explain what is happening at the particulate/molecular (microscopic) level. Any animations used to illustrate what is occurring at the molecular level will also increase students' understanding of the processes involved.

Topic 6: Electrochemistry

Specific Learning Outcomes

C12-6-01: Develop an activity series experimentally.

C12-6-02: Predict the spontaneity of reactions using an activity series.

(continued)

Animations/Simulations

Have students use online resources to perform simulations or to view animations of electrochemistry.

Sample Websites:

Chemical Education Research Group, Iowa State University. "Chemistry Experiment Simulations and Conceptual Computer Animations." *Chemical Education*. <http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/simDownload/index4.html> (22 Nov. 2012).

In the Electrochemistry section, download and unzip the following simulation:

- Reactions of Metals and Metal Ions Experiment

  In this simulation, students discover the activity series by placing different metals in various aqueous solutions. Students can observe the simulation at the molecular level.

Virtual Crezlab Qualitative Analysis. "Displacement Reaction." *Teaching Laboratory*. Crescent Girls' School. <www.crescent.edu.sg/crezlab/webpages/pptReaction3.htm> (3 Apr. 2012).

This animation shows the displacement reaction between aqueous copper(II) sulphate solution, $Cu_SO_{4(aq)}$, and zinc metal, $Zn_{(s)}$.

Laboratory Activity

For learning outcomes C12-6-01 and C12-6-02, students are required to perform an experiment or investigation that shows, qualitatively, how an activity series is derived. Most chemistry textbooks and resource manuals outline an experiment that uses metals such as Zn, Cu, Pb, Fe, and even Ag, with their corresponding ions. By reacting solid metals with aqueous ions of other metals, students can record their observations and rank them from most to least reactive. For a suggested experiment, refer to Appendix 6.1: Activity Series: Lab Activity.

SKILLS AND ATTITUDES OUTCOMES

C12-0-S1: Demonstrate work habits that ensure personal safety and the safety of others, as well as consideration for the environment.

Include: knowledge and use of relevant safety precautions, Workplace Hazardous Materials Information System (WHMIS), and emergency equipment

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

Journal Writing

Have students

- research the origin of the name *electromotive series*
- discuss the importance of the electromotive series
- relate position on the Standard Reduction Potentials table to chemical reactivity, as discussed in Grade 10 Science or Grade 11 Chemistry

Visual Displays

Have students draw representations of reactants and products (or redox reactions) and show how the transfer of electrons occurs in solution.

SUGGESTIONS FOR ASSESSMENT

Laboratory Skills

Students should exhibit appropriate lab skills at all times during the lab activity. Sample checklists for assessing students' lab skills and work habits are available in *SYSTH* (6.10, 6.11).

Paper-and-Pencil Tasks

Part A

Have students predict the spontaneous and/or non-spontaneous reactions between metal and ionic species using Appendix 6.2: Table of Standard Reduction Potentials.

1. A zinc metal strip is placed into a 1.0 mol/L solution of copper(II) nitrate.

   Answer:

   The species available for reacting are: $Zn^0_{(aq)}$, $Cu^{2+}_{(aq)}$, and $NO_3{}^-{}_{(aq)}$

   $$Zn^0_{(aq)} + Cu^{2+}_{(aq)} + NO_3{}^-{}_{(aq)} \longrightarrow ?$$

   $NO_3{}^-{}_{(aq)}$ ions will not react unless the solution is acidic. See the table in Appendix 6.2.

   $$Cu^{2+}_{(aq)} + 2e^- \longrightarrow Cu^0_{(s)}$$

   $$Zn^{2+}_{(aq)} + 2e^- \longrightarrow Zn^0_{(s)}$$

   According to the table, Cu^{2+} has a greater affinity for electrons than Zn^{2+}, and so Cu^{2+} will attract electrons to become reduced in the process to Cu^0. This causes Zn^0 to give up electrons and become oxidized to Zn^{2+}.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-01: Develop an activity series experimentally.

C12-6-02: Predict the spontaneity of reactions using an activity series.

(continued)

The two reactions are

$$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu^0_{(s)}$$

$$Zn^0_{(s)} \rightarrow 2e^- + Zn^{2+}_{(aq)}$$

$$Cu^{2+}_{(aq)} + Zn^0_{(s)} \rightarrow Cu^0_{(s)} + Zn^{2+}_{(aq)}$$

Net reaction and spontaneous reaction

2. An aluminum strip of metal is placed into a 1.0 mol/L solution of silver nitrate.

Answer:

The species available for reacting are: $Al^0_{(s)}$, $Ag^+_{(aq)}$, and $NO_3^-{}_{(aq)}$

$$Al^0_{(s)} + Ag^+_{(aq)} + NO_3^-{}_{(aq)} \rightarrow ?$$

$NO_3^-{}_{(aq)}$ ions will not react unless the solution is acidic. See the table in Appendix 6.2.

$$Ag^+_{(aq)} + 1e^- \rightarrow Ag^0_{(s)}$$

$$Al^{3+}_{(aq)} + 3e^- \rightarrow Al^0_{(s)}$$

According to the table, Ag^+ has a greater affinity for electrons than Al^{3+}, and so Ag^+ will attract electrons to become reduced in the process to Ag^0. This causes Al^0 to give up electrons and become oxidized to Al^{3+}.

The two reactions are

$$3[Ag^+_{(aq)} + 1e^- \rightarrow Ag^0_{(s)}]$$

$$Al^0_{(s)} \rightarrow 3e^- + Al^{3+}_{(aq)}$$

The first reaction is multiplied by 3 to balance the electrons lost and gained.

$$3Ag^+_{(aq)} + Al^0_{(s)} \rightarrow 3Ag^0_{(s)} + Al^{3+}_{(aq)}$$

Net reaction and spontaneous reaction.

SKILLS AND ATTITUDES OUTCOMES

C12-0-S1: Demonstrate work habits that ensure personal safety and the safety of others, as well as consideration for the environment.

Include: knowledge and use of relevant safety precautions, Workplace Hazardous Materials Information System (WHMIS), and emergency equipment

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

Part B

Have students use a Standard Reduction Potentials table to answer the following questions about these species: Au^{3+}, $Cr^{0}_{(s)}$, Sr^{2+}, and Br^{-}.

	Answers:
1. Which species is the most easily reduced (i.e., is the strongest oxidizing agent)?	Au^{3+}
2. Which species has the greatest affinity for electrons?	Au^{3+}
3. Which species is the least easily oxidized?	Br^{-}
4. Which species is the most easily oxidized?	Cr^{0}
5. Which species will oxidize Sn^{2+} to Sn^{4+}?	Au^{3+}
6. Which species will reduce $F_{2(g)}$ to $2F^{-}_{(aq)}$?	Br^{-} and Cr^{0}

Part C

Inform students that in an investigation (similar to the one done in class), strips of gold, silver, and tin were placed in beakers containing their ions, resulting in the following reactions:

1. $Sn^{0}_{(s)} + Ag^{+}_{(aq)} \longrightarrow$ metallic Ag deposited
2. $Au^{3+}_{(aq)} + Sn^{0}_{(s)} \longrightarrow$ metallic Au deposited
3. $Au^{0}_{(s)} + Ag^{+}_{(aq)} \longrightarrow$ no reaction

Have students arrange the ions used in the investigation in order of decreasing tendency to attract electrons (i.e., the species with the greatest affinity for electrons would be at the top).

Answers:

- Reaction 1 tells us that for the reaction to proceed as written, Ag^{+} must have a greater affinity for electrons than Sn^{2+}; therefore, Ag^{+} must be above Sn^{2+} on a Standard Reduction Potentials table that has the species with the greatest affinity for electrons at the top.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-01: Develop an activity series experimentally.

C12-6-02: Predict the spontaneity of reactions using an activity series.

(continued)

- Similarly, reaction 2 tells us that for the reaction to proceed as written, Au^{3+} has a greater affinity for electrons than Sn^{2+}; therefore, Au^{3+} must be above Sn^{2+} on a table that has the species with the greatest affinity for electrons at the top.

  Note: The reverse logic in this explanation is of interest.

- If reaction 3 had produced products, then, using the same logic as in the previous two reactions, Ag^+ would have been above Au^{3+}. However, the reaction did not occur, and so the reverse is true, or Au^{3+} is above Ag^+.

- The complete list of reactions or species having the greatest affinity for electrons would be as follows:

  Au^{3+}, then Ag^+, then Sn^{2+}

  or

  $Au^{3+} + 3e^- \longrightarrow Au^0_{(s)}$

  $Ag^+ + 1e^- \longrightarrow Ag^0_{(s)}$

  $Sn^{2+} + 2e^- \longrightarrow Sn^0_{(s)}$

Part D

Challenge students with the following question:

> Substances A, B, C, D, and E are metals that form positive ions. Ions of metal A react with metal E but not with metal C. However, metal C does react with solutions containing ions of metals D and B. Metal D will not react with ions of metal B. List the metal ions, placing the best oxidizing agent at the top.

Answers:

As students are becoming more familiar with the logic used to arrange the various species, a shorter explanation will now be used. Assume the easiest case, where the metal ions are 1^+.

$A^+ + E^0 \longrightarrow$ Reaction	Therefore, A^+ over E^+
$A^+ + C^0 \longrightarrow$ No reaction	Therefore, C^+ over A^+
$D^+ + C^0 \longrightarrow$ Reaction	Therefore, D^+ over C^+
$B^+ + C^0 \longrightarrow$ Reaction	Therefore, B^+ over C^+
$B^+ + D^0 \longrightarrow$ No reaction	Therefore, D^+ over B^+

The species order, according to the best oxidizer first, would be: D^+, B^+, C^+, A^+, E^+.

SKILLS AND ATTITUDES OUTCOMES

C12-0-S1: Demonstrate work habits that ensure personal safety and the safety of others, as well as consideration for the environment.

Include: knowledge and use of relevant safety precautions, Workplace Hazardous Materials Information System (WHMIS), and emergency equipment

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

LEARNING RESOURCES LINKS

Chemistry in Microscale, Book 1 (Ehrenkranz and Mauch)
Metal Reactivities, 80

Glencoe Chemistry: Matter and Change (Dingrando, et al. 288)

Prentice Hall Chemistry (Wilbraham, et al.)
Table 21.1: Activity Series of Metals, with Half-Reactions for Oxidation Process, 664 (stresses the reduction process)

Investigations

Nelson Chemistry 12: College Preparation, Ontario Edition (Davies, et al.)
Activity 5.3: Developing an Activity Series of Metals, 385

Prentice Hall Chemistry: Laboratory Manual (Wilbraham, Staley, and Matta)
Experiment 46: Oxidation-Reduction Reactions, 275

Prentice Hall Chemistry: Small-Scale Chemistry Laboratory Manual (Waterman and Thompson)
Experiment 34: Determination of an Activity Series, 241

Websites

Chemical Education Research Group, Iowa State University. "Chemistry Experiment Simulations and Conceptual Computer Animations." *Chemical Education*. <http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/simDownload/index4.html> (22 Nov. 2012).

Simulation: Reactions of Metals and Metal Ions Experiment

Virtual Crezlab Qualitative Analysis. "Displacement Reaction." *Teaching Laboratory*. Crescent Girls' School. <www.crescent.edu.sg/crezlab/webpages/pptReaction3.htm> (3 Apr. 2012).

Appendices

Appendix 6.1: Activity Series: Lab Activity

Appendix 6.2: Table of Standard Reduction Potentials

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-03: Outline the historical development of voltaic (galvanic) cells.
Include: contributions of Luigi Galvani and Alessandro Volta

(1 hour)

SLO: C12-6-03

SUGGESTIONS FOR INSTRUCTION

TEACHER NOTES

Historical Development of Voltaic (Galvanic) Cells

Electrochemical cells are also referred to as *voltaic cells* or *voltaic piles*, named after their inventor Allessandro Volta. Another term for electrochemical cells is *galvanic cells*, in honour of Luigi Galvani, who influenced Volta's invention.

Luigi Galvani (1737–1798), Italian physician and physicist, discovered a link between electricity and animal tissue in the 1770s. While his primary interests were comparative anatomy and medicine, he also studied electricity. He observed that a steel scalpel that had been near his electrostatic generators would cause the legs of preserved frogs to twitch if the blade touched a nerve. He also observed twitches when brass hooks were holding the frog specimens as he dissected the frogs with his scalpel. He concluded that an electrical fluid, which he called "animal electricity," was being sent along the frog nerves.

Alessandro Volta (1745–1827), an Italian physicist and contemporary of Galvani, was doing pioneer work in electricity. When Galvani's "animal electricity" findings were published, Volta was skeptical and began designing experiments to explain Galvani's observations. Volta soon discovered that having two different metals in contact with each other in a moist environment would generate electricity. He concluded that the frog tissues were just indicators that there was a current

General Learning Outcome Connections

- GLO A1: Recognize both the power and limitations of science as a way of answering questions about the world and explaining natural phenomena.
- GLO A2: Recognize that scientific knowledge is based on evidence, models, and explanations, and evolves as new evidence appears and new conceptualizations develop.
- GLO A4: Identify and appreciate contributions made by women and men from many societies and cultural backgrounds that have increased our understanding of the world and brought about technological innovations.
- GLO C2: Demonstrate appropriate scientific inquiry skills when seeking answers to questions.
- GLO C4: Demonstrate appropriate critical thinking and decision-making skills when choosing a course of action based on scientific and technological information.
- GLO C5: Demonstrate curiosity, skepticism, creativity, open-mindedness, accuracy, precision, honesty, and persistence, and appreciate their importance as scientific and technological habits of mind.
- GLO C6: Employ effective communication skills and use information technology to gather and share scientific and technological ideas and data.
- GLO C8: Evaluate, from a scientific perspective, information and ideas encountered during investigations and in daily life.

SKILLS AND ATTITUDES OUTCOMES

C12-0-R1: Synthesize information obtained from a variety of sources.
Include: print and electronic sources, specialists, and other resource people

C12-0-R2: Evaluate information obtained to determine its usefulness for information needs.
Examples: scientific accuracy, reliability, currency, relevance, balance of perspectives, bias . . .

C12-0-R3: Quote from or refer to sources as required and reference information sources according to an accepted practice.

C12-0-N1: Explain the roles of theory, evidence, and models in the development of scientific knowledge.

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-N3: Describe how scientific knowledge changes as new evidence emerges and/or new ideas and interpretations are advanced.

---

between the metals. This became know as *metallic electricity*. Volta maintained that the only source of electricity was through two dissimilar metals. He studied different combinations of metals and conditions and, in 1800, built the first *electrochemical cell*, which consisted of three plates or discs: zinc and copper sandwiching pasteboard that had been soaked in salt water or vinegar. By stacking several of these three-disc cells (called *voltaic piles*), he created a reliable, constant current of electricity that revolutionalized electrical research and started the study of electrochemistry.

The debate over whether animal or metallic electricity was the correct explanation went on in the scientific community for many years. We now know that both Galvani and Volta were right and wrong about the frog legs: electric potential in nerves does stimulate muscle tissue, but this is not a special biological electricity.

Research and Reports

Have students research the historical development of the voltaic (galvanic) cell, using various print and online resources, and report their findings either individually or in small groups.

Sample Websites:

Carboni, Giorgio. *Experiments in Electrochemistry*. 1998. *Fun Science Gallery*. <www.funsci.com/fun3_en/electro/electro.htm> (5 Apr. 2012).

This website presents an explanation of various electrochemical cells.

Corrosion Doctor. *Who's Who in Electrochemistry*. <www.corrosion-doctors.org/Who's_who.htm> (5 Apr. 2012).

This website features biographies of famous scientists, including Luigi Galvani and Alessandro Volta.

Energy Quest. *Super Scientists: A Gallery of Energy Pioneers*. 2006. <www.energyquest.ca.gov/scientists/> (5 Apr. 2012).

This website provides information about Luigi Galvani and Alessandro Volta.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-03: Outline the historical development of voltaic (galvanic) cells.
Include: contributions of Luigi Galvani and Alessandro Volta

(continued)

Greenslade, Thomas B. "The Electrochemical Cell." *Instruments for Natural Philosophy.* <http://physics.kenyon.edu/EarlyApparatus/Electricity/Electrochemical_Cell/Electrochemical_Cell.html> (5 Apr. 2012).

This website presents historical information about the electrochemical cell, along with images of some of the original voltaic cells.

Magnetic Lab: National High Magnetic Field Laboratory. "Voltaic Pile." *Education.* 1995–2012. <www.magnet.fsu.edu/education/tutorials/java/voltaicpile1/index.html> (22 Aug. 2012).

At this website, students can learn about Alessandro Volta's application of the principles of electrochemistry to the creation of the first battery, a tool that came to be known as the voltaic pile.

Süss-Fink, Georg, and Frédéric Chérioux. "6.2: Scheme of Electrochemical Cell." *Unit 5: Electron Transfer Reactions.* 2005. *General Chemistry.* <http://chimge.unil.ch/En/redox/1red13.htm> (10 Apr. 2012).

This website includes a diagram that shows the various parts of an electrochemical cell.

Laboratory Activity/Demonstration

1. Have students construct a voltaic cell by building a lemon battery. This involves inserting two metals, such as zinc and copper, into a lemon and connecting the metals with wire to produce electricity (see Dingrando, et al. 663).

2. Students can also replicate Volta's experiment and make a voltaic pile. Have them alternate nickels and pennies (copper discs) and pieces of cardboard (soaked in salt water) and connect a lead from the bottom to the top of the pile. They can then demonstrate how an electric current is generated by placing a zinc disc on the bottom of the pile, with electrolyte-soaked filter paper in the middle and a copper disc on top (this "sandwich" is called an *element*). After building a stack of the six elements, and being careful that the solution does not drip down the side of the stack (this can cause a short circuit), two cables with alligator clips—one at the bottom and one at the top—can be used to measure the voltage between the bottom zinc disc and the top copper disc. The voltaic pile can power a small LCD clock, a thermometer, or a calculator.

SKILLS AND ATTITUDES OUTCOMES

C12-0-R1: Synthesize information obtained from a variety of sources.
Include: print and electronic sources, specialists, and other resource people

C12-0-R2: Evaluate information obtained to determine its usefulness for information needs.
Examples: scientific accuracy, reliability, currency, relevance, balance of perspectives, bias . . .

C12-0-R3: Quote from or refer to sources as required and reference information sources according to an accepted practice.

C12-0-N1: Explain the roles of theory, evidence, and models in the development of scientific knowledge.

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-N3: Describe how scientific knowledge changes as new evidence emerges and/or new ideas and interpretations are advanced.

SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Task

Ask students to describe how electrochemistry is involved in producing energy in batteries (see Fisher 294).

Laboratory Skills

If students were asked to recreate Volta's experiment as either a demonstration or a lab activity, lab skills could be assessed using rubrics and checklists. Sample checklists for assessing lab skills and work habits are available in *SYSTH* (6.10, 6.11).

Class Discussion

Have the class brainstorm a list of items that require some type of battery.

Research Presentations

Have students present their research findings on the historical development of voltaic cells. Use a presentation rubric to assess students' presentations (e.g., see Rubric for Assessment of Student Presentation in Appendix 11).

Journal Writing

1. Have students answer the following questions:

   What would be the effect of not having any kind of electrochemical cell? How would our lives change?

2. After completing their research, students could describe the research done by any of the scientists responsible for the development of electrochemical cells.

Visual Displays

Students can diagram and illustrate Volta's voltaic pile, explaining why it produces an electric current. These visual displays could be assessed using the Rubric for Assessment of Student Presentation and the Rubric for Assessment of Class Presentation (see Appendix 11).

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-03: Outline the historical development of voltaic (galvanic) cells.
Include: contributions of Luigi Galvani and Alessandro Volta

(continued)

LEARNING RESOURCES LINKS

Glencoe Chemistry: Matter and Change, Science Notebook (Fisher 294)

Prentice Hall Chemistry (Wilbraham, et al.)
Section 21.1: Electrochemical Cells, 663–668 (shows Volta's electric piles)

Investigation

Glencoe Chemistry: Matter and Change (Dingrando, et al.)
Discovery Lab: A Lemon Battery? 663

Websites

Carboni, Giorgio. *Experiments in Electrochemistry*. 1998. *Fun Science Gallery*. <www.funsci.com/fun3_en/electro/electro.htm> (5 Apr. 2012).

Corrosion Doctor. *Who's Who in Electrochemistry*. <www.corrosion-doctors.org/Who's_who.htm> (5 Apr. 2012).

Energy Quest. *Super Scientists: A Gallery of Energy Pioneers*. 2006. <www.energyquest.ca.gov/scientists/> (5 Apr. 2012).

Greenslade, Thomas B. "The Electrochemical Cell." *Instruments for Natural Philosophy*. <http://physics.kenyon.edu/EarlyApparatus/Electricity/Electrochemical_Cell/Electrochemical_Cell.html> (5 Apr. 2012).

Magnetic Lab: National High Magnetic Field Laboratory. "Voltaic Pile." *Education*. 1995–2012. <www.magnet.fsu.edu/education/tutorials/java/voltaicpile1/index.html> (22 Aug. 2012).

Süss-Fink, Georg, and Frédéric Chérioux. "6.2: Scheme of Electrochemical Cell." *Unit 5: Electron Transfer Reactions*. 2005. *General Chemistry*. <http://chimge.unil.ch/En/redox/1red13.htm> (10 Apr. 2012).

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.

SKILLS AND ATTITUDES OUTCOMES

C12-0-R1: Synthesize information obtained from a variety of sources.
Include: print and electronic sources, specialists, and other resource people

C12-0-R2: Evaluate information obtained to determine its usefulness for information needs.
Examples: scientific accuracy, reliability, currency, relevance, balance of perspectives, bias . . .

C12-0-R3: Quote from or refer to sources as required and reference information sources according to an accepted practice.

C12-0-N1: Explain the roles of theory, evidence, and models in the development of scientific knowledge.

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-N3: Describe how scientific knowledge changes as new evidence emerges and/or new ideas and interpretations are advanced.

NOTES

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-04: Explain the operation of a voltaic (galvanic) cell at the visual, particulate, and symbolic levels.
Include: writing half-cell reactions, the overall reaction, and shorthand (line) notation

C12-6-05: Construct a functioning voltaic (galvanic) cell and measure its potential.

(3 hours)

SLO: C12-6-04
SLO: C12-6-05

SUGGESTIONS FOR INSTRUCTION

Entry-Level Knowledge

In Grade 9 Science (Cluster 3: The Nature of Electricity), students completed a detailed study of electricity. They related the particle model of electricity to atomic structure (S1-3-04), constructed diagrams for electrical circuits (S1-3-13), and used appropriate instruments to measure voltage (S1-3-14). As a result, students will have prior knowledge concerning electrical circuits; however, a review should be done.

Demonstration/Discrepant Event

To start the class with a demonstration, walk into the classroom while drinking orange juice. After taking a sip, pour the remaining juice into a beaker in which there are two electrodes: one of magnesium metal and the other of copper. Ensure that both electrodes are connected to a large display clock. As the clock starts running, state that "we are now on the clock and we can begin the class."

An alternative demonstration might be to have a piece of copper and a piece of clean zinc metal stuck into a lemon connected to either a voltmeter or a similar clock. This demonstration may be viewed online.

Sample Website:

Carboni, Giorgio. "The Lemon Battery." *Experiments in Electrochemistry*. 1998. *Fun Science Gallery*. <www.funsci.com/fun3_en/electro/electro.htm#2> (10 Apr. 2012).

This website outlines the procedure for performing "The Lemon Battery" demonstration.

General Learning Outcome Connections

GLO C1: Recognize safety symbols and practices related to scientific and technological activities and to their daily lives, and apply this knowledge in appropriate situations.

GLO C2: Demonstrate appropriate scientific inquiry skills when seeking answers to questions.

GLO C5: Demonstrate curiosity, skepticism, creativity, open-mindedness, accuracy, precision, honesty, and persistence, and appreciate their importance as scientific and technological habits of mind.

GLO D3: Understand the properties and structures of matter, as well as various common manifestations and applications of the actions and interactions of matter.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-S4: Select and use scientific equipment appropriately and safely.

Examples: volumetric glassware, balance, thermometer . . .

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

C12-0-A1: Demonstrate confidence in their ability to carry out investigations in chemistry and to address STSE-related issues.

TEACHER NOTES

The Operation of a Voltaic Cell

Students should be asked to explain the operation of electrochemical cells using the three modes of representation: visual (macroscopic), particulate (microscopic), and symbolic. Chemistry texts provide clear particulate diagrams of electrochemical cell processes.

After addressing specific learning outcomes C12-6-04 and C12-6-05, students should understand that a chemical reaction can be used to create an electric current. A *voltaic cell* is an apparatus that uses a spontaneous redox reaction to produce electrical energy. According to the law of conservation of energy, energy cannot be created or destroyed; it is simply converted from one form of energy into another. In a voltaic cell, the chemical energy from a spontaneous redox reaction is converted into electrical energy.

Many chemical and electrical processes occur in an electrochemical cell. Students must be able to explain the reactions in both half-cells in terms of electron flow, anion flow, and cation flow.

Constructing a Voltaic Cell

Students should first construct a spontaneous, working voltaic cell based on their understanding of the electromotive series discussed in relation to learning outcomes C12-6-01 and C12-6-02. Students should have access to voltmeters, wire, alligator clamps, U-tubes, cotton wool, a number of common metals together with 1.0 mol/L solutions of their ions, and a 1.0 mol/L solution of sodium, potassium, or ammonium nitrate to use in their salt bridge.

Have students write out the spontaneous reaction and identify the reduction reaction, the oxidation reaction, and the two half-cell reactions, using Appendix 6.2: Table of Standard Reduction Potentials. After confirming spontaneity, have each group of students construct their cell and measure the voltage across the electrodes.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-04: Explain the operation of a voltaic (galvanic) cell at the visual, particulate, and symbolic levels.
Include: writing half-cell reactions, the overall reaction, and shorthand (line) notation

C12-6-05: Construct a functioning voltaic (galvanic) cell and measure its potential.

(continued)

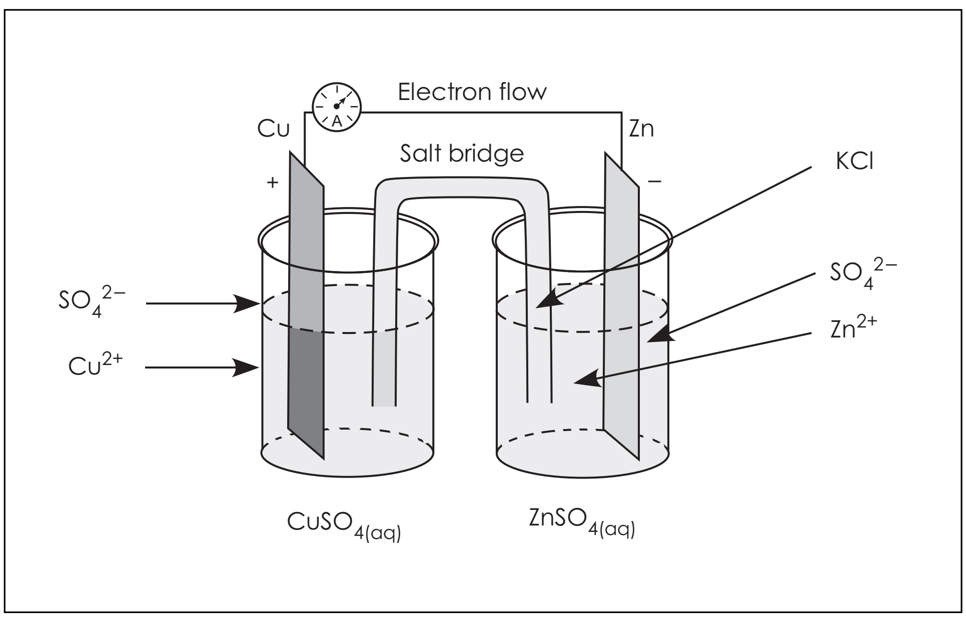
Note that students will likely not achieve the predicted net cell potential (E^0_{cell}) voltage. According to the Nernst equation, the maximum voltage is dependent on concentration and assumes that temperature is constant. Immediately after the connections are made, concentrations will change. The reactant ions will decrease as they are used up, and the product ions will increase as they are produced. Le Châtelier's principle will then cause a stress on the system and attempt to re-establish equilibrium by the reverse reaction and by reducing the net cell voltage. At this point, ask students what conditions would cause the equilibrium to shift forward and increase voltage.

A concentration gradient would occur at each electrode, causing both an excess of one ion and a shortage of other ions for the net reaction.

The Daniell Cell

The diagram below illustrates the electrochemical cell for the following net reaction:

$$Cu^{2+}_{(aq)} + Zn^0_{(s)} \longrightarrow Cu^0_{(s)} + Zn^{2+}_{(aq)} + 1.10\ V$$



SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-S4: Select and use scientific equipment appropriately and safely.

Examples: volumetric glassware, balance, thermometer . . .

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

C12-0-A1: Demonstrate confidence in their ability to carry out investigations in chemistry and to address STSE-related issues.

The illustrated cell is a special case of an electrochemical cell. It was first successfully constructed in 1836 by British chemist John Frederic Daniell (1790–1845). (An Internet search will generate extensive information, if required.) This particular electrochemical cell with copper and zinc electrodes is now called a Daniell cell.

In the diagram, the two half-cell reactions are connected by a salt bridge containing a soluble ionic salt such as potassium chloride (KCl). The salt bridge is used as an internal circuit and allows the half-cells to remain electrically balanced. In the case of this cell, as zinc ions are produced at the anode, making the anodic compartment positive with an excess of positive ions, the chloride ions move from the salt bridge toward the anode to maintain electrical neutrality within that half-cell. In the case of the cathodic copper cell, copper ions are being removed from the solution, making it electrically negative. To counteract this, positive potassium ions from the salt bridge move toward the cathode, again to maintain electrical neutrality within the cathodic cell. When the two half-cells are joined with a wire path for the electrons and another path for the positive and negative ion movement, an electrochemical cell is made.

Each galvanic cell should consist of

- an anode (zinc), which oxidizes (loses e^-)
- a cathode (copper), which reduces (gains e^-)

$Cu_2^{+} + 2e^- \longrightarrow Cu^0$ Reduction reaction at the cathode—cations removed and limiting

$Zn^0 \longrightarrow Zn^{2+} + 2e^-$ Oxidation at the anode—anions produced and in excess

Electrons flow from the anode to the cathode of an electrochemical cell.

Anions move toward the anode, and cations move toward the cathode.

The migration of ions is essential to the operation of the cell, since the accumulation of ionic charge in the solution around the electrodes would oppose the movement of electrons. The result is a voltage of +1.10 V.

The same cell can be constructed with a porous cup acting as the salt bridge. Give students the opportunity to construct cells using either a salt bridge or a porous cup.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-04: Explain the operation of a voltaic (galvanic) cell at the visual, particulate, and symbolic levels.

Include: writing half-cell reactions, the overall reaction, and shorthand (line) notation

C12-6-05: Construct a functioning voltaic (galvanic) cell and measure its potential.

(continued)

A shorthand (line) notation is often used to represent the voltaic cell diagram.

Reactant → $Zn_{(s)}$; Product → Zn^{2+} ; Reactant → Cu^{2+} ; Product → $Cu_{(s)}$

$$Zn_{(s)} \mid Zn^{2+}\ (1\ mol/L) \parallel Cu^{2+}\ (1\ mol/L) \mid Cu_{(s)}$$

Oxidation half-cell ($Zn_{(s)} \mid Zn^{2+}$)   Reduction half-cell ($Cu^{2+} \mid Cu_{(s)}$)

- The single vertical line (|) represents a phase boundary between the metal and the ion in solution.
- The double vertical line (||) represents the salt bridge. By convention, the anode is written first, to the left of the double lines, and the cathode reaction is written second, to the right of the double lines.

Animations/Simulations

Animations help students appreciate particulate (microscopic) events and subsequent symbolic representations. Have students perform simulations or view animations online.

Sample Websites:

Chemical Education Research Group, Iowa State University. "Chemistry Experiment Simulations and Conceptual Computer Animations." *Chemical Education*. <http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/simDownload/index4.html> (22 Nov. 2012).

In the Electrochemistry section, download and unzip the following simulation:

- Electrochemical Cell Experiment

  This simulation helps students create a voltaic cell. Students select the electrodes and the ionic solutions needed to create a functioning electrochemical cell.

The North Carolina School of Science and Mathematics (NCSSM). Distance Education and Extended Programs. "Chemistry—Electrochemistry." *Teacher's Instructional Graphics and Educational Resource (TIGER).* <www.dlt.ncssm.edu/tiger/chem6.htm#electro> (11 Apr. 2012).

This website contains a set of six narrated Flash animations explaining how a voltaic cell works.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-S4: Select and use scientific equipment appropriately and safely.
Examples: volumetric glassware, balance, thermometer . . .

C12-0-S5: Collect, record, organize, and display data using an appropriate format.
Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

C12-0-A1: Demonstrate confidence in their ability to carry out investigations in chemistry and to address STSE-related issues.

SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Tasks

Have students draw a diagram of a voltaic cell on which they identify the positive and negative electrodes, anode, cathode, half-cell reactions, direction of electron flow, direction of ion flow, the solutions used, which electrode erodes, which electrode plates, the net cell reaction, and the voltage produced. They should focus on the particulate nature of matter when explaining electrode reactions, the movement of ions, and electrons through the circuit, and the maintenance of electrical neutrality in all parts of the cell.

Laboratory Skills

Students should be able to build and test simple voltaic cells. Assess students' lab skills as necessary. Sample checklists for assessing students' lab skills and work habits are available in *SYSTH* (6.10, 6.11). Have groups of students compare the results of their voltaic cells and explain differences in voltage. Try to have several groups use the same electrodes to allow for comparison of results.

Research and Reports

Have students research the electrochemical cell, using online resources, and report their findings.

Sample Websites:

Carboni, Giorgio. *Experiments in Electrochemistry*. 1998. *Fun Science Gallery.* <www.funsci.com/fun3_en/electro/electro.htm> (5 Apr. 2012).

This website presents an explanation of various electrochemical cells.

Greenslade, Thomas B. "The Electrochemical Cell." *Instruments for Natural Philosophy.* <http://physics.kenyon.edu/EarlyApparatus/Electricity/Electrochemical_Cell/Electrochemical_Cell.html> (5 Apr. 2012).

This website presents historical information about the electrochemical cell, along with images of some of the original voltaic cells.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-04: Explain the operation of a voltaic (galvanic) cell at the visual, particulate, and symbolic levels.

Include: writing half-cell reactions, the overall reaction, and shorthand (line) notation

C12-6-05: Construct a functioning voltaic (galvanic) cell and measure its potential.

(continued)

Süss-Fink, Georg, and Frédéric Chérioux. "6.2: Scheme of Electrochemical Cell." *Unit 5: Electron Transfer Reactions.* 2005. *General Chemistry.* <http://chimge.unil.ch/En/redox/1red13.htm> (10 Apr. 2012).

This website includes a diagram that shows the various parts of an electrochemical cell.

Journal Writing

After students have read and viewed online information about the electrochemical cell, they can describe the research done by any of the scientists responsible for the development of electrochemical cells.

LEARNING RESOURCES LINKS

Glencoe Chemistry: Matter and Change (Dingrando, et al.)
Section 21.1: Voltaic Cells, 663

Prentice Hall Chemistry (Wilbraham, et al.)
Voltaic Cells, 665

Investigation

Prentice Hall Chemistry: Small-Scale Chemistry Laboratory Manual (Waterman and Thompson)
Experiment 36: Small-Scale Voltaic Cells, 257

Websites

Carboni, Giorgio. *Experiments in Electrochemistry.* 1998. *Fun Science Gallery.* <www.funsci.com/fun3_en/electro/electro.htm> (5 Apr. 2012).

_____. "The Lemon Battery." *Experiments in Electrochemistry.* 1998. *Fun Science Gallery.* <www.funsci.com/fun3_en/electro/electro.htm#2> (10 Apr. 2012).

Chemical Education Research Group, Iowa State University. "Chemistry Experiment Simulations and Conceptual Computer Animations." *Chemical Education.* <http://group.chem.iastate.edu/Greenbowe/sections/projectfolder/simDownload/index4.html> (22 Nov. 2012).

Simulation: Electrochemical Cell Experiment

Greenslade, Thomas B. "The Electrochemical Cell." *Instruments for Natural Philosophy.* <http://physics.kenyon.edu/EarlyApparatus/Electricity/Electrochemical_Cell/Electrochemical_Cell.html> (5 Apr. 2012).

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-S4: Select and use scientific equipment appropriately and safely.

Examples: volumetric glassware, balance, thermometer . . .

C12-0-S5: Collect, record, organize, and display data using an appropriate format.

Examples: labelled diagrams, graphs, multimedia applications, software integration, probeware . . .

C12-0-A1: Demonstrate confidence in their ability to carry out investigations in chemistry and to address STSE-related issues.

The North Carolina School of Science and Mathematics (NCSSM). Distance Education and Extended Programs. “Chemistry—Electrochemistry.” *Teacher’s Instructional Graphics and Educational Resource (TIGER)*. <www.dlt.ncssm.edu/tiger/chem6.htm#electro> (11 Apr. 2012).

Süss-Fink, Georg, and Frédéric Chérioux. “6.2: Scheme of Electrochemical Cell.” *Unit 5: Electron Transfer Reactions*. 2005. *General Chemistry*. <http://chimge.unil.ch/En/redox/1red13.htm> (10 Apr. 2012).

Appendix

Appendix 6.2: Table of Standard Reduction Potentials

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-06: Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07: Calculate standard cell potentials, given standard electrode potentials.

C12-6-08: Predict the spontaneity of reactions using standard electrode potentials.

(2.5 hours)

SLO: C12-6-06
SLO: C12-6-07
SLO: C12-6-08

SUGGESTIONS FOR INSTRUCTION

Entry-Level Knowledge

Students focused on electricity in great depth in Grade 9 Science, and they have studied electron transfer extensively in Grade 12 Chemistry. However, each time students add a new layer of knowledge, a review and assessment of their understanding is necessary.

TEACHER NOTES

Electrode Potentials

When scientists first constructed voltaic (galvanic) electrochemical cells, they recorded net cell potentials (standard reduction potential, E^0) that resulted from the reactions, but they did not know how much each half-cell contributed to the total net cell voltage. Many experiments were done in an attempt to determine the absolute E^0 for any half-cell reaction.

During their experiments, chemists found that not only did temperature affect the net cell potential, but so did the concentration of ions in solution and the pressure, if a gas was used. Another term that is often used synonymously with *cell potential* is *electromotive force* (emf).

Many "reference" electrodes were tried before chemists chose the hydrogen half-cell as the standard against which all other electrodes would be measured. Students will readily see that this choice was reasonable, as the hydrogen half-cell reaction appears in the middle of the Standard Reduction Potentials table and has an emf value of 0.

General Learning Outcome Connections

GLO D3: Understand the properties and structures of matter, as well as various common manifestations and applications of the actions and interactions of matter.

SKILLS AND ATTITUDES OUTCOME

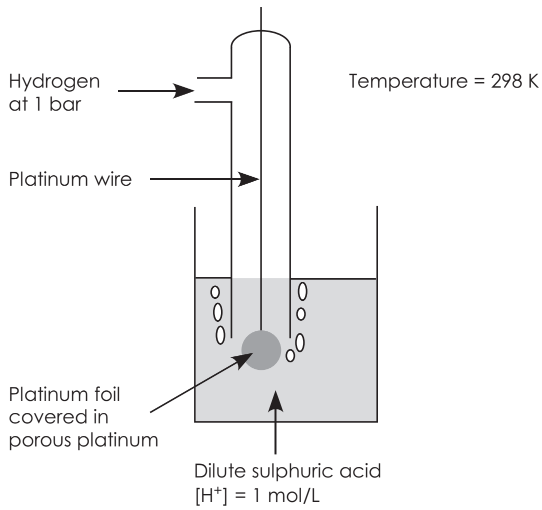
C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

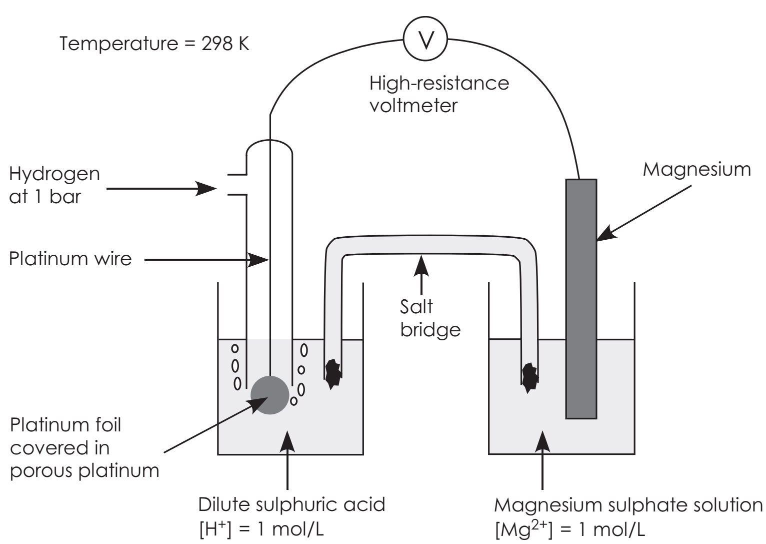
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

Standard Hydrogen Electrode

In the hydrogen electrode diagram shown below, hydrogen gas (H_2) is bubbled into hydrochloric acid (HCl) solution at 25°C. The platinum electrode provides a surface on which the dissociation of hydrogen molecules can occur, as well as serving as an electrical conductor to the external circuit.

Standard Hydrogen Electrode





Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-06: Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07: Calculate standard cell potentials, given standard electrode potentials.

C12-6-08: Predict the spontaneity of reactions using standard electrode potentials.

(continued)

Under standard conditions of 1 atm for H_2 and 1 mol/L HCl, the potential for the reduction of H^+ at 25°C is taken to be exactly zero.

$$2H^+ \text{ (1 mol/L)} + 2e^- \longrightarrow H_2 \text{ (1 atm)} \qquad E^0 = 0 \text{ V}$$

Once the standard half-cell had been chosen, scientists were able to use this cell to determine the electrode potential for all the other half-cell reactions on the electromotive series. These values were placed on a table of half-cell reactions containing Standard Reduction Potentials.

Example:

A galvanic cell with a zinc electrode and a standard hydrogen electrode (SHE).

During the reaction, the zinc electrode loses mass, indicating that the zinc electrode half-cell reaction must be

$$Zn_{(s)} \longrightarrow Zn^{2+}{}_{(aq)} + 2e^-$$

The shorthand notation for this cell is

$$Zn_{(s)} \mid Zn^{2+} \text{ (1 mol/L)} \parallel H^+ \text{ (1 mol/L)} \mid H_2 \text{ (1 atm)} \mid Pt_{(s)}$$

The half-cell reactions are as follows:

Anode (oxidation)	$Zn_{(s)} \longrightarrow Zn^{2+}$ (1 mol/L) + $2e^-$
Cathode (reduction)	$2H^+$ (1 mol/L) + $2e^- \longrightarrow H_2$ (1 atm)
Net reaction	$Zn_{(s)} + 2H^+$ (1 mol/L) $\longrightarrow Zn^{2+}$ (1 mol/L) $+H_2$ (1 atm)

SKILLS AND ATTITUDES OUTCOME

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

By convention, the standard emf of the cell, E^0_{cell}, composed of a contribution from the cathode and the anode, is given by

$$E^0_{cell} = E^0_{cathode} - E^0_{anode}$$

$$E^0_{cell} = E^0\left(\frac{H^+}{H_2}\right) - E^0\left(\frac{Zn^{2+}}{Zn}\right)$$ (the voltage was measured for the cell at 0.76 V)

$$0.76\ \text{V} = 0 - E^0\left(\frac{Zn^{2+}}{Zn}\right)$$ $$\left(\text{solving for } E^0\left(\frac{Zn^{2+}}{Zn}\right)\right)$$

$$E^0\left(\frac{Zn^{2+}}{Zn}\right) = -0.76\ \text{V}$$

In a similar way, all electrode potentials were determined and placed together with their half-cell reactions on a table that chemists call the Standard Electrode Potentials.

Students should now be shown how to determine the net cell emf using half-cell reactions from the table of Standard Reduction Potentials.

Using the Standard Reduction Potentials Table

The table is organized according to the tendency of a substance to gain electrons, which is its *reduction potential*. For every redox reaction, the half-reaction that is more positive will proceed as a *reduction reaction*, and the half-reaction that is more negative will proceed as an *oxidation reaction*.

The Standard Reduction Potentials table is used to determine spontaneity and electrical potential of a given cell. Any *positive cell potential* value determined by finding the difference between the cathode and anode half-reaction potentials will result in a *spontaneous redox reaction*. Any *negative cell potential* value will indicate a *non-spontaneous redox reaction*.

Example:

Calculate the cell potential for a silver-copper cell.

1. Find the half-reactions for silver and copper from the Standard Reduction Potentials table.

   $Cu^{2+}_{(aq)} + 2e^- \longrightarrow Cu_{(s)}$ $E^0 = +0.34$ V

   $Ag^{+}_{(aq)} + 1e^- \longrightarrow Ag_{(s)}$ $E^0 = +0.80$ V

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-06: Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07: Calculate standard cell potentials, given standard electrode potentials.

C12-6-08: Predict the spontaneity of reactions using standard electrode potentials.

(continued)

Since Ag^{+} ions are more easily reduced than Cu^{2+} ions,

$Ag^{+}_{(aq)} + 1e^{-} \longrightarrow Ag_{(s)}$	half-reaction is the reduction half-reaction
$Cu^{2+}_{(aq)} + 2e^{-} \longrightarrow Cu_{(s)}$	needs to be reversed to become the oxidation half-reaction

Another way of saying this is that the Ag^{+} has a greater affinity for electrons than the Cu^{2+} ion and, as a result, the reaction with the lower + emf will become the oxidation reaction. When reversing any half-reaction, the sign of the reduction potential is also reversed.

Therefore, the oxidation half-reaction will be

$Cu_{(s)} \longrightarrow Cu^{2+}_{(aq)} + 2e^{-}$	$E^0 = -0.34$ V	Oxidation
$Ag^{+}_{(aq)} + 1e^{-} \longrightarrow Ag_{(s)}$	$E^0 = +0.80$ V	Reduction

2. Substitute the half-cell potentials into the equation.

$$E^0_{cell} = E^0_{oxidation} + E^0_{reduction} = (-0.34 \text{ V}) + (+0.80 \text{ V}) = +0.46 \text{ V}$$

This cell has a potential of +0.46 V and confirms its spontaneity.

Note:

Chemistry texts will often show two methods for the calculation of E^0 cell:

$$E^0_{cell} = E^0_{oxidation} + E^0_{reduction}$$

$$E^0_{cell} = E^0_{cathode} - E^0_{anode}$$

Either relationship will produce the correct result.

Students may also use the formula $E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$ to obtain cell potential. Then they do not have to flip positive and negative signs before calculating values.

For a summary of the Standard Reduction Potentials, refer to *Chemistry* (Chang 825–830).

SKILLS AND ATTITUDES OUTCOME

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Tasks

Part A

Students should be able to answer questions such as the following about the standard hydrogen electrode.

1. What was the necessity of finding the standard hydrogen electrode?

   Answer:

   Any given pair of electrodes will give a specific cell potential, but to compare the relative strengths of the electrodes on cell dynamics, scientists needed to find a cell to which all others could be compared. Many reference cells were initially used, but the hydrogen cell conveniently fell in the middle of the table of Standard Reduction Potentials.

2. What would the table have looked like if chemists had chosen a standard electrode other than the standard hydrogen electrode?

   Answer:

   If another cell were used instead of hydrogen, the reactions would still be in the same order of electron affinity; however, the new reference cell would be given the value of zero and all the others would then be compared to that cell. On either side of the new reference, positive and negative numbers would become larger, moving away from the reference cell.

Part B

Students should be able to find the net (overall) cell potential of a given reaction or electrochemical cell and predict whether the reaction will be spontaneous, and explain why or why not.

1. Complete the following reactions based on a Standard Reduction Potentials table. Calculate the net cell potential and indicate the reason why the reaction proceeds spontaneously as written.

   Answers will vary, depending on the tables used.

   a) $Zn^{0}_{(s)} + Hg^{2+}_{(aq)} \longrightarrow (Zn^{2+} + Hg^{0}_{(l)})$

      Answer:

      $E_{cell} = +1.54$ V

      This cell would run spontaneously. The net cell voltage is positive.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-06: Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07: Calculate standard cell potentials, given standard electrode potentials.

C12-6-08: Predict the spontaneity of reactions using standard electrode potentials.

(continued)

b) $Cu^0_{(s)} + 2Ag^+_{(aq)} \longrightarrow (Cu^{2+} + 2Ag^0)$

Answer:

E_{cell} = +0.46 V

This cell would run spontaneously. The net cell voltage is positive.

c) $Mn^0_{(s)} + 2Cs^+_{(aq)} \longrightarrow$ No reaction

Answer:

E_{cell} = –1.74 V

This cell would not function. The net cell voltage is negative.

Part C

For each of the following situations, have students write balanced net ionic reactions, indicate the oxidation and reduction reactions, specify the cell emf, and predict whether the reaction will be spontaneous, briefly explaining why or why not.

1. In the Middle Ages, iron was used to make pots and pans. Could a solution of copper(II) acetate be stored in such an iron container? Explain your answer with reactions and a discussion of emf.

   Answer:

   The acetate ion does not occur in the Standard Reduction Potentials table and is, therefore, a spectator ion. The expected reaction will be

   $Fe^0 + 2Cu^+ \longrightarrow Fe^{2+} + 2Cu^0$ $\quad\quad E_{cell}$ = +0.59 V

   As the net cell potential is positive, a reaction would occur spontaneously. It would not be a good idea to store the solution in an iron container.

   The iron metal is oxidized to Fe^{2+}, and the Cu^+ is reduced to elemental copper.

SKILLS AND ATTITUDES OUTCOME

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

2. A lead(II) nitrate solution is poured into a container in which a piece of zinc metal has been placed.

   Answer:

   The nitrate ion only reacts when it is placed in an acidic solution, so in this example it will be a spectator ion. The expected reaction will be

   $Zn^0 + Pb^{2+} \longrightarrow Zn^{2+} + Pb^0$ $\qquad E_{cell} = +0.63$ V

   As the net cell potential is positive, a reaction will occur between the zinc metal and the lead solution.

   The zinc metal is oxidized to Zn^{2+}, and the Pb^{2+} ion is reduced to metallic lead.

3. What metal container(s) could be used to hold a 0.20 mol/L solution of copper(I) acetate safely? Explain your answer.

   Answer:

   The acetate ion does not appear in the Standard Reduction Potentials table, and so it will be a spectator ion.

   Cu^+ appears in the following reduction reaction:

   $Cu^{2+} + e^- \longrightarrow Cu^{1+}$ $\qquad E^0 = +0.15$ V

   For a reaction to occur, the species must be above Cu^+ and to the left on the Standard Reduction Potentials table for the net cell potential to be positive. So, we must be looking for a metal below Cu^+. Possible containers in which a 0.20 mol/L solution of copper(I) acetate could, therefore, be Pb^0, Sn^0, Ni^0, Co^0, Fe^0, Cr^0, and so on.

Extension/Enrichment

Students have used Le Châtelier's principle in their discussion of chemical equilibria in acid-base chemistry and solubility. Le Châtelier's principle applies equally to electrochemical cells.

Students already know that when a stress is placed on a system at equilibrium, the reaction shifts so as to offset or ameliorate the stress applied. After studying Grade 11 and Grade 12 chemistry, students know that as a reaction proceeds, the reactants decrease and the products increase. Have students consider what could be done to an electrochemical cell to prolong the voltage, given that the initial emf will decrease over time.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-06: Define *standard electrode potential*.
Include: hydrogen electrode as a reference

C12-6-07: Calculate standard cell potentials, given standard electrode potentials.

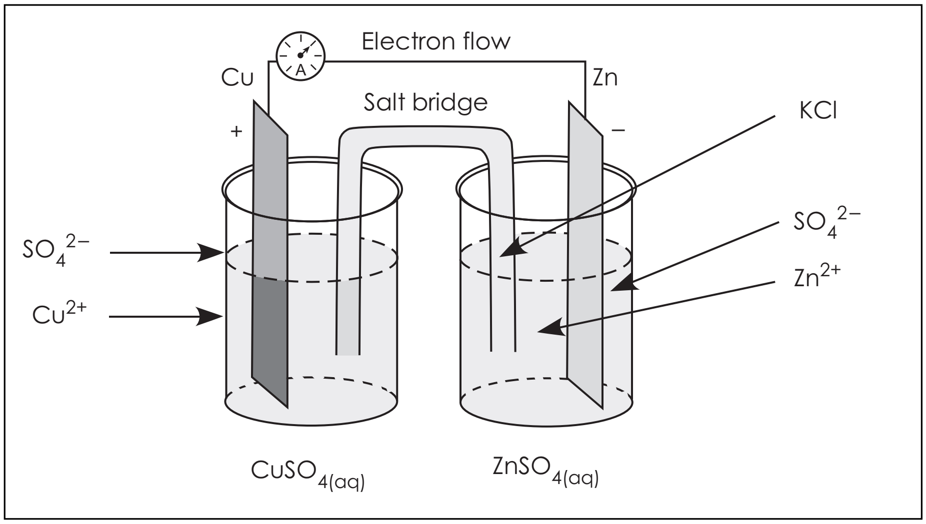
C12-6-08: Predict the spontaneity of reactions using standard electrode potentials.

(continued)

The following example uses a Daniell cell to explore the effects of adding or removing substances from a system.

Recall that a Daniell cell is a special case of a voltaic (galvanic) cell having the net reaction of:

$$Cu^{2+}_{(aq)} + Zn^{0}_{(s)} \longrightarrow Cu^{0}_{(s)} + Zn^{2+}_{(aq)} + 1.10\ V$$



Facts

- Immediately after the circuit is connected, the voltage will begin to decrease from an emf of 1.10 V.
- The blue colour in the cathodic (reduction) cell due to the $Cu^{2+}_{(aq)}$ ion will become less dark as the ions are reduced to solid copper atoms that are deposited on the copper cathode.
- The concentration of $Zn^{2+}_{(aq)}$ ions will increase around the zinc anode.

As a result, the concentration of reactants will continue to decrease and the concentration of products will increase.

SKILLS AND ATTITUDES OUTCOME

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

Effects to consider using Le Châtelier's principle include the following:

- The addition of $Cu^{2+}_{(aq)}$ ions in any form using a soluble salt of $Cu^{2+}_{(aq)}$ will have a tendency to move the equilibrium in the forward direction.
- The removal of $Zn^{2+}_{(aq)}$ ions by the addition of a precipitating anion will effectively remove soluble $Zn^{2+}_{(aq)}$ to a solid form that will precipitate (e.g., sulphide ion S^{-}), forming solid ZnS (e.g., hydroxide OH^{-} ion), forming solid $Zn(OH)^{2}$, and so on.

Journal Writing/Process Notes

Students can

- provide reasons for the great attention currently being given to electrochemistry
- "write the steps for the process of predicting whether any proposed redox reaction will occur spontaneously" (Fisher 287)
- explain the difference between positive and negative E_{cell} values (Fisher 286)

LEARNING RESOURCES LINKS

Chemistry, 9th ed. (Chang 825–830)

Glencoe Chemistry: Matter and Change (Dingrando, et al.)
Table 21–1: Standard Reduction Potentials at 25°C, 1 atm, and 1*M* Ion Concentration, 667

Glencoe Chemistry: Matter and Change, Science Notebook (Fisher 286, 287)

Prentice Hall Chemistry (Wilbraham, et al.)
Table 21.2: Reduction Potentials at 25°C with 1*M* Concentration of Aqueous Species, 674

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-09: Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10: Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.

Include: a molten ionic compound and an aqueous ionic compound

C12-6-11: Describe practical uses of electrolytic cells.

Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

(3.5 hours)

SLO: C12-6-09
SLO: C12-6-10
SLO: C12-6-11

SUGGESTIONS FOR INSTRUCTION

Entry-Level Knowledge

The following study of electrolytic cells complements previous discussions of electrochemical cells; however, a review and assessment is necessary to secure students' prior knowledge before adding a new layer of related information.

TEACHER NOTES

Electrolysis is the process in which electrical energy is used to cause a non-spontaneous reaction to occur.

Demonstration: Electrolysis of Water

The electrolysis of water, a method by which hydrogen gas and oxygen gas can be generated, is an effective demonstration to begin the discussion of electrolytic cells even though it is generally a slow reaction.

The following schematic diagram shows how a simple apparatus can be used for the decomposition of water. Many teachers will be familiar with the equipment, since it is often found in chemistry labs. The Hofmann apparatus was designed by German chemist August Wilhelm von Hofmann for the electrolytic decomposition of water. As water is a relatively poor conductor of electricity, the use of a 0.1 mol/L solution of either hydrochloric acid or sulphuric acid will speed up the reaction.

General Learning Outcome Connections

GLO A5: Recognize that science and technology interact with and advance one another.

GLO B2: Recognize that scientific and technological endeavours have been and continue to be influenced by human needs and the societal context of the time.

GLO D3: Understand the properties and structures of matter, as well as various common manifestations and applications of the actions and interactions of matter.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

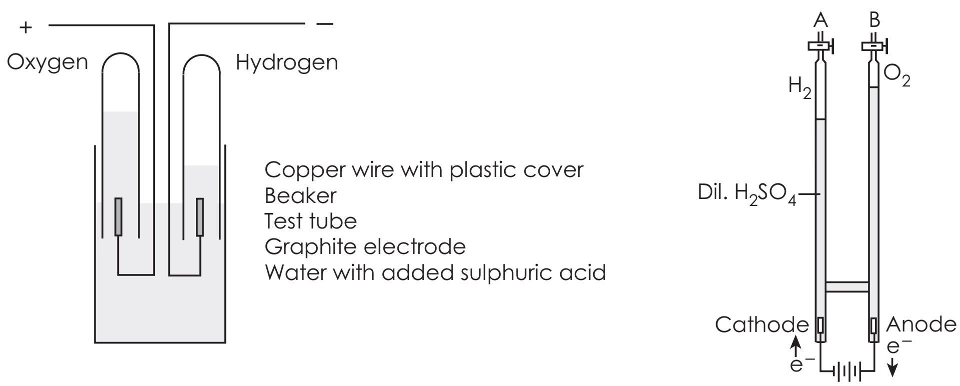
C12-0-U2: Demonstrate an understanding of chemical concepts.
Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-R4: Compare diverse perspectives and interpretations in the media and other information sources.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

C12-0-A4: Be sensitive and responsible in maintaining a balance between the needs of humans and a sustainable environment.

Hofmann Apparatus



The addition of universal indicator to the acidic solution will cause a colour change when the reaction begins. The colour will also help the observer to note the difference in the volumes of gas produced.

The volume of gas is related to the empirical formula of water and, therefore, twice as much hydrogen gas is produced as oxygen gas. A glowing splint can be used to identify whether a gas is oxygen or hydrogen. If the splint glows brighter, the gas is oxygen, and if there is a popping sound, the gas is hydrogen.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-09: Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10: Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.

Include: a molten ionic compound and an aqueous ionic compound

C12-6-11: Describe practical uses of electrolytic cells.

Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

(continued)

Comparison of Electrochemical and Electrolytic Cells

The following table compares electrochemical (voltaic) and electrolytic cells.

Comparison of Electrochemical and Electrolytic Cells		
	Electrochemical Cell	**Electrolytic Cell**
Reaction spontaneity	Spontaneous	Non-spontaneous
Cell potential	Positive	Negative
Electricity	Produces	Consumes
Electrode charge*	Cathode (+) Anode (–)	Cathode (+) Anode (–)
Cathode	Reduction	Reduction
Anode	Oxidation	Oxidation
Change in energy	Converts chemical energy to electrical energy	Converts electrical energy to chemical energy

* The discussion of electrode charge can be confusing to students, and should have a lower priority than the discussion of chemical processes that occur at each electrode.

The Operation of an Electrolytic Cell

Students should be able to describe the processes involved in the operation of electrolytic cells in terms of the various modes of representation (visual, particulate, and symbolic), just as they were expected to for electrochemical cells. The particulate nature of matter is just as relevant with electrolytic cells.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.

Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

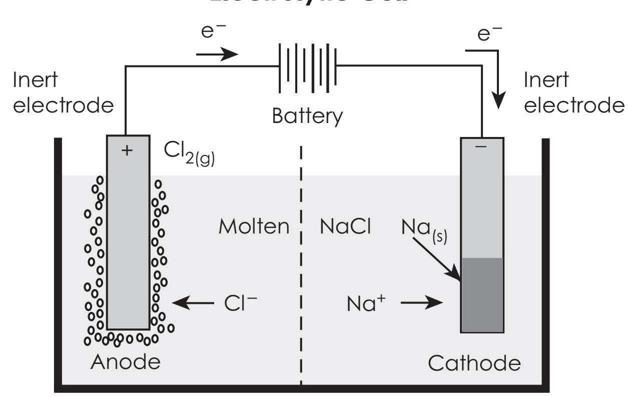
C12-0-R4: Compare diverse perspectives and interpretations in the media and other information sources.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

C12-0-A4: Be sensitive and responsible in maintaining a balance between the needs of humans and a sustainable environment.

A labelled diagram of an electrolytic cell is provided below. Note the similarities of an electrolytic cell to an electrochemical cell. One of the differences in the setup of the apparatus is that in an electrolytic cell, a source of electricity is required to push the usually non-spontaneous reaction to occur, whereas in an electrochemical cell, the cell generates electricity through a spontaneous chemical reaction. Another difference is that in an electrolytic cell, both reactions occur in the same container, whereas separate containers are needed for each electrode in an electrochemical cell.

Electrolytic Cell



The following items should be included in a diagram of an electrolytic cell: a container, an electrolytic solution (acid, base, or salt), the two electrodes, an external electron "pump" (battery), the positive electrode of the battery connected to the anode, and the negative electrode of the battery connected to the cathode. Half-cell reactions and the net reaction are still necessary.

There are two different types of electrolytic cells:

- The more straightforward cell occurs when electricity is applied to a molten solution. The industrial applications of this particular cell will be discussed later.
- The second type of cell occurs when electricity is applied to an aqueous solution. This cell is complicated by the fact that there are many more species that can be oxidized and reduced.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-09: Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10: Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.
Include: a molten ionic compound and an aqueous ionic compound

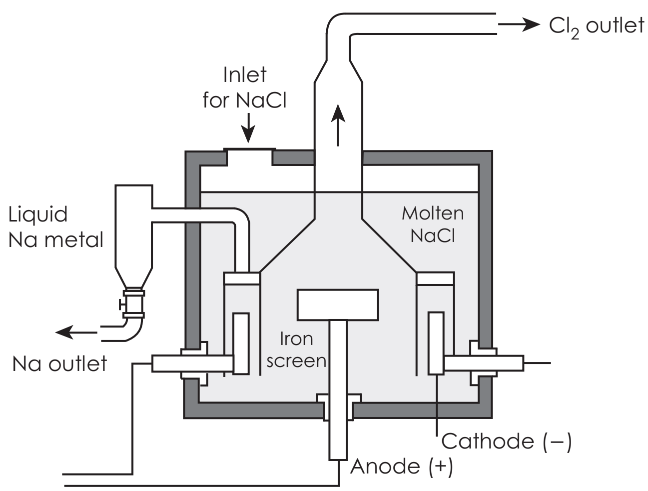
C12-6-11: Describe practical uses of electrolytic cells.
Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

(continued)

Electrolysis of Molten Solutions

Molten solutions are melted forms of the pure substance. Obviously, the electrolytic cell container would be made of material that could withstand the high temperatures required to maintain the solution in the molten state. A diagram of an industrial electrolytic cell follows.

Industrial Electrolytic Cell



The negative side of the battery is connected to the cathode. In an electrolytic cell, as in an electrochemical cell, the cations move towards the cathode and the anions to the anode, according to the following reactions:

Anode (oxidation)	$2Cl^-_{(l)} \longrightarrow Cl_2{}^0_{(g)} + 2e^-$
Cathode (reduction)	$2Na^+_{(l)} + 2e^- \longrightarrow 2Na^0_{(l)}$
Net reaction	$2Na^+_{(l)} + 2Cl^-_{(l)} \longrightarrow 2Na^0_{(l)} + Cl_2{}^0_{(g)}$

This reaction is used to produce pure supplies of sodium and chlorine gas.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.

Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-R4: Compare diverse perspectives and interpretations in the media and other information sources.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

C12-0-A4: Be sensitive and responsible in maintaining a balance between the needs of humans and a sustainable environment.

Electrolysis of Aqueous Brine Solution

Teachers should carefully review their own knowledge of the following information before teaching it to students.

The electrolysis of brine (a saturated solution of sodium chloride), produces chlorine gas, hydrogen gas, and sodium hydroxide. The presence of water adds species that could either oxidize or be reduced.

An examination of the Standard Reduction Potentials table shows that the following oxidation reactions could occur at the anode:

1. $2Cl^{-}_{(aq)} \longrightarrow Cl_2{}^{0}{}_{(g)} + 2e^{-}$ Anode (oxidation)
2. $2H_2O_{(l)} \longrightarrow O_{2(g)} + 4H^{+}_{(aq)} + 4e^{-}$

According to the table, both reactions have been reversed, and must be written as follows:

3. $Cl_2{}^{0}{}_{(g)} + 2e^{-} \longrightarrow 2Cl^{-}_{(l)}$ $E^0 = +1.36$ V
4. $O_{2(g)} + 4H^{+}_{(aq)} + 4e^{-} \longrightarrow 2H_2O_{(l)}$ $E^0 = +1.23$ V

The half-cell emf values are close, but still indicate that for the reverse oxidation reaction, the $H_2O_{(l)}$ should be the first to be oxidized. However, it has been found experimentally that a much higher potential is required to oxidize water, and in fact $Cl_2{}^{0}{}_{(g)}$ is produced, and not $O_{2(g)}$. The voltage required for the oxidation reaction in excess of the expected value is called the *overvoltage*. The causes of overvoltage are very complex. In simple terms, a greater voltage is caused by difficulties encountered by the various species transferring electrons to atoms on the electrode/solution interface. As a result of this anomaly, E^0 values must be used cautiously in predicting the actual order of the oxidation or reduction of species in aqueous solutions.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-09: Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10: Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.
Include: a molten ionic compound and an aqueous ionic compound

C12-6-11: Describe practical uses of electrolytic cells.
Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

(continued)

Similarly, the following reduction reactions could occur at the cathode:

5. $2H^{+}_{(aq)} + 2e^{-} \longrightarrow H_2{}^{0}{}_{(g)}$ $E^0 = 0.00$ V
6. $2H_2O_{(l)} + 2e^{-} \longrightarrow H_2{}^{0}{}_{(g)} + 2OH^{-}{}_{(aq)}$ $E^0 = -0.83$ V Cathode (reduction)
7. $Na^{+}{}_{(aq)} + 1e^{-} \longrightarrow Na^{0}{}_{(s)}$ $E^0 = -2.71$ V

According to the Standard Reduction Potentials table, the species that is most readily reduced is No. 5; however, in an aqueous salt solution at a pH of 7, the concentration of $H^{+}{}_{(aq)}$ would be too low to consider at 1×10^{-7} mol/L. Consequently, the preferred reaction at the cathode would be No. 6.

The reactions for the electrolysis of aqueous brine solution would be as follows:

Anode (oxidation)	$2Cl^{-}{}_{(aq)} \longrightarrow Cl_2{}^{0}{}_{(g)} + 2e^{-}$
Cathode (reduction)	$2H_2O_{(l)} + 2e^{-} \longrightarrow H_2{}^{0}{}_{(g)} + 2OH^{-}{}_{(aq)}$
Net reaction:	$2H_2O_{(l)} + 2Cl^{-}{}_{(aq)} \longrightarrow H_20_{(g)} + 2OH^{-}{}_{(aq)} + Cl_2{}^{0}{}_{(g)}$

Research: Applications of Electrolytic Cells

Many useful reactions centre on the use of electricity to produce chemical changes. If time permits, encourage students to research the applications of electrolytic cells. According to the media, fuel cells appear to be the energy of the future. Chemistry texts, such as those cited as Learning Resources Links, provide topical discussions of electrolytic cells.

1. Electrolysis of brine (a saturated solution of sodium chloride) is used for the purification of water and collection of sodium hydroxide, hydrogen, and chlorine (also known as the *chloro-alkali process*).
2. Electrolysis of molten sodium chloride within a *Down's cell* is used to obtain elemental sodium and chlorine gas.
3. Aluminum metal is obtained by the electrolysis of aluminum oxide, which is refined from bauxite ore.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.

Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-R4: Compare diverse perspectives and interpretations in the media and other information sources.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

C12-0-A4: Be sensitive and responsible in maintaining a balance between the needs of humans and a sustainable environment.

4. Extraction is the process by which a metal is obtained from an ore. Reactive metals, including lithium, beryllium, magnesium, calcium, and radium, are extracted industrially by the electrolysis of their molten chlorides.
5. Refining/purification of metal occurs following extraction. During this process, impurities are removed electrolytically to produce pure metals, such copper or nickel. The result is 99.99% pure metals.
6. Electroplating coats an object with a thin layer of protective/decorative metal, such as copper or silver.
7. Galvanizing is a process in which iron is covered with a protective layer of zinc.
8. Cathodic protection is a method of preventing rusting in which a more reactive metal (sacrificial anode) is attached to an object. For example, this method is used to protect ship hulls, oil and gas pipelines, boat motors, underground iron pipes, and gasoline storage tanks.

Class Discussion

Discuss the environmental impact of mining and extraction procedures and the implications for sustainability.

Laboratory Activity/Demonstration

Construct (or have students construct) an electrolytic cell using a solution of copper(II) sulphate, a copper metal strip, a nickel or quarter coin, and a 6-V battery. The copper from the solution plates onto the nickel. Reversing the current removes the plated copper from the nickel.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOMES

C12-6-09: Compare and contrast voltaic (galvanic) and electrolytic cells.

C12-6-10: Explain the operation of an electrolytic cell at the visual, particulate, and symbolic levels.

Include: a molten ionic compound and an aqueous ionic compound

C12-6-11: Describe practical uses of electrolytic cells.

Examples: electrolysis of water, electrolysis of brine, electroplating, production and purification of metals . . .

(continued)

SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Tasks

1. Have students demonstrate their ability to calculate the cell potential of electrolytic cells.
2. Ask students to draw a diagram of an electrolytic cell on which they identify the positive and negative electrodes, anode, cathode, half-cell reactions, direction of electron flow, direction of ion flow, solutions used, the net cell reaction, the electrode that erodes, and the electrode that plates.
3. Have students explain the complete operation of a working electrolytic cell in terms of the three modes of representation: visual, particulate, and symbolic.

Compare and Contrast

Students can complete a Compare and Contrast think sheet for electrolytic and electrochemical cells (see *SYSTH* 10.24).

Research Project

Students can research electrolytic processes by conducting an Article Analysis (see *SYSTH* 11.30, 11.40, 11.41) or by creating a poster. The projects should emphasize local applications, where relevant.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.

Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.

Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-R4: Compare diverse perspectives and interpretations in the media and other information sources.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

C12-0-A4: Be sensitive and responsible in maintaining a balance between the needs of humans and a sustainable environment.

LEARNING RESOURCES LINKS

Glencoe Chemistry: Matter and Change (Dingrando, et al.)
Section 21.3: Electrolysis, 683

Prentice Hall Chemistry (Wilbraham, et al.)
Section 21.3: Electrolytic Cells, 678

Investigations

Glencoe Chemistry: Matter and Change: Laboratory Manual (Dingrando, et al.)
Lab 21.2: Electroplating, 165

Prentice Hall Chemistry: Laboratory Manual (Wilbraham, Staley, and Matta)
Experiment 48: Electrochemistry, 287 (constructing electrolytic cells)

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-12: Solve problems related to electrolytic cells, using Faraday's law.

(2 hours)

SLO: C12-6-12

SUGGESTIONS FOR INSTRUCTION

Entry-Level Knowledge

In their discussion of electricity in Grade 9 Science, students learned that the quantity of electric charge is equal of the product of the current and time. Teachers should help students review prior knowledge before proceeding with new information.

TEACHER NOTES

Faraday's Law

English chemist and physicist Michael Faraday (1791–1867) experimented extensively to determine the stoichiometric relationship between electric charge and chemical energy. He determined that the amount of substance produced or consumed in an electrolysis reaction is directly proportional to the quantity of electricity that flows through the circuit.

An ampere is defined as 1 coulomb flowing through a conductor in 1 second.

Amperage = coulombs/second, or rearranged as

$Q = I\Delta t$

Q = charge (coulombs)

I = current (amperes)

Δt = change in time (seconds)

General Learning Outcome Connections

GLO A4: Identify and appreciate contributions made by women and men from many societies and cultural backgrounds that have increased our understanding of the world and brought about technological innovations.

GLO B1: Describe scientific and technological developments—past and present—and appreciate their impact on individuals, societies, and the environment, both locally and globally.

GLO D3: Understand the properties and structures of matter, as well as various common manifestations and applications of the actions and interactions of matter.

GLO D4: Understand how stability, motion, forces, and energy transfers and transformations play a role in a wide range of natural and constructed contexts.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.
Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-T1: Describe examples of the relationship between chemical principles and applications of chemistry.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

Faraday's constant (*F*) is the quantity of electricity carried by 1 mole of electrons.

1 faraday = Avogadro's number × the charge on an electron

$= 6.02 \times 10^{23} \cdot \text{mol}^{-1} \times 1.602192 \times 10^{-19} \text{ coulombs} \cdot \text{electron}^{-1}$

$= 96\,484 \text{ coulombs} \cdot \text{mole of electrons}^{-1}$

$= 96\,500 \text{ coulombs/mole of electrons (rounded)}$

By combining electric current and Faraday's constant, chemists have a simple way to calculate how much electricity is required to produce a mole of product at a given electrode. The solid is usually deposited at the cathode.

$$\text{Moles of electrons} = \frac{\text{amp} \times \text{s}}{96\,500}$$

Depending on the problem, we use two different units for 96 500:

$$\frac{96\,500 \text{ amp} \cdot \text{s}}{\text{mole of electrons}}$$

or

$$\frac{96\,500 \text{ coulombs}}{\text{mole of electrons}}$$

We can then use unit analysis to confirm calculations and the correct units.

In class discussions, emphasize the proportionality of ion charge to the grams liberated (deposited) from a solution (molten or aqueous salt) during the passage of 1 mole of electrons.

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-12: Solve problems related to electrolytic cells, using Faraday's law.

(continued)

The following table illustrates the relationship between moles of electrons and the half-cell reactions.

Relationship between Moles of Electrons and Half-Cell Reactions				
Solution or Molten Salt	**Ion**	**Oxidation Number**	**Gram Equivalent Weight**	**Grams of Element Produced**
NaCl	Na^{+}	+1	23 g ÷ 1	23 g Na/faraday
HCl	Cl^{-}	–1	35.5 g ÷ 1	35.5 g Cl/faraday
$MgCl_2$	MG^{2+}	+2	24.3 g ÷ 2	12.2 g Mg/faraday
$Al_2(SO_4)_3$	Al^{3+}	+3	27 g ÷ 3	9 g Al/faraday

Note that with Mg^{2+}, twice as many moles of electrons (electricity) are required to discharge 1 mole of Mg than to discharge 1 mole of Na. Since there is 1 mole of electrons in a faraday, only half a mole, or 12.2 g, of Mg metal is deposited. As shown in the previous table, 1 faraday (96 500 coulombs) is required to discharge 1 mole of Na^{+} ions, 2 faradays of electricity are needed to discharge 1 mole of Mg^{2+} ions, and 3 faradays are needed to discharge 1 mole of Al^{3+} ions.

Solving Problems Using Faraday's Law

Have students solve problems related to electrolytic cells, using Faraday's law. Some sample problems and solutions follow.

Example 1:

How many coulombs of current would be produced if 12.0 amp flow for 15.0 minutes?

Solution:

$$\begin{aligned} Q &= I\Delta t \\ &= \text{amp} \times \text{seconds} \\ &= 12.0 \text{ amp} \times 15.0 \text{ min} \times 60 \text{ s/min} \\ &= 10\,800 \text{ coulombs} \end{aligned}$$

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.
Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-T1: Describe examples of the relationship between chemical principles and applications of chemistry.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

Example 2:

If 7.85 amp flow through a molten solution of copper(I) chloride for 45.0 minutes, how many moles of electrons flow though the cell?

Solution:

Half-reaction: $Cu^{+} + 1e^{-} \longrightarrow Cu^{0}$

$$\text{Moles of electrons} = \frac{\text{amp} \times \text{s}}{96\ 500}$$

$$\text{Moles of electrons} = \frac{7.85\ \cancel{\text{amp}} \times 45\ \cancel{\text{min}} \times 60\ \cancel{\text{s}}}{96\ 500\ \cancel{\text{amp}} \cdot \cancel{\text{s}} \cdot \text{mole of electrons}^{-1} \cdot \cancel{\text{min}}}$$

$$= 0.220 \text{ mole of electrons}$$

Example 3:

Calculate the grams of zinc deposited if 5.00 moles of electrons pass through a zinc sulphate solution.

Solution:

1. Write the reduction half-reaction.

   $Zn^{2+} + 2e^{-} \longrightarrow Zn$

2. Use the mole ratio from the reaction.

   2 moles of electrons $\longrightarrow$ 1 mole of zinc metal

   5 mol $\longrightarrow$ x mol

   $x = 2.50\ \cancel{\text{mol}} \times 65.38\ \text{g} \cdot \cancel{\text{mol}}^{-1}$ or 163.45 g (or 164 g to 3 sig. figs.)

Topic 6: Electrochemistry

SPECIFIC LEARNING OUTCOME

C12-6-12: Solve problems related to electrolytic cells, using Faraday's law.

(continued)

Example 4:

If 9.00 amp flow for 10.0 minutes through a molten silver fluoride solution, what mass of silver metal would be deposited at the cathode?

Solution:

The cathode reaction: $Ag^{+}_{(aq)} + 1e^{-1} = Ag^{0}_{(s)}$

Therefore, according to the stoichiometry of the reaction, 1 mol of electrons produces 1 mol of Ag metal.

$$\text{Moles of electrons} = \frac{\text{amp} \times \text{s}}{96\ 500}$$

$$\text{Moles of electrons} = \frac{9.00\ \cancel{\text{amp}} \times 10.0\ \cancel{\text{min}} \times 60\ \cancel{\text{s}}}{96\ 500\ \cancel{\text{amp}} \cdot \cancel{\text{s}} \cdot \text{mole of electrons}^{-1} \cdot \cancel{\text{min}}}$$

$$= 0.0560 \text{ mole of electrons} \rightarrow 0.0560\ \cancel{\text{mol}} \text{ of Ag} \times 107.9\ \text{g}/\cancel{\text{mol}}$$

$$= 6.04 \text{ g of Ag to 3 sig. figs.}$$

Laboratory Activity

Students can perform a lab experiment in which a potassium iodide solution is electrolyzed using carbon electrodes.

Note:
Remember to have students present the redox projects they began preparing in Topic 1: Reactions in Aqueous Solutions.

SKILLS AND ATTITUDES OUTCOMES

C12-0-U1: Use appropriate strategies and skills to develop an understanding of chemical concepts.
Examples: analogies, concept frames, concept maps, manipulatives, particulate representations, role-plays, simulations, sort-and-predict frames, word cycles . . .

C12-0-U2: Demonstrate an understanding of chemical concepts.
Examples: use accurate scientific vocabulary, explain concepts to others, compare and contrast concepts, apply knowledge to new situations and/or contexts, create analogies, use manipulatives . . .

C12-0-N2: Describe, from a historical perspective, how the observations and experimental work of many individuals led to modern understandings of matter.

C12-0-T1: Describe examples of the relationship between chemical principles and applications of chemistry.

C12-0-T3: Provide examples of how chemical principles are applied in products and processes, in scientific studies, and in daily life.

SUGGESTIONS FOR ASSESSMENT

Paper-and-Pencil Tasks

When solving problems related to electrolytic cells, students should be able to calculate any specific variable, when given all the other variables.

Examples:

- Find the mass, given the cathode reaction, amperage, and time.
- Find the time required to deposit a given mass of metal at the cathode, given the amperage and the cation.
- Find the amperage required to deposit a given mass of metal at the cathode for a given time period.
- Find the volume of gas generated at the anode, given the amperage, the time, the gas produced, and the temperature and pressure of the gas liberated.

Journal Writing

Ask students to

- write an account of the various industrial uses of electrolytic cells
- discuss the environmental effects of using an electrochemical cell to manufacture pure elements

LEARNING RESOURCES LINKS

Investigation

Essential Experiments for Chemistry (Morrison and Scodellaro)
Experiment 14E: Electrolytic Cells, 256

Selecting Learning Resources

For additional information on selecting learning resources for Grade 11 and Grade 12 Chemistry, see the Manitoba Education website at <www.edu.gov.mb.ca/k12/learnres/bibliographies.html>.