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TECH COMMENTARY

ELECTROSEPARATION PROCESSES

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SEPARATING MATERIALS WITH ELECTRICITY

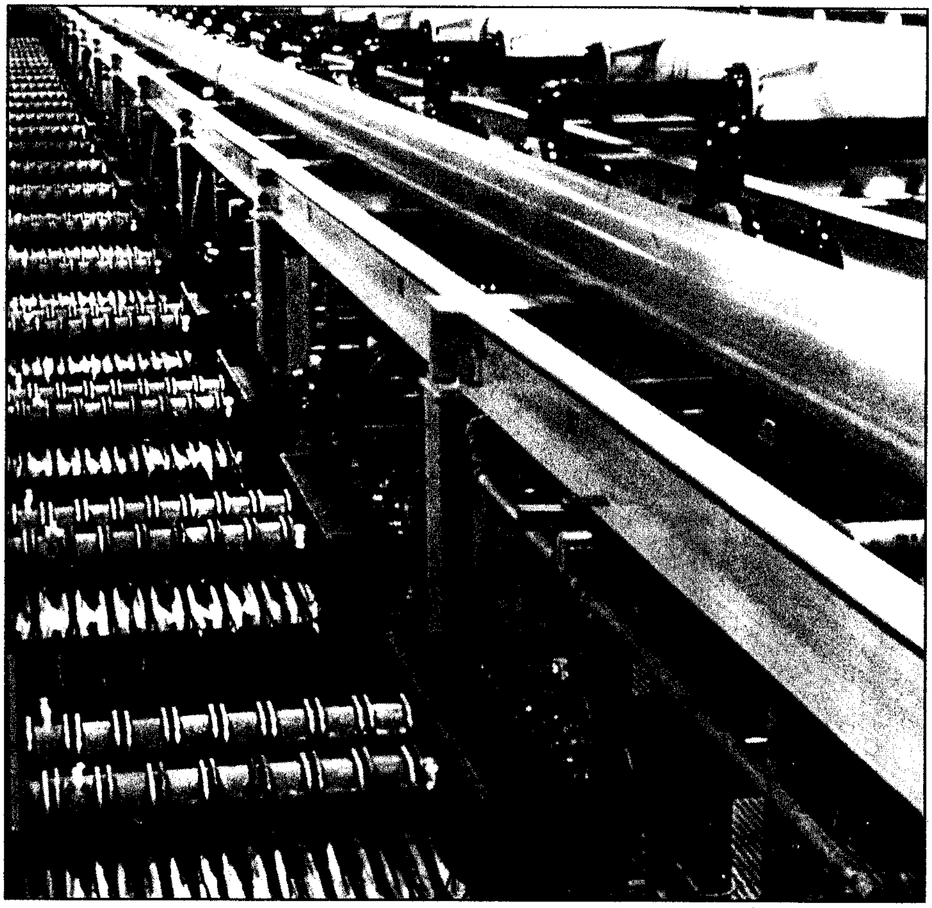
Electroseparation processes are used throughout industry to produce, refine, and recover materials. By modifying or moving compounds and molecules in electric fields, specific materials can be produced or isolated directly. Electroseparation includes processes such as electrolysis, electrodialysis, electrophoresis, electrorefining, and electrowinning.

In general, electroseparation processes can reduce energy use and raw material costs and increase product yield. They may also allow low temperature processing of heat-sensitive materials, recovery of metals from ore, and provide a means of removing or recovering hazardous or valuable compounds from waste streams.

The industrial production of chlor-alkali and aluminum has used electroseparation technology since 1890. In several industries, electroseparation processes are replacing existing, less efficient processes, or are satisfying new application requirements. In others, these processes provide the only competitive production methods. Applications of electroseparation processes include:

- Chemical production
- Metals production
- Seawater desalinization
- Wastewater treatment
- Hazardous waste treatment
- Food processing
- Pigment recovery
- Materials dewatering
- Biological product refinement

Numerous electroseparation processes exist, for a wide range of applications. Each relies on fundamental scientific principles that describe the interaction between matter and electricity. The various processes can be differentiated by the manner in which they are driven by electric fields or currents:



Electroseparation Membrane Cells

- **Electrolysis** — which includes electrosynthesis, electrowinning, electrorefining, electrodeposition, and electroadsorption — is the production of new products as the result of passing an electrical current through a conductive electrolyte. Chlor-alkali production from brine is a significant example of an electrolytic process.
- **Electrokinetic Processes** are critical in all electrochemical technologies, but represent the principal mechanism for those that do not proceed to the formation of new compounds. Instead, they separate ions, molecules, or particles according to their varying mobilities in electric fields. Electrophoresis, electrodialysis, electroosmosis, electrodesalination and electrodewatering are all examples of such electrokinetic processes. The desalination of brine and separation of complex biological materials from living cells are examples of electrokinetic processes.
- Other processes may use **electroinduced** effects to allow separation. Microwave irradiation — dielectrophoresis — generates heat and induces molecular excitation to allow effective separation. Electroflotation

Dynamics of Electrolysis

A basic electrolytic process is the dissociation of water to form hydrogen and oxygen:

$$2H_2O \longrightarrow O_2 + 2H_2$$

Oxygen is produced at the anode along with protons that provide a conductive path:

$$2OH^- \longrightarrow O_2 + 2H^+ + 4e^-$$

At the cathode, which donates electrons to protons, hydrogen is formed:

$$2e^- + 2H^+ \longrightarrow H_2$$

For producing metals, ions are deposited on the cathode from solutions. Aluminum, titanium, and other highly reactive metals are deposited from molten salts. Less reactive metals such as copper, nickel, gold, cadmium and lead can be deposited from aqueous solutions. In each case, the electron deficient ion receives electrons from the cathode, forming the metal.

uses electrodes to generate bubbles, which can carry isolated compounds to the surface for skimming. Electrostatic separation places charges on dry particles or granules in a gas stream to separate them with an electric field.

- Finally, more traditional mechanical and thermal separation processes, such as membrane or freeze concentration, can be driven electrically, and are discussed in detail in PICO *TechCommentary* Vol. 1, Nos. 1 and 2, 1988.

The applications of electroseparation are increasing rapidly, as key technologies are improved and provide innovative solutions to challenging environmental problems and competitive forces.

ADVANTAGES

Aluminum, chlorine and some other reactive materials can be produced most cost effectively by electrochemical methods. Other operations — such as seawater desalination, caustic soda production, copper and magnesium refining, and materials dewatering — allow other process choices. In general, electroseparation processes offer several advantages over thermal and mechanical separation methods:

Lower energy costs.—Electroseparation does not rely on water vaporization, eliminating one component of the energy requirement of traditional thermal processes.

Reduced raw materials costs.—Traditional catalytic processes can be thought of as complex methods of delivering electrons. Providing the electrons "directly" may allow the use of naturally occurring and less expensive raw materials, and may eliminate the need for expensive refined compounds or catalysts. Moreover, electroseparation provides methods of recovering raw materials from waste streams in a form that permits immediate recycling.

Higher product yield/purity.—The selective nature of electroseparation dynamics allows the isolation or production of materials to a high degree of purity. This helps avoid further processing, and increases net output.

Toxic material removal.—Consistent with effecting high purity separations, electroseparation processes can be used to remove low concentrations of materials. For example, toxic compounds can be removed from wastewater, resulting in water suitable for discharge or reuse.

Lower shipping costs.—Dewatering by electroseparation can reduce product volume and weight, increasing its value-to-weight ratio and reducing unit transportation costs.

Non-thermal processing.—Immense energies — up to 50 kcal/mole — can be transferred at low temperatures and pressures through electrolytic processes, allowing the processing of heat sensitive materials. This is particularly important in biological, pharmaceutical, and food applications.

In-situ processing.—Electroseparation processes can be built into conventional on-site diked wastewater ponds, allowing the removal of toxics and reducing the problems and expenses of off-site processing.

ALTERNATIVE TECHNOLOGIES

Electroseparation technologies compete with numerous thermal, chemical, and mechanical alternatives. For example, centrifuges and cyclones are used widely to separate materials by size and density. In many processing applications amenable to electroseparation techniques, three technologies would typically compete — vaporization, freeze concentration, and membrane separation:

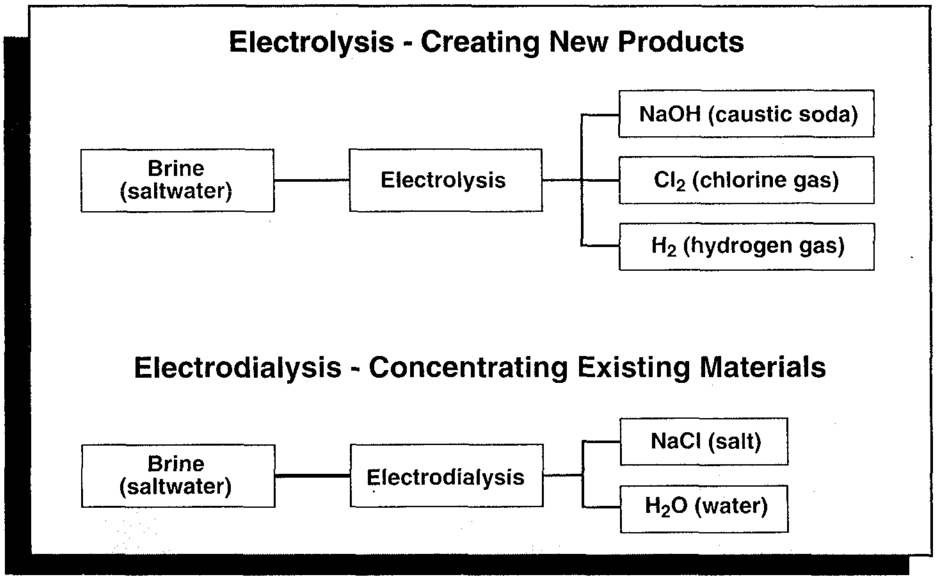


Figure 1. **Creating New Products vs. Concentrating Existing Materials**

Vaporization.—This separation method applies heat to a liquid mixture until one component vaporizes and can be removed, and includes evaporation and distillation (fractionation). Simple flash vaporization is an example of an evaporation process, and multistage refluxed vaporization is a distillation process. Electroseparation processes allow the removal of the desired product from the liquid without requiring vaporization, which otherwise would require significant energy.

Freeze Concentration.—Separations can be achieved by removing heat until one component crystallizes. Four types of freeze concentration systems may be used depending on the type of mixture and operating conditions expected. These types include indirect, direct-primary, direct-secondary, and direct-clathrate. The food industry has been using such processes to concentrate juice, beer, wine, vinegar and coffee and is beginning to use them for milk and whey. Other applications include wastewater treatment, pulp and paper black liquor concentration, industrial alcohols and chlor-alkali products, separation of xylene mixtures in the petroleum industry, and seawater desalination. Freeze concentration processes can be driven electrically, but the basic science underlying the technology is thermodynamic, not electrical. (PICO *TechCommentary* Vol.1, No.1, 1988 covers this topic.)

Membrane Separation.—Permeable barriers can filter selected components from mixtures, for example, to concentrate whey, clarify juices, desalinate seawater, and remove toxic components from waste streams. Membranes may be made out of polymers, ceramics and metals and are usually distinguished by the particle size filtered: reverse osmosis, ultrafiltration, and microfiltration. Some electroseparation technologies (i.e., electrodialysis) rely on selective membranes, and new membrane developments can quickly alter the economic tradeoffs among these technologies. For example, the development of a new thin-film composite membrane has improved the economics of reverse osmosis for seawater desalination, shifting some demand away from electrodialysis. (PICO *TechCommentary* Vol. 1, No. 2, 1988 covers membrane separations.)

ELECTROSEPARATION TECHNOLOGIES

Direct-current electric fields can be used to concentrate electrically-charged ions and molecules by modifying or moving them. (See Figure 1.) Electroseparation processes can be characterized by the interaction of the electric field and the processed material. The most direct effects result in chemical changes (e.g., electrolysis). Next are the processes that use electric fields to move the materials for membrane or filter separation (e.g., electrodialysis and electrophoresis). Electric fields or probes could also be used to induce other effects, such as generating heat or agitation (e.g., dielectrophoresis and electroflotation). Processes that use electricity primarily to drive pumps, compressors or other equipment are not considered here.

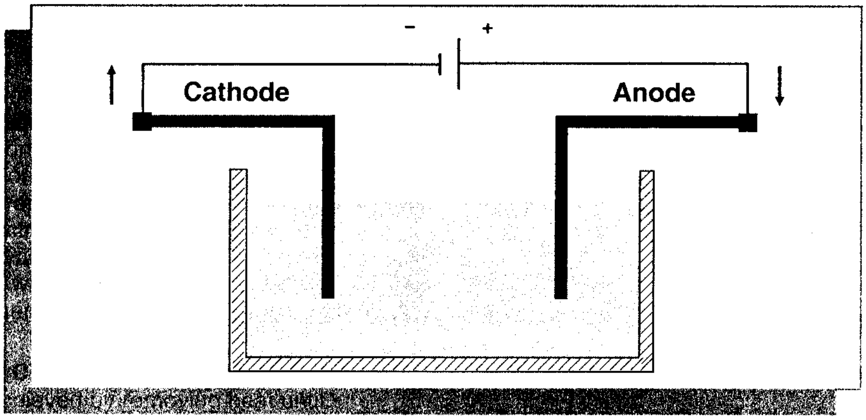


Figure 2. **Key Elements of an Electrochemical Cell**

ELECTROLYSIS

Electrolysis refers to processes in which new products result from passing an electric current through a conductive electrolyte. In a typical cell, electrodes are immersed in an electrolyte or conductive solution and are connected to a direct-current power supply. Figure 2 shows a simple electrolytic cell, the basic components of which are usually present in electroseparation processes. One of several reactions occurs at each electrode when current flows through the cell. Reduction, a reaction in which electrons are "consumed", occurs at the cathode; oxidation occurs at the anode. The reduction and oxidation products, formed at the electrodes, can then be collected.

Electrolytic technologies for the separation of chemicals and metals were among the earliest commercialized applications of electricity and have been economically significant since the turn of the century.

Low-temperature reduction, used for both chemical and metals production, is employed when the material to be separated can be maintained in ionic form within a bath of water (i.e. an aqueous solution). Low temperature electrolysis of aqueous metallic solutions is classified as either electrorefining or electrowinning.

Electrorefining is a method used to refine a metal by applying an electric current to selectively transfer metal ions from an impure anode of the metal to a pure cathode.

Electrowinning applies a difference in electrical potential from an inert anode through the electrolyte, which contains metal ions, to an inert cathode. The metal is "won" from the solution and selectively deposited on the cathode (for example, in electroplating) and is not often as pure as an electrorefined metal.

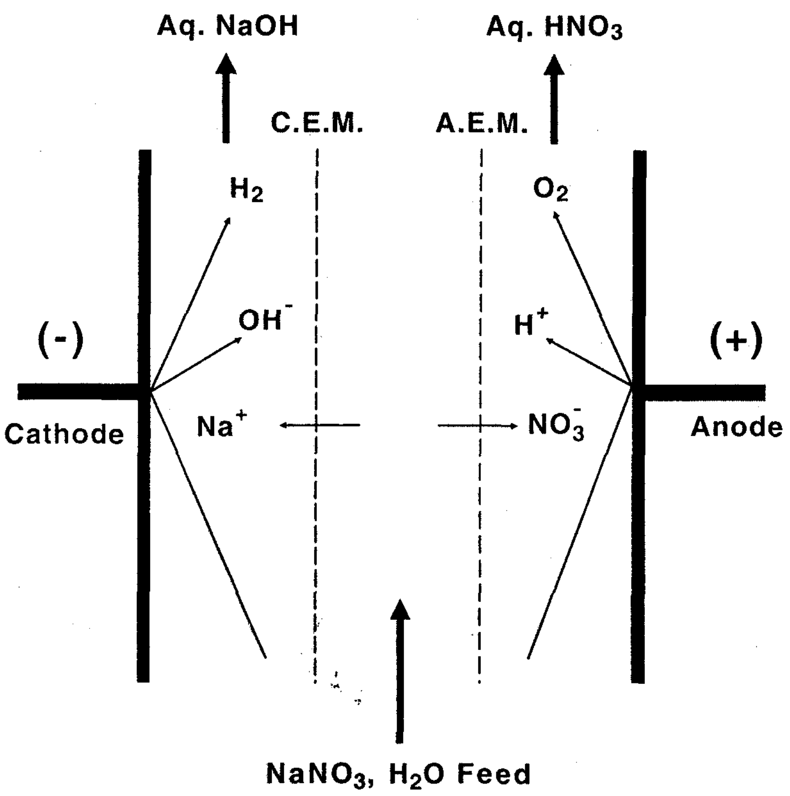
Electrodeposition and ***electroadsorption*** are two electrolytic methods of removing toxic metals from effluent streams, using electrodes made of porous carbon, metal sponges, and ceramic materials. Various systems have been designed to provide the large electrode surface area and mass transfer required, including fluidized beds, rotating electrodes, and carbon fiber electrodes.

The predominant application of ***high-temperature reduction***, or fused-salt electrolysis, is to reduce metal ions from molten metal salts to produce refined metal. High-temperature conditions are required to allow migration of the ions to the charged electrodes. This technology was first demonstrated for aluminum production in 1886.

ELECTROKINETIC EFFECTS

Ions, molecules, and particles can be separated according to their varying charges, masses and mobilities in electric fields. So, while electrolysis is characterized by the production of new materials, electrokinetic technologies separate materials without chemically altering the species in the electrolyte. Electrolysis, of course, depends on the electrokinetic effects as well.

Electrodialysis cells, for example, include basic components similar to those used for electrolysis, but employ



An aqueous sodium nitrate ($NaNO_3$) feed is converted to:
Aqueous caustic soda (NaOH) and hydrogen gas, using a cation exchange membrane (CEM).
Aqueous nitric acid (HNO_3) and oxygen gas using an anion exchange membrane (AEM).

Figure 3. **Electrodialysis of Sodium Nitrate**
(*Source:* Electrosynthesis Company, Inc.)

an ion exchange membrane that allows passage of only particular ions, either cations or anions. The ions are selectively transported within the cell to allow concentration and removal of the desired product. (See Figure 3.) Depending on the application, the desired products may be concentrated around either electrode or between the membranes. In desalination, for example, the water in the compartment between the membranes is the valuable product. Other related membrane processes, such as reverse osmosis, ultrafiltration, and microfiltration, use electro-mechanical pressure to force water or microscopic species through or onto a semipermeable membrane. These technologies are discussed in detail in PICO *TechCommentary* Vol. 1, No. 2.

Electrophoresis is another process that relies on the electrokinetic effect. The movement of particles and macromolecules in an electric field is closely analogous to sedimentation in a gravitational field. Fluid drag forces have a decreasing relative effect on particles with increasing size, allowing larger particles to move faster in an electric field than smaller ones. Electrophoresis relies on these effects to separate materials while minimizing thermal impacts, and is particularly useful for biological compounds and other materials that could be damaged by heat. ***Countercurrent electrophoresis*** uses a directed flow of fluid, perpendicular to the particle movement to sweep away the smaller, unwanted particles.

ELECTRO-INDUCED EFFECTS

Electric fields and charges can be used to generate heat at a molecular level or mechanically separate materials. ***Microwave processing***, for example, relies on radiation that generates heat and induces molecular excitations. This technology, when used for separation, is also known as ***dielectrophoresis***. It differs from electrophoresis in that it acts on neutrally-charged particles and is intended to heat the molecules. Because of this ability, microwave processing can be used to separate mixtures which cannot be easily separated by other means, such as oil-water emulsions. Although this application is primarily driven by heat, the induced molecular excitation facilitates separation.

Electroflotation applies electrodes in liquids (i.e., wastewater) to generate bubbles, which capture toxic compounds in the resulting froth. This technology typically exploits the net electric charge on solid suspensions and emulsions of colloidal particles. The froth, promoted by added flocculants, can then be skimmed away to complete the de-toxifying process. The process relies on the interaction of impurities and the bubbles, which may be more effectively generated by electrodes rather than mechanical or thermal methods.

Electrostatic separation can be used to separate granular materials using the differential attraction or repulsion of charged particles under the influence of an electric field. These technologies usually require the application of an extrinsic electrostatic charge to the process material.

APPLICATIONS

Electricity has been used for separation processes for over a century. New applications are being considered, driven by increasing concerns for environmental, cost, and product quality issues. At the same time, improvements in electrodes, membranes and cell designs are enabling electroseparation technologies to be considered for both existing and new applications.

By changing electrodes, electrolyte composition, and the operating parameters, many electroseparation processes can be adapted to widely diverse uses. The extraction of aluminum from alumina using a molten salt and the synthesis and separation of monomers for making nylon are both examples of electrolysis applications. Key applications of these technologies follow, and are summarized in Table 1.

Chlor-alkali.—The most common application of low-temperature aqueous electrolysis is the production of chlorine and caustic soda. Chlorine gas and sodium hydroxide (caustic soda) are produced by separating sodium chloride (NaCl) and reacting the components with water. Electrolytic production of these byproducts dates back to 1890. Of all electrochemical applications, chlor-alkali is by far the largest application of electrolytic separation, in terms of volume, and the second largest in terms of electricity consumption. The production of chlorine and caustic alone accounts for approximately 3 percent of the electricity used by all industry.

Chemicals.—In addition to chlor-alkali, inorganic chemicals produced electrolytically include: hydrogen, fluorine, sodium, potassium, lithium, manganese dioxide, ozone, hydrogen peroxide, chlorates, perchlorates, permanganates, persulfates, potash and soda ash. Electrolysis is increasingly being explored as an alternative to catalytic or thermal processing for organics, and may be used for synthesizing adiponitrile, fluorocarbons, ethylene glycol, and quaternary ammonium salts.

Metal Refining.—Electrowinning and electrorefining are widely used in the metals industry. Aluminum, magnesium, sodium, zinc, nickel, copper, and manganese production rely on electrolytic processes. Aluminum and titanium, for example, are produced from electrolytes made from molten salts.

Food Processing.—Electrodialysis is used for the removal of salt from whey cheeses and concentration of fruit juices, with manufacturers looking at other related applications. Electrodialysis provides a highly selective method of removing compounds without disturbing the delicate balance of the food mixture.

Product Dewatering.—Electrolysis is used to remove water from materials, such as china clay, prior to shipping, thus saving transportation costs. The wet, caked material is placed on a porous cathode under pressure from a covering anode. The current moves protons, carrying water molecules, to the cathode. Water is released to the porous cathode, with the formation of hydrogen, reducing the water content of the cake.

Desalination.—Hundreds of electrodialysis installations worldwide are generating potable water from brine, and are removing minerals from water at processing plants, hospitals, and municipal facilities.

Biotechnology.—Electrophoresis has been widely used as analytic tool in the biological sciences and is now being scaled up to process sensitive biological compounds and pharmaceuticals.

Waste Treatment.—Some of the newest and most promising applications for electroseparation technologies are found in the treatment of wastewater and processing waste streams. In some cases, the applications are driven by environmental regulations and concerns; in others, the potential for recovering valuable processing materials is paramount. (Figure 4 describes electroincineration, a new electroseparation application for destroying pollutants.)

- Electrodialysis is used in industrial wastewater treatment, and the recovery of valuable materials from processing waste streams (e.g. electroplating or microcircuit production). Electrodialysis has also been used to treat blowdown cooling tower effluent at thermal power stations.
- Electrolysis is applied to wastewaters on sites where potential water table contamination could arise. By placing electrodes in diked wastewater ponds, for example, chemical or other toxic wastes can be removed on-site, without costly off-site processing. Other applications of electrolysis of wastewaters includes the recovery of coating pigments and toxic metals.
- Electroflotation is being developed to separate metals and toxic materials from wastewater streams.
- Microwave demulsification may be used to separate oil-water mixtures in the petrochemical, food, and textile industries. Although not widely used in commercial applications yet, the technique has been demonstrated successfully in refinery applications.

TECHNICAL CONSIDERATIONS

Electroseparation processes satisfy diverse application requirements, ranging from bench-scale production of biologicals to the production of up to 40,000 tons per day of chlorine and caustic

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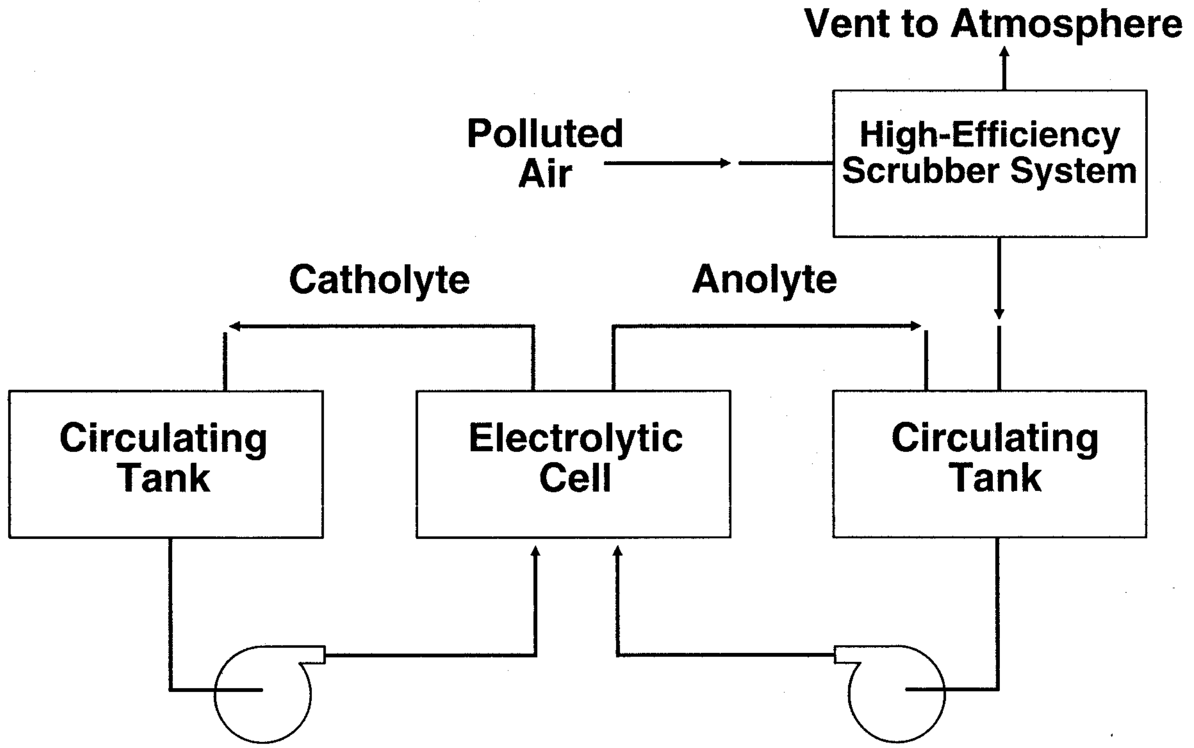

A new extension of electroseparation technology is being developed to destroy pollutants. Polluted air (from manufacturing plants, laboratories, or sewage treatment plants, for example) is first scrubbed in a high efficiency scrubber by a proprietary aqueous solution, which absorbs, dissolves, complexes, and partially or totally destroys a range of pollutants. The solution continuously recirculates through an electrolytic cell which regenerates the active solution components and destroys the more inert pollutants.

Figure 4. **Electroincineration of Pollutants** (*Source:* Electrocinerator Technologies, Inc.)

Table 1. **Applications of Electroseparation Technologies**

Electrolysis	Electrically-driven chemical changes at electrodes Movement of ions and molecules in electric field generated by electrodes	Low-temperature electrolysis	Chlorine Caustic soda Fluorine Persulfates Chlorates Perchlorates Adiponitrile
		Electrowinning	Copper Zinc Manganese
		Electrorefining	Copper Lead
		Electrodeposition	Toxic metals Dischargeable wastewater
		Electroadsorption	Toxic metals Dischargeable wastewater
		High-temperature reduction	Aluminum Magnesium
Electrokinetic Effects	Movement of ions, molecules and particles in electric fields driven by electrodes Separation assisted by selective membranes which provide filtration	Electrodialysis	Demineralization Potable water concentrated brine Waste treatment Materials recovery in process streams: Nickel, zinc, silver, and gold
	Movement of ions, molecules and particles in electric fields generated charged electrodes Larger particles separated from smaller particles due to relative variations in fluid dynamics effects	Electrophoresis	Biological products Pharmaceuticals
Electro-induced Effects	Dielectric-induced molecular rotations generate heat and assist separation by breaking forces which suspend the particles in emulsions	Dielectrophoresis (microwave irradiation)	Oil/water emulsion separation
	Electrodes generate bubbles which capture toxic compounds in froth, to be skimmed away	Electroflotation	Wastewater treatment Toxics removal
	Differential movement of extrinsically-charged particles in an electric field	Electrostatic Separation	Mineral processing Metal powder separation Food processing

Acid/Base Recovery from Sodium Sulfate

Sodium sulfate is produced in large quantities as a byproduct in many industries. Although some of the material is recycled internally or sold, most is disposed of in landfills, in deep wells, or in surface water. *Salt-splitting* — electrolytic regeneration of caustic soda and sulfuric acid — could reduce waste and raw material costs.

Disposal cost increases and transportation restrictions may make sodium sulfate regeneration more attractive. Further, the price of caustic soda may continue to increase rapidly due to the imbalance in demand for caustic soda and chlorine. Since caustic soda and chlorine are produced electrochemically in equal electrochemical units, the demand for each would ideally be equal. However, chlorine demand is expected to continue declining in response to environmental concerns. Caustic soda demand is not expected to decline, so prices are likely to increase.

Advances in ion exchange membranes and anode materials allow the separation of the sulfuric acid and caustic soda according to the following formula:

$$3H_2O + Na_2SO_4 \longrightarrow 2NaOH + H_2SO_4 + H_2 + {}^{1}/_{2}O_2$$

The process requires between 2,000 and 3,000 kWh per ton of sulfate, at 3.1 kA/square meter and 5V, and can electrolyze several hundred pounds of sulfate daily per square meter of membrane. A typical industrial application might allow the processing of 8-10,000 tons per year, requiring a capital investment of about $3 million. The expected lifetime of such a plant would be 8-10 years. The operating costs, dominated by the cost of electricity and periodic cell membrane renewal, would run from $75 to $150 per ton of sodium sulfate.

These costs vary directly by: electricity price, current density, feedstock quality and product concentration and purity required.

While this process may not provide the most economic method of producing caustic soda, market dynamics and external factors might make on-site sodium sulfate regeneration very attractive for a wide range of facilities.

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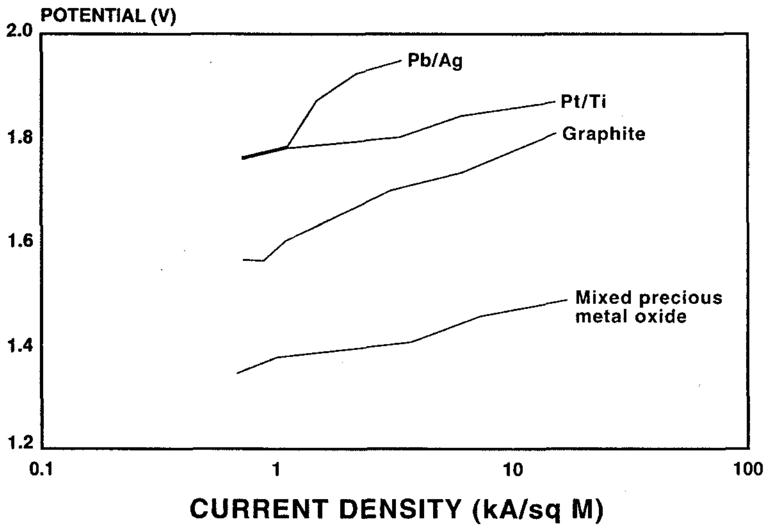
soda. Three threshold criteria are important for each application:

- Can the desired materials be isolated or produced electrochemically with output rates matching demand?
- Can the power and space requirements of electrochemical equipment be accommodated within existing or planned facilities?
- Are the electrochemical processes and their needs for special fluids, materials, and technical skills compatible with on-site capabilities?



Anode potential is important in comparing the energy consumption of electrodes. Lower potential reduces operating costs by minimizing power consumption. This graph compares the potential (Volts) of various types of anodes as a function of current density (kA/m²).

Figure 5. **Anode Potential** *(Source:* Electrode Corp.)

There may also be overriding regulatory or process requirements to recover or isolate specific hazardous or valuable materials, for which electrochemical methods provide the only solution.

Electrochemical cells are chosen to satisfy the desired *output per unit time, process requirements, and capital constraints* — there are a wide variety of designs possible, tailored within specific processes and economics. Cells are specified in terms of **electrical consumption** (given in kilowatt hour per unit produced) and cell's **current capacity** (given in kiloamps). Electrolytic cell design is based on optimization of: transport of electroactive species from the cell volume to the electrode surface; materials and geometry of the electrode; and the recovery of anode and cathode reaction products.

Most electrochemical cells are custom-designed to fit specific process needs. Cell design factors of greatest importance include:

- **Electrode Material.** The electrodes and electrolyte are central to the processes. The selection of electrode materials is usually based on the results of laboratory studies on the particular electrochemical reaction, and directly influences product quality and process characteristics. For example, carbon-based electrodes might be used for waste treatment processes, while oxide-coated titanium electrodes might be used for plating processes. In general, electrode material must have adequate electrical and thermal conductivity, good mechanical properties (strength, machinability), corrosion resistance, and low cost (See Figure 5). Advances in electrode material and designs are increasing effectiveness and improving process stability.

- **Electrolyte Flow.** An electrolyte stream must be distributed uniformly at a constant velocity within a cell to eliminate stagnant zones and enhance separation. Insufficient flow distribution might cause concentration polarization, a condition in which reactants are converted faster than they are delivered to the electrode surface. This results in unwanted side reactions, low current efficiency, and high electrode overvoltage. The handling and storage of electrolytic solutions, which may include regulated chemicals, could require special equipment and facilities.

- **Separator Material.** Some electrochemical processes require the separation of electrolyte streams within the cell. This is necessary to minimize mixing the solutions which might lead to side reactions and low current efficiency. For example, ion exchange membranes are necessary in many electro-organic processes to segregate the anolyte and catholyte zones. The particular electrochemical reaction and operating conditions normally determine which separator (i.e. membrane, diaphragm) material is to be chosen. Several factors affect membrane selection, including resistance to fouling, ion selectivity, voltage drop, and dimensional stability.

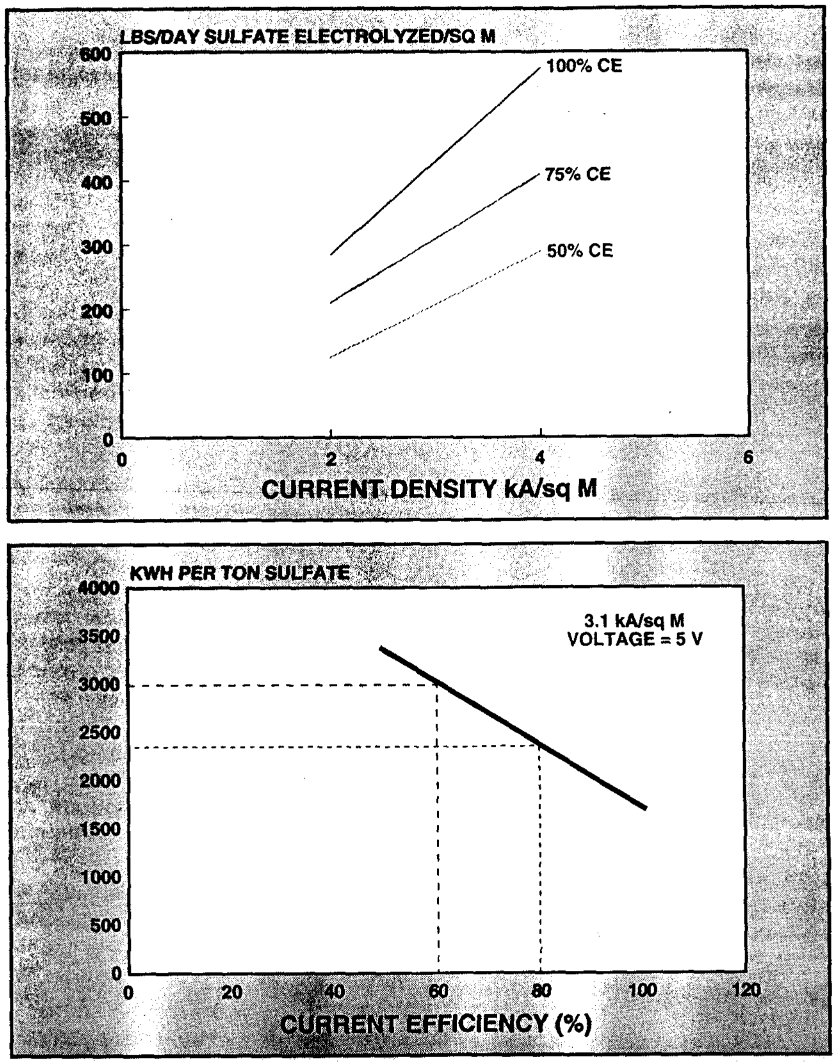


Figure 6. **Current Density/Efficiency in Regeneration of Sodium Sulfate.** (*Source:* Coin, *et al.*)

- **Reliability and Availability.** For many applications, electroseparation processes have a long history of successful operation. For example, in a typical chlor-alkali plant, anodes last 8 - 15 years, depending on their operating range. For newer applications, less information is available about how well the systems will perform and whether such systems have already been designed and used. Many electroseparation processes in other than traditional applications have been designed and built with "in-house" capabilities. The equipment supply industry for the newer applications is still developing.

- **Current Density.** Cell current density directly affects power consumption in the reaction process, with efficiency generally increasing with decreasing current density. Both electrical power usage and electrolysis system capital are dependent on current density. Empirical formulas and graphs are usually used to determine the relation between current density and the achievable power efficiency (See Figure 6). For a given production rate, low-current density cells have a high capital cost because of increased size and number of cells required. On the other hand, operating costs in high-current density cells are high because of decreased power efficiency. The selection of an electrochemical cell with an optimum size-current density combination is based on the trade-off between investment and operating costs. Figure 7 shows the nature of tradeoffs among the various cost elements.

ECONOMIC CONSIDERATIONS

Electroseparation processes are becoming more competitive as membranes and electrodes are rapidly improved, and as new applications are demonstrated. The economics vary significantly and are influenced by:

- Product: Physical characteristics, value, and quantities produced span a wide range. The economics of recovering metals from a process stream would differ from those of desalinating brine, for example.
- Cell and component characteristics: The efficiency, reliability, and durability of various components may vary by application.
- Electricity: The scale of an operation and the price of electricity will directly influence process costs.

In some applications, economic choices may be straightforward. In chlor-alkali production, plant managers are increasingly converting mercury to membrane

Energy (3.53 kWh/kgal)	0.176	32.6
-Rectifier (0.58 kWh/kgal)	*0.029*	
- Pumps and Blowers (2.95 kWh/kgal)	*0.147*	
Chemicals	0.016	2.9
Replacements (Filters, Membranes, Components)	0.140	26.0
Daily Labor	0.155	28.7
Maintenance Labor	0.053	9.8
	$ 0.540	100.00

Table 2. **Electrodialysis Reversal (EDR) Operating Costs** (*Source:* Ionics, Inc.)

cell plants to capture demonstrated economic benefits and reduce environmental/health concerns associated with mercury.

Significant uncertainties exist, however, regarding the economics of newer applications, for which scaled-up demonstration experience is limited. The equipment market for new electroseparation applications is relatively new: until recently much of the equipment was developed in-house or adapted from other processes. Today, there are electrochemical cells on the market that are readily adaptable to many new processes. Suppliers are responding to these niche markets, and the economic uncertainties are decreasing.

Some processes may become more attractive as the dynamics of related markets change the value of materials in waste streams. For example, *salt-splitting* — dialysis to reconvert waste salts to their acid and base constituents — may provide economic and environmental gains.

There are no good general rules of thumb for comparing the costs of chemical and electrolyte processes. Electroseparation technologies need to be analyzed and compared with alternatives for each specific application. In each, the tradeoffs can shift rapidly. The competition between reverse osmosis and electrodialysis plants for water desalination, for example, may shift to favor reverse osmosis with the development of a more efficient and durable membrane. Table 2 shows the energy requirements and costs of an electrodialysis reversal process to desalinate water for an industrial processing plant. Table 3 shows the energy use and costs of representative electroseparation applications.

For organic chemical synthesis, new investment in electrochemical equipment may prove more economic than new investment in catalytic processes. However, the relevant comparison may be with existing catalytic processing capacity, which will generally be more cost effective, unless no comparable catalytic process exists.

The pricing strategies that suppliers will use for similar electroseparation technologies may also vary. In some cases, developers may license processes and equipment. This would keep initial costs low, but might be offset by royalties tied to production. On the other hand, some developers will choose to sell the technology and equipment outright.

Some general characteristics of electroseparation costs follow:

Capital Costs. The capital cost of an electrochemical cell is determined mainly by the *cell components, size,* and *current density.* Usually, cell cost increases linearly with increasing size and decreasing current density. Additional factors that influence the cost of electrochemical cells include:

- cell type, configuration, and construction materials
- electrode material and configuration
- membrane material

The capital costs associated with the electrochemical cell and power supply can account for 50 - 60% of the total capital costs of the production system,

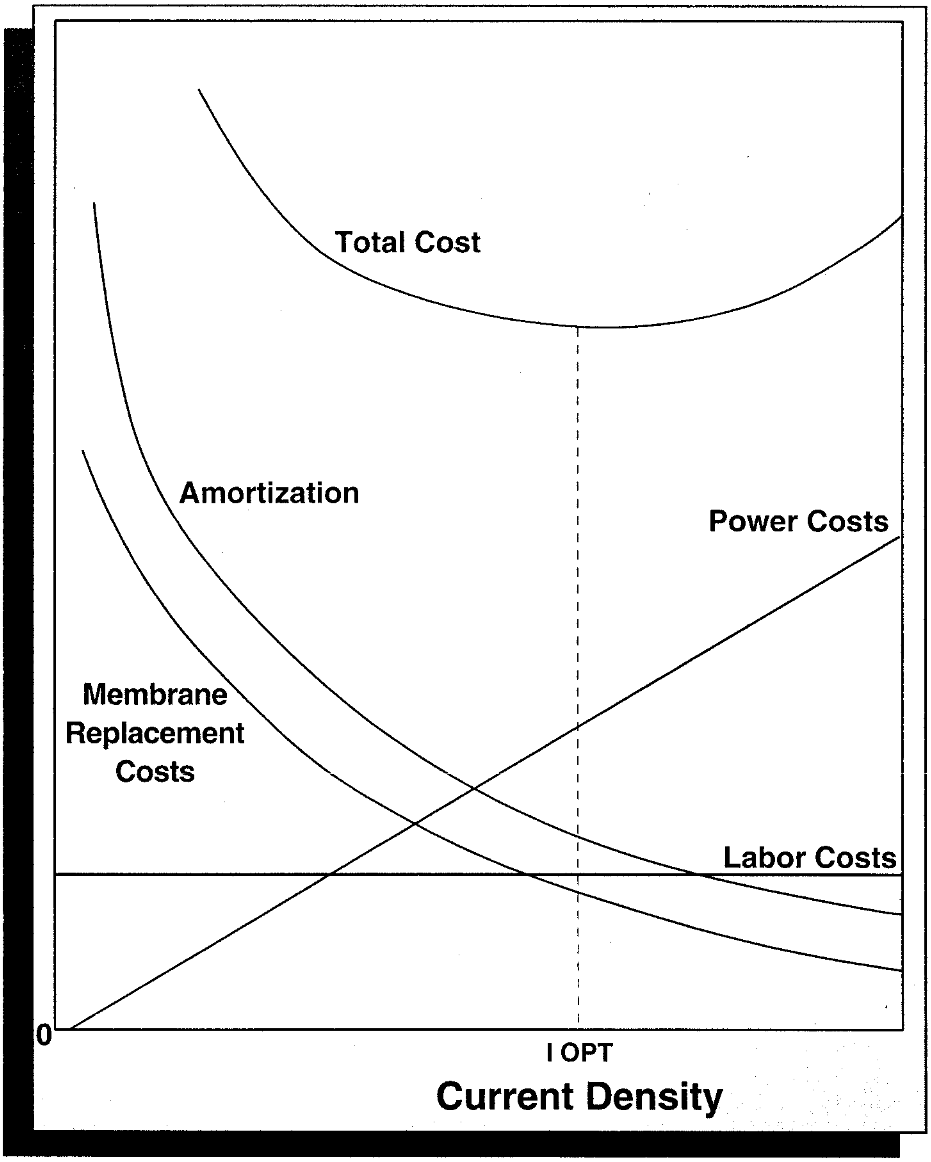


Figure 7. **Optimizing tradeoffs between current density and process cost components.** (*Source:* ASAHI Glass Co., LTD.)

Faraday's Laws: The Cost of Electricity for Electroseparation

The basic phenomena that drive electrochemical reactions have been known for more than a century. Michael Faraday (1791-1867) described the underlying relationship between the quantities of electricity and matter involved in electrolysis:

Faraday's First Law states:

> *The quantities of substances set free at the electrodes are directly proportional to the quantity of electricity which passes through the solution.*

Faraday's Second Law states:

> *The same quantity of electricity sets free the same number of equivalents of substances at the electrodes.*

Thus, the quantity of silver liberated at the cathode by the passage of 20 coulombs — a unit of electrical charge — through a solution of silver salt, for example, is twice that resulting from the passage of 10 coulombs. Further, the passage of a specific quantity of electricity through solutions of a silver salt, a copper salt, and an acid, will liberate silver, copper, and hydrogen in amounts proportional to their equivalent weights.

So, while the electrical costs of electrochemical processes vary with many factors, they are all related by the generic relationships described by Faraday. In general, the passage of F coulombs, where F is Faraday's constant (9.649×10^4), will result in the deposition of X grams of material, where X is its atomic weight divided by the number of electrons involved in the process.

For a metal, such as silver, with an atomic weight of 107.88 and one electron involved, the passage of 96490 coulombs would result in the deposition of 107.8 grams of silver if the process were 100% efficient. With electricity costing $0.06/kWh, this would translate into a cost of $0.09/kg. Similarly, one Faraday produces 1 gram of hydrogen, so with 100% efficiency, the electricity would cost $2.80/kg of hydrogen.

In practical applications, the costs would vary by electricity price, current efficiency (ranging from 50% to 99%, depending on process parameters, reactant concentration, and current density), and losses in ac to dc conversion (2% to 10%).

although they could be as low as 15 - 25%. The remaining "hard" costs are for tanks and pipes, instruments, heat exchangers, pumps, and other equipment (See Figure 8). These amortized capital costs are estimated to range from $0.40 to $1.75 per kilogram of product for some specialized electrosynthesis process. The capital cost per kilogram of product for a hydrogenation plant may in many cases be less, but is often offset by lower materials and labor costs of electrochemical processing.

Operating Costs. Two principal factors influence operating costs of electrochemical processes:

- product selectivity and feedstock requirements
- cell voltage and current efficiency

These factors together determine a cell's *power consumption*, which has a direct influence on process costs. (Cell *current capacity*, on the other hand, is a measure of capital productivity, since increasing current translates directly to increased output per unit time.) The electrical requirements for an electrochemical organic synthesis process can range from $0.10 to $3.00 per kilogram of product. This electricity cost can be viewed as supplying "reagent electrons," which replace hydrogen and catalysts in catalytic processes. In addition, the electrochemical processes can often use feedstock more efficiently, reducing the raw materials cost. Table 4 compares the costs of a catalytic hydrogenation process and cathodic reduction of the same material.

APPLICATION	Electrodialysis	Electrolysis	Freeze Concentration	Reverse Osmosis
	Regeneration of spent pickle liquor used in removing oxidation from stainless steel.	Removal of heavy metals from electroplating wastewater.	Concentration of water-based hazardous waste.	Recovery of nickel plating solution.
Size (million gallons/year)	1.5	12.5	6.5	1.5
Capital Cost (Dollars)	2,000,000	180,000	1,200,000	68,000
Electricity Demand (kW)	100	12	130	5
Energy Use (kWh/gallon)	0.01	0.002	0.1	0.015

Table 3. **Examples of Electroseparation Processes: Cost and Energy Use**

Cost component	Electrochemical $/kg product	Catalytic $/kg product
Organic raw material	8.16	12.70
Hydrogen and catalyst	—	0.59
Reagent electrons	0.32	—
Solvents, other reagents	0.48	1.27
Labor, utilitites, maintenance and over head	4.13	5.53
Capital depreciation	1.36	0.86
Total	14.47	20.95

*The same material, at the same price, is used for both types of synthesis, however, more is needed for the catalytic method.

Table 4. **Cost comparison for typical catalytic hydrogenation and cathodic reduction of the same starting material.** (*Source:* Toomey and Yu)

SUMMARY AND OUTLOOK

Electroseparation processes have been of major commercial importance since the earliest days of electrification. These processes rely on fundamental electrochemical and electrokinetic phenomena. To date, the most widespread uses have been in a few key applications, such as chlor-alkali production, metals recovery or extraction from ore, and seawater desalination. Advances in electrode materials, membranes, and cell designs are making electroseparation technologies more economically and technically competitive with mechanical and thermal technologies for a range of applications in traditional chemical and materials processing. Concomitantly, increased attention to environmental issues, waste stream constituents, and product quality are opening new opportunities for applying electroseparation techniques in water treatment, materials recovery, food processing, and biotechnology.

Continued development of the enabling technologies and demonstrations of scale-up successes will provide increased application opportunities. Their potential cost advantages and technical capabilities notwithstanding, however, electroseparation technologies will often compete with proven alternative processes and existing capacity, which may slow their penetration in established industrial processing and production markets. Electroseparation technologies may be adopted most rapidly in newer applications such as waste management and innovative materials processing niches.

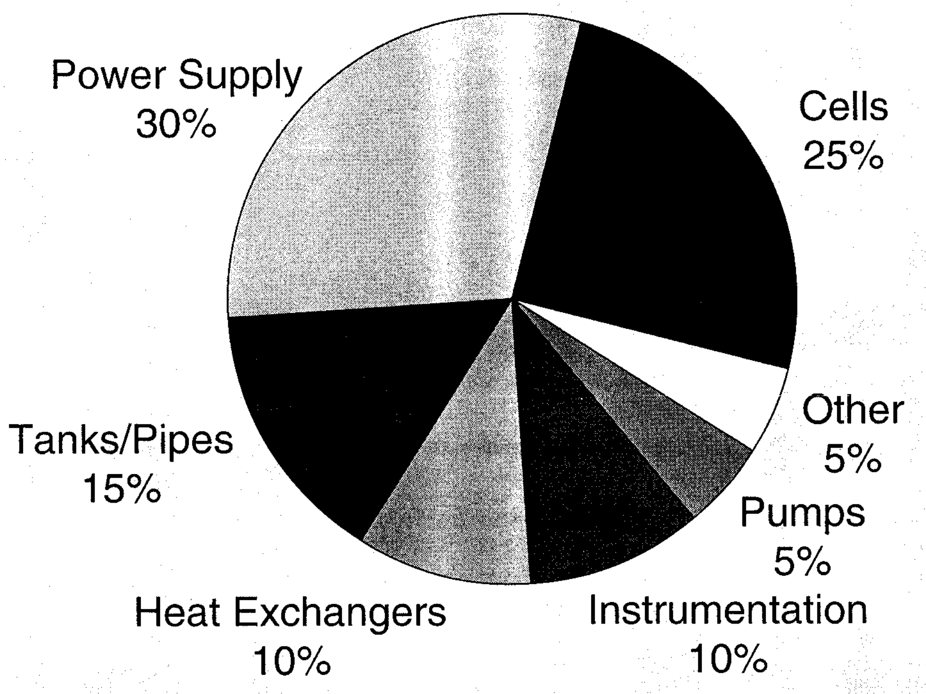


Figure 8. **Distribution of capital costs for an electrochemical plant.**
(*Source:* Toomey and Yu)

This *TechCommentary* presents general information about basic aspects of electroseparation technologies. For additional information about the technologies and specific applications, contact your electric utility marketing representative or an equipment supplier.

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