Focus on Processes

New Horizons in Electrochemical Science and Technology

Prepared by Richard C. Alkire
Dept. of Chem. Eng., University of Illinois

Stanley M. Wolf
NMAB, National Research Council

INTRODUCTION

Electrochemical phenomena underpin a wide range of technologies. For more than a century, traditional electrochemical processes have provided humanity with essential materials, many of which cannot be created by any other economical method. In addition, a broad range of technological opportunities that depend intimately on electrochemical phenomena lie outside the conventional electrochemical industries.

Electrochemical phenomena control the existence and movement of charged species in the bulk of, as well as across interfaces between, ionic, electronic, and dielectric media and systems. Phenomena arising in these materials include conduction and convection processes, potential field effects, ion exchange, adsorption, interfacial and colloidal activity, wetting, membrane transport, passivity, electrocatalysis, and many others. Processes critically depending on these phenomena include energy storage and conversion, corrosion, membrane separations, deposition and etching by electrolytic and plasma processes, electrosynthesis of chemicals, production and refining of metals, pollution detoxification. Products resulting from these processes include microelectronic devices, sensors, membranes, batteries and fuel cells, coatings and films, and materials.

Recent advances in several disciplines (physics, chemistry, chemical engineering, life sciences, etc.) have fostered a renaissance in electrochemical science. Today, precisely-characterized systems can be created for fundamental study, behavior can be monitored at previously unattainable levels of sensitivity, and properties can be predicted (i.e., designed) with new theories and computational skill. These capabilities have led to the invention of new materials and improved engineering methods which have truly revolutionized the electrolytic process industries. For example, electrolytic cells for the production of chlorine and caustic had evolved for 80 years based on the unique electrochemical properties of carbon electrodes. Today, over 90 percent of the cells in the United States use coated titanium electrodes, which were a laboratory curiosity only 20 years ago. Other new materials have also had a dramatic impact, including membranes and separators, and new solid and porous electrodes. In addition, the electrolytic technologies have recently made significant design adjustments in response to changed availability of energy, feedstock, and capital as well as to waste treatment. These and other events have shattered the empirical traditions of the past and served to trigger new interest in electrochemical science and engineering.

SOCIOECONOMIC SIGNIFICANCE

Electrochemical devices and processes represent a major market force in the United States through such activities as metal winning, chemical and semiconductor production, electroplating, corrosion cost avoidance, batteries and fuel cells, sensors (for health systems, industrial use, and home applications), and membranes. The current domestic annual electrochemical markets are worth nearly $30 billion, excluding corrosion. Within a decade, substantially greater sales are anticipated for batteries, fuel cells, semiconductors, sensors, corrosion control, and membranes. Estimates of these markets project an additional $20 billion annually. Further, the introduction of new technology could slow the current trend to offshore electrochemical production of metals and chemicals and electroplating, which are major markets.

The impact of electrochemical technology is seen in three areas. The first involves the economic value of materials produced by electrochemical methods. A summary of market estimates are featured in the tables as well as Figure 1. The dollar amounts represent conservative dollar values since only a few selected markets were....

<table>
<thead>
<tr>
<th>Product</th>
<th>Domestic Production (thousands of tons per year)</th>
<th>Approximate Price per Ton ($)</th>
<th>Annual Market ($ billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>4,000</td>
<td>1,000</td>
<td>4.0</td>
</tr>
<tr>
<td>Caustic</td>
<td>13,000</td>
<td>250</td>
<td>3.3</td>
</tr>
<tr>
<td>Chlorine</td>
<td>12,000</td>
<td>200</td>
<td>2.4</td>
</tr>
<tr>
<td>Copper (Electrolytic)</td>
<td>1,500</td>
<td>1,500</td>
<td>2.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>130</td>
<td>2,500</td>
<td>0.3</td>
</tr>
<tr>
<td>Soda Ash</td>
<td>8,300</td>
<td>100</td>
<td>0.8</td>
</tr>
<tr>
<td>Zinc (Electrolytic)</td>
<td>260</td>
<td>1,000</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>13.3</strong></td>
</tr>
</tbody>
</table>
Electrochemical production of metals and chemicals

Electroplating

Batteries

Semiconductor production and processing

Sensors

Fuel cells

Corrosion control

Membranes

Figure 1. Summary of electrochemical product and device market values in the United States.

evaluated. Estimates were based only on verifiable sales, and dollar values were assigned to the product just after electrochemical processing. The second area of impact involves contribution to the success of other industries or products that have a socioeconomic relevance far greater than the dollar value of associated electrochemical processes. For example, automobiles cost more than 100 times the price of the battery, but the battery permits easy, reliable starting—thus enabling a convenient mode of transportation for normal lifestyles.

Electrochemical processing and production of semiconductors leads to even greater market leverage in the case of microelectronic devices. The final area of impact represents socially important aspects that are impossible to quantify. For example, the "value" of electrochemistry to medical science greatly exceeds its dollar market size.

OPPORTUNITIES IN PARTICULAR TECHNOLOGIES

Chapter 5 of NMB report describes opportunities for research and development where advances in electrochemical devices and processes will probably have a significant economic impact in the near term (less than 10 years). The reported R&D opportunities include:

- **Batteries and Fuel Cells**—Technical requirements are documented for advanced applications in ground-based vehicles, space and central electric utility systems, communication systems, medical applications, and weapons. Associated research and development topics are summarized.

- **Biomedical Science and Health Care**—Electrochemical processes characteristic of living systems are reviewed, including such aspects as applications based on neuroscience, enzyme biocatalysis, adhesion and cell fusion, and electrophoresis.

- **Coatings and Films**—Most paints and coatings degrade by a photoelectrochemical mechanism. Applications are summarized that include protective coatings for automobiles, encapsulants for microelectronic devices, electrocatalysts, and microencapsulation techniques for controlled release of electroactive components.

- **Electrochemical Corrosion**—Under the auspices of the committee, a panel was formed to conduct a critical evaluation of issues and oppor-