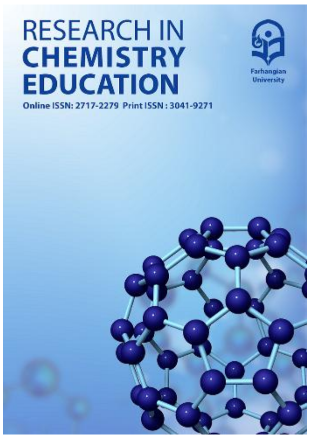
Research in Chemistry Education (2026), Volume 8, Issue 2. Pages 1-23.
Print ISSN: 3041-9271
ISSN (Online): 2717-2279

Received: 12 May 2025
Revised: 03 August 2025
Accepted: 15 September 2025
Published: 22 June 2026

Designing STEM-based interactive educational content on electroplating subject

1. Masoumeh Ghalkhani *: Department of Chemistry, Faculty of Science, Shahid Rajaee Teacher Training University, Tehran, Iran
2. Fatemeh Sabahi: Department of Chemistry, Faculty of Science, Shahid Rajaee Teacher Training University, Tehran, Iran

*Corresponding Author's Email Address: ghalkhani@sru.ac.ir



How to Cite: Ghalkhani, M.; Sabahi , F. (2026). Designing STEM-based interactive educational content on electroplating subject. *Research in Chemistry Education,* 8(2), 1-23.

DOI: 10.48310/chemedu.2025.19375.1334

Abstract:

Background and Objective: The objective of the current investigation is to design a skill training activity in applied chemistry employing a science, technology, engineering, and mathematics (STEM) approach for undergraduate students majoring in chemistry, concentrating specifically on electroplating, with the intent to enhance scientific literacy, foster awareness, and cultivate a practical attitude towards chemical industrial activities. **Materials and Methods**: This investigation is characterized as applied in nature, regarding its objectives, the process of data collection employed to fulfill the aims, research inquiries, and essential information is predominantly bibliographic. Based on the collected information, educational content was developed to teach the topic of electroplating. **Findings**: Initially, the various applications, coating methodologies, and the historical development of the electroplating sector were explicated. Subsequently, the foundational principles of electroplating were systematically examined under the titles of copper and nickel-plating, sequentially. The concluding segment of the instructional material was devoted to the design of an electroplating system by the learner. This section was designed in such a way that the learner could create and test the electroplating system based on the theoretical and practical foundations presented in the first two sections of the content. At this stage, the learner reaches the skill of hands-on practice. **Conclusion:** Combining the topic of electroplating with a STEM approach can create motivation and interest in chemistry students and make them more scientifically and practically prepared to enter a teaching or industrial job.

Keywords: Chemistry education, STEM, Electrochemistry, Electroplating, Content design

Introduction

Most people, including students, see their lives as being separate from science, and the reasons for this include a lack of attention to basic sciences, inconsistency between learners' daily life experiences and science, and a lack of proper understanding of concepts (Mani, 2013). Chemistry plays a key role in science and technology and in explaining various phenomena. However, the existence of complicated and abstract concepts in chemistry and the difficulty of understanding concepts by learners have rendered chemistry lessons difficult and challenging for learners (Moradpour, 2019). The acquisition of knowledge is not a linear event but an organic process of development. Much like growth, it is defined by continuity; each stage builds upon and is inherently connected to what came before, while simultaneously shaping what is to come. The process of learning is inherently cumulative, drawing its form and substance from the learner's personal history. Consequently, pedagogical effectiveness hinges on ensuring that new instructional content is contextually relevant and appropriately situated within the learner's present sphere of experience (Kuhy Fayeq and Shah Mohammadi Ardebili, 2011). Effective learning, as the central aim of education, is predominantly mediated through educational content. This intrinsic link elevates content from a mere resource to a foundational pillar of the curriculum, making its judicious selection and sequencing a primary concern in educational planning (Safavi, 1999).

Research background

Pedagogically, electrochemistry is often identified as one of the most cognitively demanding areas within the chemical sciences. Despite this inherent learning difficulty, its inclusion in core education is strongly justified by its extensive industrial applicability—spanning from production and recycling to sensing and corrosion control (Khosravi, 2013). As the frontiers of science advance, embedding this key discipline, which explores reactions between electricity and chemistry (Abdollah Mirzaei, 2013), into curricula becomes not just beneficial, but imperative (Abdollah Mirzaei, 2013).

Electrochemical oxidation and reduction are characterized by the consumption or production of electric current. A key technological application of this principle is electrolysis, where electrical energy drives non-spontaneous reactions such as the metallic deposition used in industrial plating (Rohana & Sanaria, 2017). Plating serves as a critical method of cathodic protection, dramatically mitigating the economic and material losses from corrosion. Its economic and environmental logic is powerful: by plating a thin, resistant metal layer onto inexpensive substrates like iron, manufacturers reduce costs, conserve scarce mineral resources, and enhance product properties like durability and finish. Since corrosion directly impacts national capital and industrial sustainability, its mitigation through techniques like plating justifies a dedicated place in educational content. This instruction should be context-sensitive, tailored to a region's specific industrial and geographical realities (Sofian & Mirnezami, 2013). Therefore, this study seeks to build a novel interdisciplinary connection between industrial electrochemistry and pedagogy. The goal is to formulate an integrated technical-scientific framework that actively stimulates and refines conceptual understanding and practical research in this vital applied field.

Effective education in industrial electrochemistry requires a pedagogical shift that addresses its inherent complexity while highlighting its critical applications. The STEM (Science, Technology, Engineering, and Mathematics) framework offers a robust solution. By design, STEM education moves learners from theoretical concepts to applied problem-solving, fostering the deep, meaningful learning necessary to master difficult subjects (Ahmadi et al., 2023). This method not only builds scientific skills (Zakaria, 2012), but also is uniquely targeted at aligning academic outcomes with workforce needs (Tantari, 2014). Its effectiveness depends on embedding learning within the context of real-life challenges (Ra Madani, 2016), a prerequisite for true understanding (Chenkaf & Soukhamek, 2019). The topic of electroplating presents an ideal vehicle for this approach. As a pivotal anti-corrosion technique and a final, indispensable step in manufacturing, it embodies the practical importance of electrochemistry. However, its current treatment in curricula is often inadequate. To bridge this gap, we propose the systematic creation of new educational materials. These resources should employ a STEM-based design to teach the scientific principles, technical practices, and environmental considerations of industrial plating, thereby developing essential competencies and making advanced chemical concepts both accessible and relevant to students' future.

The present study is applied research in terms of its purpose. The data collection method is a library research method. The aim of the present study is to design an educational activity with a STEM approach for the topic of electroplating for undergraduate chemistry students.

Findings: In the following, you can see the designed content.

Designing STEM-based interactive educational content for teaching electrochemical plating

Figure 1- William Bloom[1]

The foundational principles for effective training in the electroplating industry were articulated early on by William Bloom. Speaking at the 50th anniversary of the National Association for Surface Finishing (NASF), Bloom (1959), the inaugural recipient of the NASF Scientific Achievement Award, observed that mechanization does not eliminate the need for a deeply knowledgeable workforce capable of supervising complex processes. He advocated for practical, accessible education, stating that even basic laboratory setups with small tanks are adequate for conveying core operational principles—a crucial point for resource-constrained educational institutions. For Bloom, the learner's intrinsic motivation and perseverance were paramount, especially for those balancing study with work. He also framed instructor competency in dual terms: a firm grasp of industrial applications must be coupled with the pedagogical enthusiasm necessary to inspire and retain students, highlighting a holistic view of vocational education that remains relevant.

Think 1

Look at theset of images provided below.

What common feature do you notice in all of them?

What process has made them look like this?

Are you familiar with the scientific term for this phenomenon?

---

[1] https://www.electrochem.org/blum

Corrosion

Corrosion is defined as the deterioration of a material, typically a metal, caused by chemical or electrochemical reactions with its environment. While this degradation process can affect all materials, the term is most frequently applied to metals due to their significantly higher corrosion rates compared to non-metals like plastics, wood, or stone. A common example is the rusting of iron, which produces a characteristic reddish-brown oxide layer. Figure 2 illustrates this concept: a metal component corrodes when exposed to environmental factors such as moisture and oxygen, whereas a component protected by an anti-corrosion coating remains largely unaffected.

Figure 2 - Demonstrated efficacy of a protective coating in preventing corrosion on a metal screw (2004, EcoCortec Corporation)

- Corrosion is a spontaneous process that leads to the production of more stable species in terms of energy level.

The corrosion of metals is a continuous chemical process wherein metals react with environmental agents to form more stable compounds. A classic example is the rusting of iron, where iron metal, oxygen, and water react to produce iron oxide. Similarly, other metals may convert to oxides, sulfides, or carbonates. This transformative process begins at the metal's surface and gradually penetrates its bulk. However, because corrosion advances at a slow rate, it is possible to implement strategies to mitigate or prevent it.

Protective Coatings

The application of protective coatings is a primary method for preventing the corrosion of parts and equipment, serving critical functions in protection, aesthetics, and safety. Achieving a high-quality coating that performs these functions, however, is fundamentally dependent on the condition of the underlying metal surface. Consequently, proper surface preparation through a series of mechanical and chemical pre-treatment operations is an essential prerequisite to the main coating process to ensure optimal adhesion and longevity.

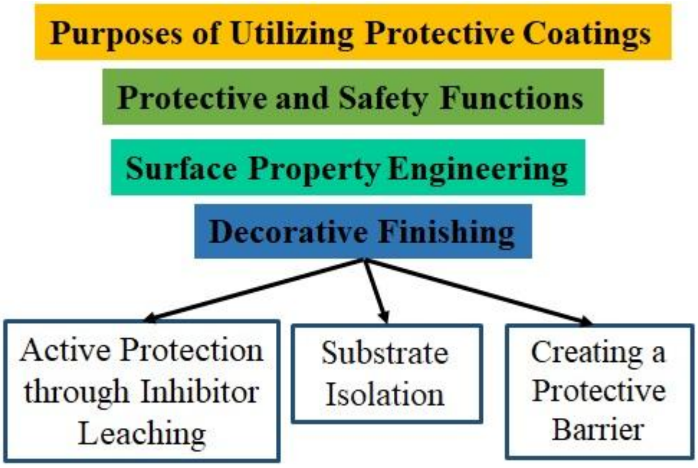


Figure 3 - Coating objectives on metals

Think 2

Potpuna zaštita od korozije, opća brošura, St. Paul, 2004.

https://classifyingmatter.weebly.com/chemical-properties.html

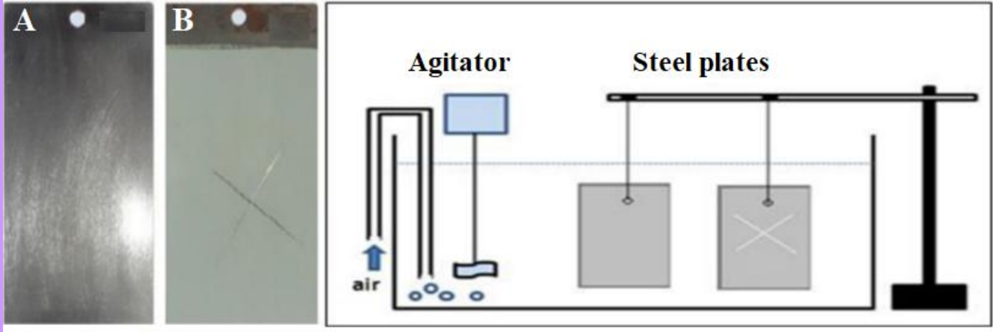
Look carefully at the images above:

- Compare the tools in each image.
- What changes do you see?
- Why do you think these changes have occurred?
- What are the uses and benefits of making these changes to the tool above?

Think 3

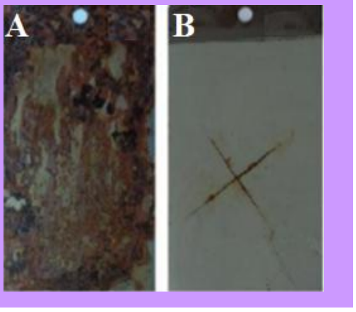
Two carbon steel plates—one coated with copper (Figure B)—are placed in a sodium chloride solution (representing seawater) within a 50-liter container (Mainier, 2013).

Note: On a copper-plated screen, we will make a cross-shaped scratch from the very beginning.



1) What changes are anticipated for each plate after a 15-day period?
2) Which factors are likely responsible for these changes?
3) Explain the mechanism by which these factors affected the plates.

The image opposite shows the same plates after three days.



4) What changes are observable?
5) Was your initial prediction regarding the changes, correct?
6) What differential effects are observed after 15 days between the copper-coated and uncoated steel plates?

7) After 15 days, what differential effect is observed at the site of the cross-shaped scratch on the copper-coated steel plate relative to the intact–coated surface?

8) What is the probable cause or mechanism underlying this observed difference?

9) Based on the observations, what correlation can be inferred between the presence of the copper coating and the subsequent changes?

Coating Methods

The primary functions of industrial coatings encompass corrosion inhibition, aesthetic enhancement, and safety assurance. Consequently, the metals prevalent in daily use and engineering applications are almost invariably coated. Diagram 1 provides a classification of the prevalent methods employed for industrial coating application.

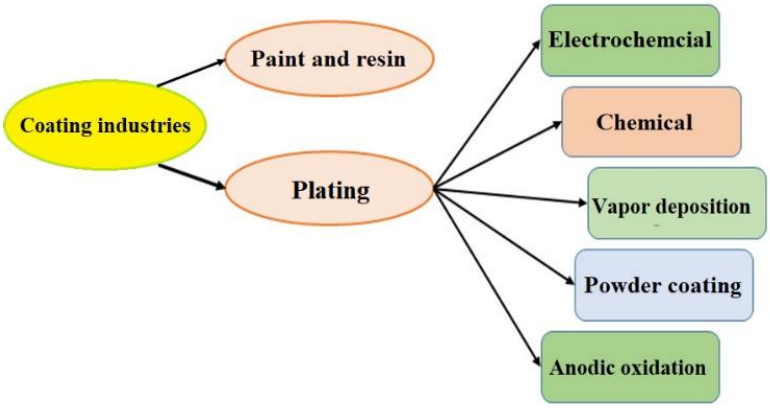


Chart 1 - Types of coating methods

This section examines the initial technique: electrochemical plating (also known as electrochemical metal deposition). The primary objective of this process is to form adherent metallic layers on a target substrate, thereby enhancing its surface properties—including chemical resistance, mechanical strength, and physical characteristics. Achieving an optimal and durable coating requires precise control over deposition parameters. Consequently, a thorough understanding of the fundamental principles of electroplating and the governing electrochemistry is essential. This knowledge enables the accurate application of the process to deposit high-performance, long-lasting coatings onto selected surfaces.

Electrochemical deposition serves to apply adherent metallic layers onto substrates, thereby enhancing their surface characteristics, including chemical stability, mechanical durability, and physical attributes. Achieving an optimal coating requires precise control over deposition parameters, which ensures long-term stability and performance. Consequently, successful application of this technique necessitates a comprehensive understanding of both **fundamental plating principles and the underlying laws of electrochemistry.** This knowledge base is essential for the accurate deposition of high-quality, functional coatings on target surfaces.

History of the electroplating industry

The Parthian Empire, a major Iranian power, established one of antiquity’s largest empires, notable for its role as a custodian of the diverse cultures within its domain. Archaeological evidence, including numismatic items, rhytons, and ceramic shards, attests to their advanced civilization. A pivotal discovery occurred in 1936 near a former Parthian capital, where excavators unearthed enigmatic artifacts such as pottery vessels, copper cylinders, and iron implements. Subsequent analysis led researchers to identify these objects as primitive galvanic cells, positing their use in electrochemical metal deposition—a finding that positions the Parthians as early pioneers of electroplating technology.

Scholars have noted the exceptional quality of Parthian gilding. Following the Mesopotamian conquest in 141 BCE, they became renowned masters of the craft, applying gold layers of remarkable purity and brilliance. As noted in a 1986 electrochemistry review, replicating such quality today necessitates advanced electrochemical methods. The so-called 'Parthian batteries' (see Figures 4 & 5)—typically comprising an earthenware jar, a copper cylinder, and an iron rod—are hypothesized to have facilitated processes like gilding silver or plating copper onto iron.

Beyond metallurgy, scholarly discourse suggests these ancient cells may have served therapeutic purposes. Given their low voltage output and the historical-medical context of the region, some researchers hypothesize they were employed in electrotherapy, drawing a functional parallel to certain modern medical applications of electricity.

Figure 4- Parthian Battery[1]

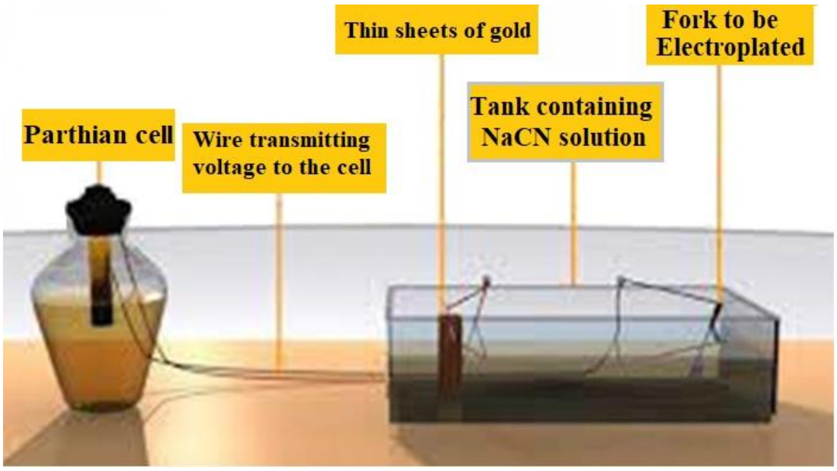


Figure 5 - Using a Parthian cell for electrochemical plating

---

[1] https://www.dawn.com/news/1105019

Applications of Electroplating

Where is electroplating used? Electroplating is a ubiquitous and critical technology in advanced manufacturing. Its primary applications are functional rather than decorative, with extensive use in the production of electronic components, communication hardware, and precision machinery parts. As the plating is often applied to internal surfaces, its role is frequently concealed within the final product. Despite this invisibility, electroplating is an integral, foundational technology that underpins countless aspects of modern industrial output and daily life.

Table 1- Applications of Electroplating

Improve the appearance of the piece	The objectives of electroplating extend beyond corrosion prevention to include significant aesthetic enhancement. In some applications, such as the gold plating of costume jewelry, the primary purpose is purely decorative, involving the application of a thin, visually appealing metallic layer to a base substrate. More commonly, however, electrodeposition serves a dual or multifunctional purpose. In these synergistic applications, the coating simultaneously improves the component's visual appeal and provides essential protective properties, such as corrosion and wear resistance. This combination is critical in consumer goods like watch cases, automotive trim, and plumbing fixtures, where surface durability and appearance are paramount.
Increased electrical conductivity	Copper's high electrical conductivity makes it indispensable in electrical components and circuitry. However, its surface is prone to forming a non-conductive oxide layer over time, which significantly increases contact resistance at critical points such as solder joints and connectors. To mitigate this issue in high-reliability applications, a thin layer of gold is often electroplated onto the copper surfaces. This gold coating prevents oxidation and maintains optimal electrical conductivity and connection integrity in sensitive devices.
Creating surface properties	Beyond the protective and conductive properties previously discussed, electroplating is a versatile surface engineering technique capable of imparting a wide range of functional characteristics. A prime example is the enhancement of optical reflectivity. For this purpose, silver is frequently electrodeposited to create highly reflective coatings, utilized in applications such as mirrors, searchlights, and specialized optical components where high light reflectance is critical.
Increased mechanical strength	In some cases, the surface of a part needs to be more resistant to wear. In this case, electroplating with nickel or chromium is employed to enhance surface hardness and wear resistance.

Think 4

While corrosion rates in the food industry are typically low, any occurrence is unacceptable. How can corrosion inside food storage cans be prevented?

Electrochemical Plating

Electrochemical plating is a process that utilizes an external voltage to drive oxidation and reduction reactions, resulting in the deposition of a coating on a substrate. This direct current can be supplied by a battery or a rectifier. The conductors that deliver this current into the solution are known as electrodes.

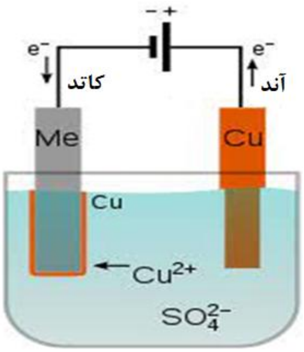


Figure 6- Electrolytic cell (2023, El-Awadi)

- Both electrochemical deposition and coating processes are performed using electrochemical reactions, but have different goals and processes.

Electrochemical deposition is defined as the process where ions in an electrolyte solution are deposited onto an electrode surface via an applied external voltage. This technique has two primary applications: metal plating and the recovery (extraction and purification) of metals from their mineral salt solutions. A fundamental example is the deposition of copper ions from a copper sulfate solution onto a copper cathode. When performed specifically to create a protective or functional coating, the process is termed electroplating. Key advantages of this method include precise control over layer thickness and composition, as well as the ability to use additives for enhancing coating properties like corrosion resistance. Practical applications include chromium plating on steel for wear resistance and gold plating on electronic components to ensure conductivity and prevent corrosion. Conceptually, deposition is the broader term encompassing any formation of a deposit, even non-adherent ones. Electroplating, however, is a subset of deposition characterized by intentional adhesion to the substrate and a clear engineering or functional purpose.

In the plating process:

The electrode connected to the positive pole of the battery, where the oxidation half-reaction takes place, is called the anode.

The electrode connected to the negative pole of the battery, where the reduction half-reaction takes place, is called the cathode. An electrolyte is a solution containing positive and negative ions, within which the anode and cathode are immersed.

The movement, or rather the migration, of positive and negative ions means the passage of electric current through the solution.

The positive ions that migrate towards the cathode are called cations, and the negative ions that migrate towards the anode are called anions.

Research: What are the purposes and benefits of electroplating metal kitchen appliances, and which metals are commonly selected as coatings?

Research: Research the uses of different metals for plating and their properties and present the findings in a table.

Noble metals

Noble metals are characterized by their resistance to oxidation and corrosion in moist air, as well as their stability against acidic attack. This stands in contrast to base metals, which oxidize and corrode readily. The group is commonly considered to include ruthenium, rhodium, palladium, silver, osmium, iridium, platinum, and gold. Some definitions also encompass copper and mercury (Figure 7). Notably, while copper is physically classified as noble, it undergoes corrosion and oxidation in moist air, rendering it less noble from a chemical perspective.

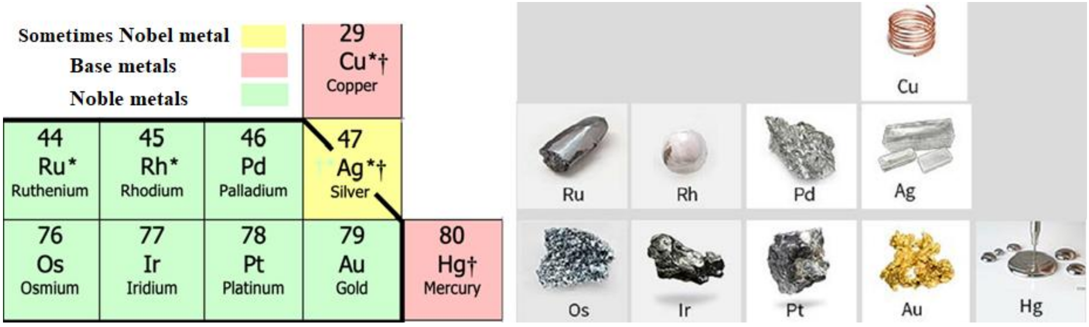


Figure 7- Noble metals

Question:

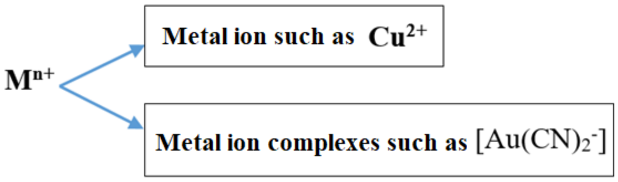
Based on the provided electrolytic cell diagram for electroplating, determine at which electrode (anode or cathode) each reaction occurs.

Answer: $\mathbf{M \rightarrow M^{n+} + ne^-}$ **B)** $\mathbf{M^{n+} + ne^- \rightarrow M}$

In the electroplating process, the metal intended as the coating serves as the anode, where the oxidation half-reaction results in its partial dissolution. $\mathbf{M \rightarrow M^{n+} + ne^-}$

The component to be coated, known as the workpiece, acts as the cathode where the reduction half-reaction takes place, resulting in metal deposition on its surface.

$$\mathbf{M^{n+} + ne^- \rightarrow M}$$



Note: The electrodeposition sequence in a multi-ion solution is governed by standard reduction potentials: the most noble metal cation reduces first. Subsequent deposition of less noble metals occurs only after the former is depleted. A practical concern arises when a metal’s reduction potential approaches that of hydrogen (+0 V), as this leads to parasitic hydrogen evolution at the cathode.

Electroplating Mathematics:

1) Faraday's Equation: In 1883, Michael Faraday—the father of electrochemistry—derived two fundamental laws of electrolysis from his experiments. These laws are encapsulated in the following equation, which calculates the mass of material deposited at the cathode of an electroplating cell.

$\mathbf{m = q/F * M_w/n}$ in this equation:

m	Mass of substance produced/destroyed at the electrode (grams).
q	$\mathbf{q = \mathit{I} \times t}$ The charge transferred (Q, in coulombs) during electrolysis is $Q = I \times t$, where I is the current in amperes and t is the time in seconds.
F	Faraday's constant, which represents the charge of one mole of electrons, is equal to 96,386 (or approximately 96,500) coulombs.
$\mathbf{M_w}$	The molar mass of the substance is expressed in grams per mole (g/mol).
n	The number of moles of electrons used to produce or consume the total mole of the substance in question at the corresponding electrode.

2) Cathode Efficiency Equation:

The observed mass of metal deposited at the cathode is typically less than the mass predicted by Faraday's law. This deviation is quantified by the cathode efficiency. The cathodic efficiency (η) is defined as the ratio of the actual coating mass to the theoretical coating mass:

$$\eta = (m_{actual} / m_{theoretical}) \times 100$$

The theoretical coating mass is the value obtained using Faraday's equation.

Example: Using Faraday's law, determine the mass of copper deposited on the cathode when a current of 50 A passes through a plating bath for 20 minutes. The atomic mass of copper is 63.5 g/mol.

Exercise 1

1) Determine the cathodic efficiency when a current of 500 A is applied for 30 minutes, resulting in an anode mass loss of 250 g.
2) In a copper plating tank containing copper sulfate solution, for copper plating at 15 A for 10 minutes with 100% cathode efficiency:

a) Calculate the mass of copper deposited (atomic mass of Cu = 63.5 g/mol).

b) Given a total plated area of 1500 cm^2 and copper density of 8.93 g/cm^3, determine the average thickness of the deposited layer.

3) Nernst equation

The reduction potential (E) at a concentration C and 25 °C can be calculated using a simplified form of the Nernst equation:

$$E = E^0 + 0.059/n \log C$$

E: the reduction potential at a concentration of C and a temperature of 25°C

E^0: the standard reduction potential

C: the molar concentration of the solution

n: the change in oxidation number

4) Electricity Cost

The electrical energy consumption (in kWh) for electroplating is calculated as W = P × t, where P is power in kilowatts (kW) and t is time in hours (h). This value forms the basis for determining electricity cost.

For electroplating to occur, the applied cell voltage must exceed the theoretical potential difference of the half-reactions. An insufficient voltage prevents deposition, while an excessively high voltage induces parasitic side reactions and energy loss. Although the deposited metal mass is directly proportional to current intensity (from $q = I \times t$), this increase is constrained by a maximum rate of ion deposition, known as the limiting current. Operating at or above this limit yields a non-adherent, powdery, and dark deposit—a condition termed burning.

Note: In electroplating, the parameter **current density (I/A)**—where A is the electrode surface area—is more commonly used than current intensity (I).

Investigate:
To what extent is the pH of the electrolyte linked to burnt coating defects?

Which operational factors lead to powdery or spongy electrodeposits?

How can spongy deposits be avoided when operating at higher current densities?

Investigate:
In the electrogravimetric analysis of a solution containing both copper and nickel ions, the procedure involves sequential measurement. First, ammonium nitrate is added to the solution to facilitate the selective deposition and measurement of copper ions. Subsequently, nitrate ions are removed, and the solution is alkalized with ammonia to enable the measurement of nickel ions. The rationale behind these specific steps requires investigation.

- Note: Electrogravimetry is analogous to electroplating, with the key distinction being the quantitative deposition of the target ion onto the electrode surface.

Reduction potential

In electrolytic processes such as electroplating, the reduction potential of the involved metals is a critical factor. It quantifies the tendency of a metal ion to gain an electron and reduce to its atomic state, as shown in the following half-reaction.

$\mathbf{M^{n+} + ne^- \rightarrow M}$ E= Reduction potential in volts

A **galvanic cell** features a positive standard cell potential (E^o) and a spontaneous reaction, whereas an **electrolytic cell** has a negative E^o and requires an external voltage to drive its non-spontaneous reaction.

Table 2- Comparison of Galvanic and Electrolytic Cells

Electrolytic cell	**Galvanic cell**
Electrical energy is converted into chemical energy	Chemical energy is converted into electrical energy
Non-spontaneous and energy-consuming reaction	Spontaneous and energetic reaction
Cathode: negative pole and anode: positive pole	Cathode: positive pole and anode: negative pole
The oxidation half-reaction occurs at the anode and the reduction half-reaction occurs at the cathode	The oxidation half-reaction occurs at the anode and the reduction half-reaction occurs at the cathode
Electrons are transferred from the anode to the cathode in the external circuit	Electrons are transferred from the anode to the cathode in the external circuit

Example: Considering a standard plating bath with coexisting K^+ and Ni^{2+} ions, determine which metal will be reduced and coat the workpiece surface.

Answer:

$K^+ + e^- \rightarrow K \qquad E° = -2.92\ V$

$Ni^{2+} + 2\ e^- \rightarrow Ni \qquad E° = -0.23\ V$

Nickel has a greater reduction potential than potassium. Consequently, Ni^{2+} ions outcompete K^+ ions for electrons at the cathode, resulting in a nickel coating on the workpiece.

Note: Empirical observations indicate that alkali metal ions like Na^+ and K^+ adversely affect the quality of electrodeposited nickel.

Example: Calculate the reduction potential of copper in a 0.1 M solution at 25 °C.

Solution: The standard reduction potential for copper (Cu^{2+}/Cu) is +0.34 V, and the change in oxidation number is 2. Substituting these values into the simplified Nernst equation gives:

$$E = 0.34 + \frac{0.059}{2} \log 0.1$$

Exercise 2
1- What is the reduction potential of nickel and chromium ions at 25°C with the following concentrations? A) Nickel ions in a 0.01 M solution. B) Chromium ions in a 0.1 M solution.

Different Parts of an Electrochemical Plating Device

The components required for electrochemical plating include the cathode, anode, and electrolyte, which are placed inside an inert container, and the electrodes are connected to a direct current source.

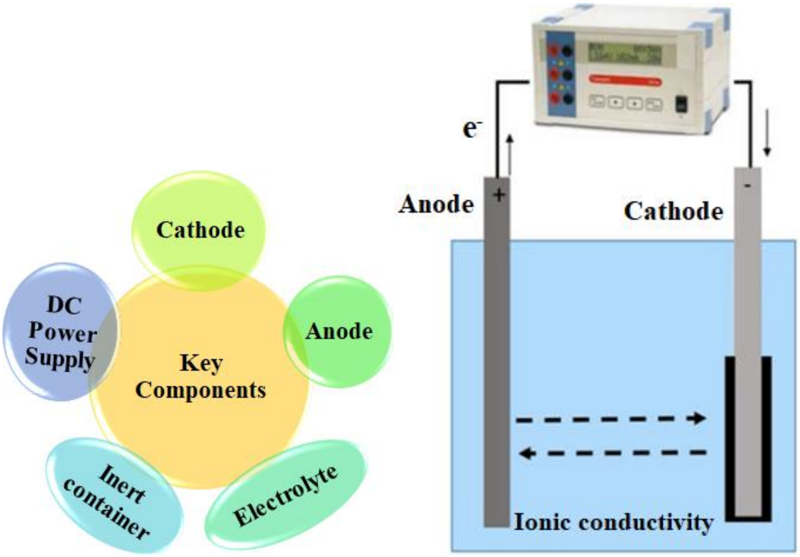


Figure 8 - Different parts of the electrochemical plating machine

Plating Solution

A **plating bath** is an aqueous electrolyte solution containing ions of the coating metal. This solution comprises several key constituents, each imparting specific properties. The primary component is a water-soluble salt of the coating metal, which supplies the ions reduced at the cathode. Additionally, various additives are incorporated, each serving a defined functional role in the process.

Electrolyte components:

1- Metal Ion: The primary component is the metal cation intended for reduction at the cathode. It may be present as a simple ion or within a complex, with typical concentrations ranging from 1 to 3 molar.

2- Buffer: A buffer system regulates the pH of the plating bath. Precise pH control is critical, as a highly acidic pH promotes hydrogen evolution ($2H^+ + 2e^- \rightarrow H_2$), while a highly basic pH favors oxygen evolution ($4OH^- \rightarrow O_2 + 2H_2O + 4e^-$), both of which are undesirable side reactions.

3- Complexing Agents: These agents form coordinated complexes with metal ions. Their primary effects are twofold. First, they lower the cathodic overpotential, reducing the energy required for deposition. This often increases the Tafel slope, slowing the deposition kinetics to produce smoother, uniform coatings. Second, they facilitate the dissolution of an active anode; for example, chloride ions (Cl^-) enhance anodic dissolution.

4- Additives: These substances are incorporated in low concentrations to modify deposit properties and morphology. They are highly diverse and serve specific functions, such as grain refinement, stress reduction, or brightness enhancement (e.g., certain organic compounds like saccharin).

Types of Additives

A. Brighteners (Glossing Agents): These additives are incorporated into the electrolyte to produce a highly reflective, mirror-like finish on the plated part at the microscopic level. By reducing surface roughness, they promote specular light reflection, resulting in a shiny appearance. Brighteners, such as sulfones, aromatic sulfones, or compounds containing CN, CS, or CO functional groups, are typically used in low concentrations (a few grams per liter).

B. Leveling Agents: These agents promote macroscopically smooth and flat deposits. They function by selectively adsorbing onto surface protrusions or high-current-density areas where deposition would otherwise occur more rapidly. By moderating the local deposition rate, levelers ensure a uniform, planar surface.

C. Grain Refiners (Crystalline Structure Improvers): These additives modify the crystal lattice structure of the deposit. They influence grain growth, which can alter the orientation and type of crystal formation, leading to a more optimized microstructure. Furthermore, they help regulate internal stress within the deposited layer, thereby preventing cracks and improving mechanical integrity.

D. Wetting Agents (Humectants): The primary function of these agents is to facilitate the release of hydrogen bubbles from the cathode surface. Hydrogen evolution is a common side reaction during electroplating. If not managed, trapped hydrogen can lead to defects such as porosity, blistering, and hydrogen embrittlement, which causes cracking and reduced ductility. Wetting agents lower the surface tension, reducing hydrogen gas adhesion and promoting its rapid detachment from the electrode.

Electrochemical Plating Deposition Process

When depositing a metal like copper onto a dissimilar substrate (non-copper), the process occurs in two fundamental stages:

Step 1: Nucleation. This initial phase involves the adsorption and reduction of solvated metal cations onto the dissimilar substrate of the cathode workpiece.

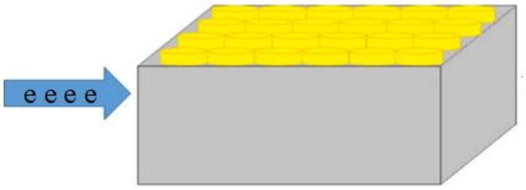


Figure 9 - First stage, nucleation

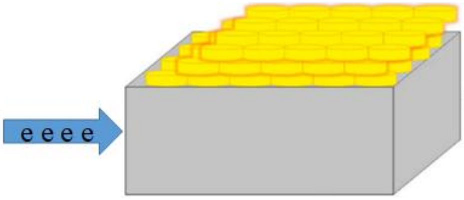


Figure 10 - Second stage, deposition

Suppose we want to deposit Cu^{2+} on a metal object other than copper. The initial reduction of Cu^{2+} ions occurs on a cathode of a different composition. This incompatibility creates a high-energy barrier, requiring an applied voltage significantly above the standard reduction potential to initiate stable nuclei formation. This overpotential is crucial for adhesion. Successful nucleation is critical; unstable or irregular nuclei will prevent the proper formation of subsequent layers, leading to poor adhesion, uneven coating, and eventual peeling.

Step 2: Growth/Deposition Stage

Once a stable initial layer (the first monolayer) is formed, the second and subsequent layers deposit onto it. The growth mode and crystal orientation depend on operational parameters like current density and bath chemistry. Atoms from the solution incorporate into the existing crystal lattice of the initial layer, requiring them to be ‘accepted’ or adsorbed by the underlying atoms to enable epitaxial growth and a coherent, adherent deposit.

Electrochemical Nickel Plating

Nickel plating serves a dual purpose as both a protective barrier and a decorative finish, with its primary industrial value derived from the inherent properties of the metal itself.

Figure 11 - Nickel-plated tool

The Watts bath is a predominant formulation for nickel electroplating, operable in both low and high pH regimes. The following outlines the composition and characteristics of the low-pH Watts nickel bath, which produces a mattte finish.

The electrolyte is based on a solution of nickel sulfate and nickel chloride. The chloride ions serve a critical function: they enable the use of an active (soluble) nickel anode by promoting its dissolution to replenish nickel ions in the bath. Boric acid (typically ~30 g/L) acts as a buffering agent, maintaining the bath pH within an optimal range of approximately 4 to 5.

Standard operating parameters include: Temperature: 40 – 70 °C

Current Density: 20 – 50 mA/cm^2 Cathodic Current Efficiency: ~95%

Common additives to modify deposit properties include coumarin, saccharin, benzene derivatives, and acetylene sulfonamide. As mentioned, the anode consists of soluble nickel pieces, compatible with the chloride-containing electrolyte.

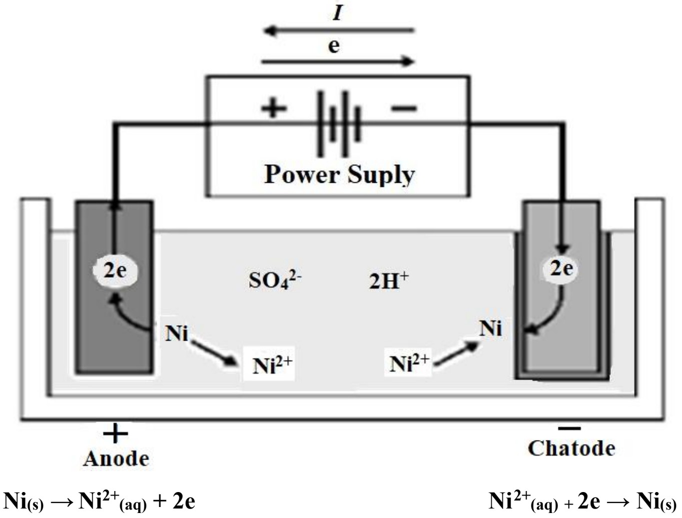


Figure 12 - Nickel plating electrolytic cell[1]

Computer simulation with software

To examine the possibility of chemically plating a metal ion from an electrolyte onto a dissimilar metal piece, it is advisable to first use a simple simulator. For example, visit the website Javalab.org. In the top menu, hover over the Chemistry option, then select Electrochemistry from the dropdown menu that appears below it. This section contains ready-made simulations for numerous reactions. By entering any page, you can easily perform the experiments in the virtual laboratory and observe the results.

Here, select the Activity Series of Metals option. You can also directly access the Activity Series of Metals simulator page by scanning the barcode in Figure 13. In this simulator, the electrochemical potential of metals is compared. By changing both

---

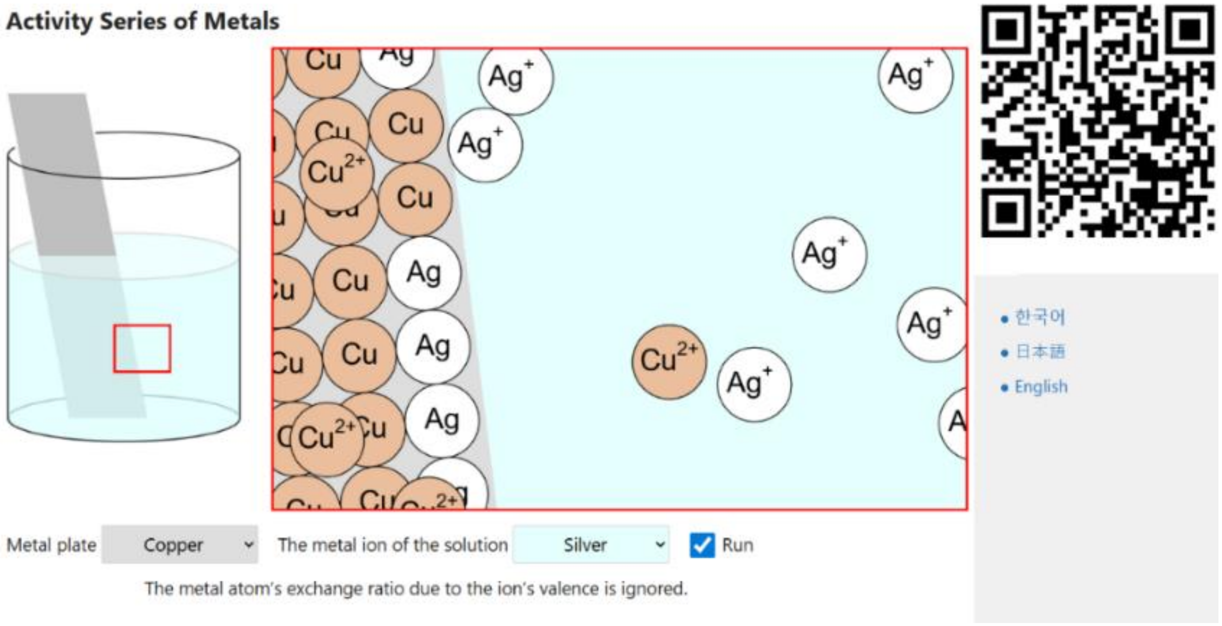
[1] https://blog.naver.com/leesangyu/220373170090

the metal to be plated and the metal ion in the solution, you can easily observe which ion is capable of accepting electrons from the surface of the target metal, thereby being reduced and deposited onto the object.

The tendency of metals to lose electrons and become cations is called the ionization tendency. The higher a metal's ionization tendency, the easier it is to oxidize and the more reactive it is. Conversely, metals with a low ionization tendency have a greater likelihood of being reduced. In other words, such a metal tends to remain in its metallic state. The reactivity of metals can be compared with one another. By placing a piece of one metal into an aqueous solution containing the ions of another metal, if a chemical reaction occurs, it indicates that the reactivity of the introduced metal piece is greater than that of the metal in the solution.

- Now, consider this: if no reaction occurs and you observe no change, which metal is more reactive? Is it the metal of the piece introduced into the solution, or the metal whose cation is present in the solution?

→ **Exercise:** Arrange the reduction potential series of metal ions by selecting the appropriate options in the metal activity series simulator.



Activity Series of Metals

Metal plate: Copper

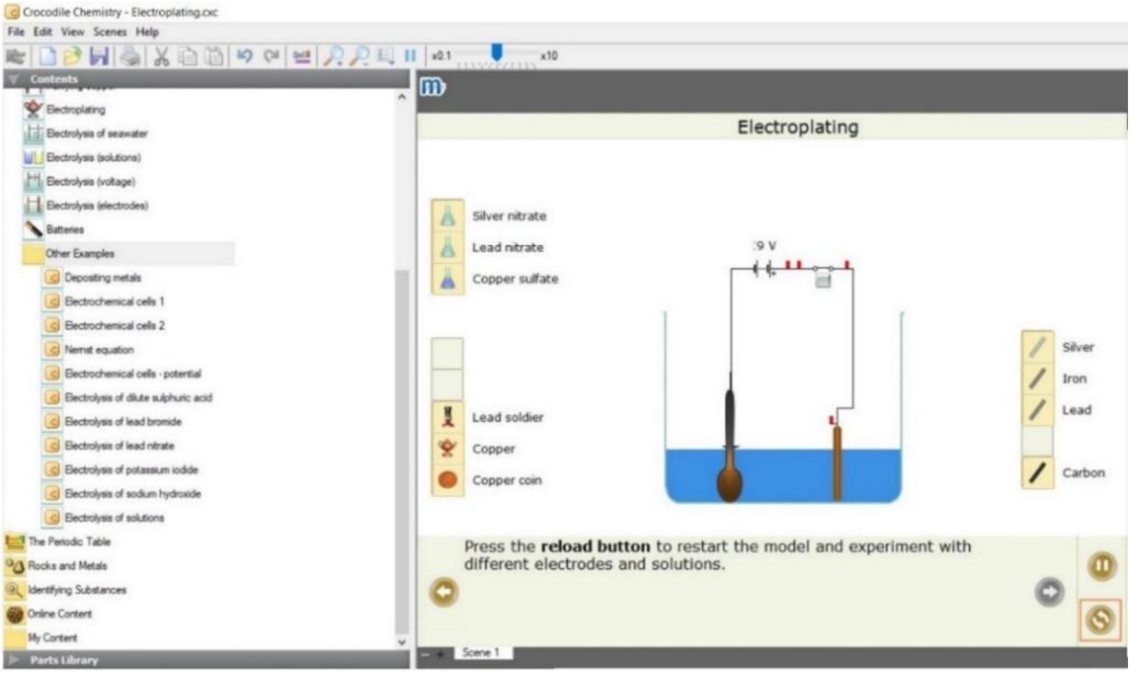
The metal ion of the solution: Silver

☑ Run

The metal atom's exchange ratio due to the ion's valence is ignored.

Figure 13. An example of simulation of silver ion chemical plating on copper metal in the Javalab.org simulator.

- Crocodile software is an effective tool for simulating electrochemical cells. Within the program, you begin by selecting the electrolyte solution and then choose the cathode and anode electrodes, placing them in their respective positions. Upon closing the circuit, the current is established, allowing you to observe the progression of metal deposition onto the target object. In this setup, the metal intended for plating is positioned at the anode (positive terminal), while the object to be coated is connected to the cathode (negative terminal). By modifying parameters such as the electrolyte composition, electrode types, and simulation time, you can investigate the feasibility and extent of the plating process. Figure 14 illustrates a view of the Crocodile simulator workspace. It is recommended to download and install the software and practice using it thoroughly.



Press the **reload button** to restart the model and experiment with different electrodes and solutions.

Figure 14. Simulation of copper plating on a spoon using Crocodile software.

There are various virtual lab simulator software. Search and use them to design a plating process. Log in to the site below or simply scan the barcode in Figure 15 to access the electrochemical plating simulator page.

https://javalab.org/en/electric_plating_en/

- **Exercise:** Observe Figure 15. What process is depicted? Provide a comprehensive explanation of the image. Carefully analyze the type and function of the electrodes, the composition of the electrolyte, the required voltage source, and the identification of the cathode and anode. Write a complete description based on this analysis.
-

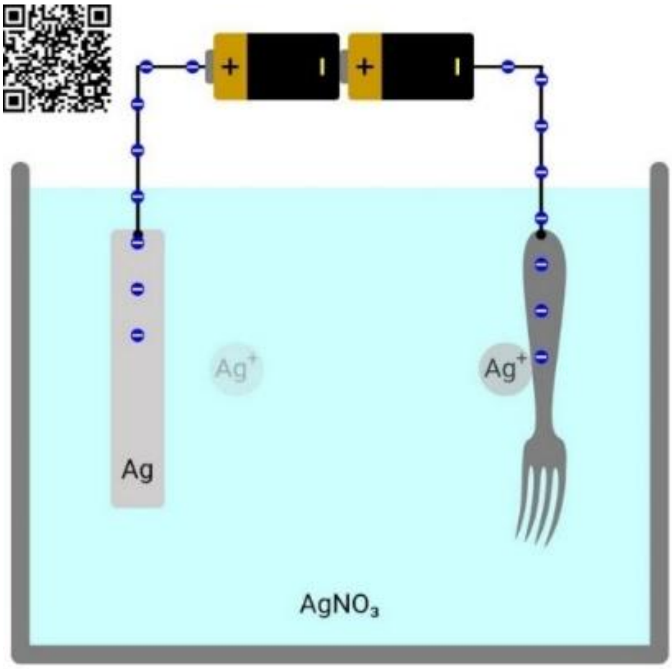


Figure 15. Demonstration of the silver-plating process on a spoon

Educational videos can also be utilized to assist you in the field of electroplating, allowing you to observe the process step by step.

Experiment:

Nickel plating on iron parts

Materials and equipment required: Nickel chloride, nickel sulfate, boric acid, nickel anode, glass stirrer, one-liter and two-liter beaker, 4 iron parts, plating tank, current rectifier, electric heater, thermometer, 10x magnifying glass, lizard clamp and connecting wires.

Composition of low pH Watt-type nickel-plating solution:

Nickel sulfate	330 g/L
Nickel chloride	45 g/L
Boric acid	37.5 g/L

This electroplating bath operates within a pH range of 4.5 to 5.5, a temperature range of 46 to 60 ^{o}C, and a current density range of 2.7 to 10.8 A/dm^2. The pH is maintained by adding boric acid, while the current density is regulated by adjusting the applied voltage and current within specified limits.

Preparation of plating solution:

Procedure:

1- Considering the volume of the plating tank, prepare the required solution in an amount that is equivalent to 3/4 of the tank volume.
2- Weigh the ingredients required for preparing a low pH nickel-plating solution for a given volume.
3- Pour distilled water into a beaker at a rate of half or three-quarters of the required solution volume and heat it on an electric heater to 50 ^{o}C and dissolve boric acid in it.
4- Dissolve the other two salts completely in the solution and stir.
5- While the solution is on the heater, gradually add hot distilled water to it while stirring until it reaches the required volume for plating.
6- Now, pour the solution into the tank and set the heater to 50-55 ^{o}C, observe and control the temperature. The plating solution is ready to use.

Nickel plating on iron parts:

Procedure:

1- Remove the four prepared iron parts from the drying stage.
2- Subject the parts to a sequential cleaning process: first organic degreasing, then alkaline degreasing, followed by acid pickling (or an equivalent method), and finally chemical etching.
3- Rinse the parts with water and dry them thoroughly after each stage.
4- Secure the prepared iron parts to the cathode (negative terminal) using suitable wire and clamps. Similarly, attach the nickel pieces to the anode (positive terminal).
5- Activate the direct current power supply. Gradually increase the voltage until a slow evolution of small bubbles from the anode surface is observed.

Note: To optimize the process, calculate the current density. Read the current on the ammeter, determine the part's submerged surface area in square decimeters, and divide the current by this area. If the calculated current density falls outside the specified range, adjust the voltage and current accordingly to bring it within the target parameters.

6- During plating, key parameters—pH, solution temperature, and current density—may drift. Gently agitate the solution to minimize localized temperature and concentration gradients. Monitor the pH every ten minutes and adjust as necessary using boric acid.
7- Plate the parts for different durations: plate one piece for 5 minutes, two pieces for 10 minutes, and the final piece for 20 minutes. Upon completion, rinse and dry all parts.

Drying Electroplated Parts

Following the electroplating process, residual electrolyte solution adheres to the coated part. This solution is removed by immersion in a water rinse. Failure to rinse thoroughly is critical, as leftover acidic or alkaline compounds can induce corrosion and pitting on the substrate.

Quality Implications and Solutions:

- Effect of Water Stains: If rinse water is allowed to dry and leave stains on the surface, it can result in water spots, localized tarnishing, and an uneven final appearance, compromising the aesthetic and functional quality of the plating.
- Recommended Drying Method: Proper drying after the final water rinse is essential to prevent such water-marking. While hot air or lint-free cloths are common, one unconventional, yet effective method is to immerse the part in a container of desiccant corn cobs, which absorb moisture without physical contact that could scratch the soft, fresh deposit.
-

Figure 16 - Corn cobs[1]

---

[1] https://www.americanplatingcompany.com/metal-plating-drying-process

- It may sound a little strange, but how many people do you know who use corn cobs for drying?

Benefits of drying with corn kernels

This method, while unconventional, offers several practical advantages based on industrial case studies:

The use of finely chopped corn cobs as an absorbent drying medium offers distinct practical benefits. The material is low-cost and reusable. It repurposes an agricultural by-product that might otherwise go to waste. Furthermore, unlike cloths, the medium requires no laundering, simplifying maintenance and operation.

Safety Tips in the Electroplating Industry

Adhering to safety protocols when handling chemicals and electrical equipment is paramount:

* Strict safety protocols are vital in the electroplating environment, which combines chemical and electrical hazards.

⁕ Essential personal protective equipment (PPE) includes appropriate work clothing, safety shoes, chemical-resistant gloves, protective goggles, and, where necessary, respirators.

* This equipment minimizes risks from contact with corrosive chemicals, solution splashes, or inhalation of fumes.

Laboratory safety

Figure 17 - Essential safety equipment for the plating process

Environmental Impacts of the Plating Industry

The environmental issue is one of the most important issues in the sustainable development of any country. On the other hand, the plating industry, despite its widespread use in daily life and various industries, is considered one of the main industries that pollute the environment. Plating processes threaten the environment by polluting water, air, and soil. For this reason, its processes and pollution must first be identified and then pollution reduction strategies must be examined. In this regard, optimizing current processes or replacing them with new methods to reduce or eliminate pollution are considered the main strategies. Plating industry wastewater contains various harmful substances such as acidic and alkaline substances, heavy metal compounds, and other toxic chemicals such as cyanides. If these substances enter the environment directly, they cause pollution and serious problems such as the following:

Environmental protection is a paramount concern for the sustainable development of any nation. The plating industry, despite its widespread application in daily life and various sectors, is recognized as a significant source of environmental pollution. Plating processes threaten ecosystems by contaminating water, air, and soil. Consequently, it is essential to first identify these processes and their pollutants, and then examine strategies for pollution reduction. In this context, optimizing existing methods or replacing them with new, cleaner technologies to mitigate or eliminate contamination are primary strategies.

Wastewater from the plating industry contains various harmful substances, including acidic and alkaline compounds, heavy metals, and toxic chemicals such as cyanides. If discharged without adequate treatment, these pollutants cause severe environmental and public health problems, such as the following:

- Contamination of water and soil with persistent heavy metals like chromium, nickel, and cadmium, which can accumulate in ecosystems and enter the food chain.
- Toxicity to aquatic life and human health from cyanides and complexed metal cyanides, which can be lethal even at low concentrations by inhibiting cellular respiration.
- Long-term environmental damage and costly remediation of historical contamination sites, which pose ongoing risks to groundwater and soil

Figure 18 - Environmental impacts of the electroplating industry (2021, Velusamy)

- **The bottom line:** Electrochemical plating serves as a window into applied chemistry. Through carefully designed interactive content, this abstract concept can be transformed into a tangible and memorable learning experience.

Conclusions

This study, acknowledging the industrial significance of electroplating, aimed to design effective educational content within a STEM framework. The objective was to equip learners with a deep, practical understanding of the electroplating process—including its advantages, disadvantages, and environmental impacts—while fostering appreciation for this valuable modern technology.

Conflict of Interest

No conflict of interest has been declared by the authors.

Acknowledgements

This research was conducted with the financial support of Shahid Rajaee Teacher Training University according to Grant No. 1404/391033 dated 1404/03/17.

References

Abdollah Mirzaei, Rasoul. (2013). *A Brief Look at Research in Chemistry Education*, First Iranian Electrochemistry Education Conference, Tehran, Shahid Rajaee Teacher Training University.

Ahmadi, Z., Sabbaghan, M., Ghalkhani, M. (2023). Integration green chemistry and STEM in battery education for chemistry student, *Chemistry Research*, *1401* (5), 215-223. https://doi.org/10.22036/cr.2023.304324.1156

Blum, W. (1959). Annual Technical Proceedings of the American Electroplater's Society, 46, 39-42

Chonkaew, P. Sukhummek, B. (2019). STEM activities in determining stoichiometric mole ratios for secondary school chemistry teaching, *Jornal of chemical education, 96* (6), 1182-1186. DOI: 10.1021/acs.jchemed.8b00985

EcoCortec Corporation: Potpuna zaštita od korozije, opća brošura, St. Paul, 2004.

El-Awadi, G. A. (2023). Review of effective techniques for surface engineering material modification for a variety of applications. *AIMS Materials Science 10*(4), 652-692. DOI: 10.3934/matersci.2023037

https://blog.naver.com/leesangyu/220373170090

https://classifyingmatter.weebly.com/chemical-properties.html

https://en.wikipedia.org/wiki/Baghdad_Battery

https://www.americanplatingcompany.com/metal-plating-drying-process

https://www.dawn.com/news/1105019

Khosravi, M. (2013). *Aligning Electrochemistry Education in Schools with Industrial Needs*, First Iranian Electrochemistry Education Conference, Tehran, Shahid Rajaee Teacher Training University.

Kouhi, F. A, Shahmohammadi Ardebili, M. (2011). Misconceptions and alternative concepts in learning water properties. The 7th Iranian Chemistry Education Conference. Zanjan, Iran.

Mainier, F. B., Monteiro, , Rocha, A. C. M., Mainie, R. J. (2013). Industrial electrochemical: a new teaching approach , *American Journal of Engineering Research* (AJER). *2*(8), 58-64.

Moradpour, S. (1398) Content analysis of electrochemical concepts presented in the 12th grade chemistry textbook based on the principles of green chemistry and bloom's taxonomi, Master's thesis, Shahid Rajaee Teacher Training University, Iran

Potpuna zaštita od korozije, opća brošura, St. Paul, 2004.

Rahmadani, D. (2016). *short analysis review of developing method study in integrating science, technology, engineering and mathematics (STEM) approach in problem-based learning model towards students' problem-solving ability*, 1st international conference of mathematics and science education, Bandung, vol. 57, pp. 140-142.

Rohana, N., Sanarya, Y. (2017). *Electrolysis practice optimization in electroplating process to develop student's worksheet based on learning cycle 7E*, in international conference on education and science, Bandung.

Safavi, A. (1999). Generalities of Teaching Methods and Techniques, 2nd edition. Tehran: Moaser Publications.

Soufian, M., Mirnezami, M. (2013). *Chemistry Education and its Role in the Electroplating Industry*, 8th Iranian Chemistry Education Seminar, Semnan, Semnan University of Chemistry.

Tantri, M. (2014). *Learning effect of integrated science, technology, engineering and mathematic (STEM) on learning outcomes*, proceedings semnas VI, the role of science literacy'.

Velusamy, S., Roy, A., Sundaram, S., & Kumar Mallick, T. (2021). A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment. *The Chemical Record, 21*(7), 1570-1610. DOI: 10.1002/tcr.202000153

Zakaria. Z, (2012). *Organic chemistry practice for undergraduates using a small lab kit*, Procedia-social and behavioral science, vol. 59, pp. 508-514. https://doi.org/10.1016/j.sbspro.2012.09.307

Zamani, N. (2013). Determining the conceptual map of misconceptions about the structure of the atom. Master's thesis. Shahid Rajaee Teacher Training University.