

Teacher's Guide to the PalmSens Educational Kit

A general introduction,
information, and instructions
for experiments

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2 Introduction

2.1 Why Electrochemistry?

Electrochemistry is a versatile discipline that has applications in various fields of research and industry.

Corrosion research develops methods to save millions of Euros that are needed to remove the damage done by corrosion. Electrochemistry delivers the insights about the processes causing corrosion and is capable to investigate means against corrosion in hours instead of weeks. Although these experiments cannot replace the long-term tests under real conditions, they can provide the knowledge for a fast pre-selection of approaches that should be investigated more closely.

Another big field of electrochemistry is energy conversion. Rechargeable batteries have been important for portable technologies for quite some time, but since the boom of the mobile internet, the limitations of batteries have become the limitations of our society. The electric cars, which presence are in a steep growth in many countries, only makes sense if we have batteries with enough capacity to drive hundreds of kilometers without recharging and this process must also be optimized and quick. Either that or we need another electrochemical device, the fuel cell, to power the cars and reduce the request for fossil oils. In the same context solar panels are important to gain energy from a sustainable source, the sun. The electrochemistry of photovoltaics is providing important knowledge to improve solar panels and brings the idea to satisfy our energy demand with solar power within our reach.

In analytical chemistry, electrochemistry makes miniaturized devices that deliver a quantitative result in the ppb range possible. These devices are easy to handle point-of-care devices. Electronic components are very suitable for mass production and therefore these devices are also affordable. The most known example of an electrochemical point-of-care device is the blood sugar test. Easy to handle, inexpensive, and improving a diabetes patient's quality of life drastically it is the most successful electroanalytical chemistry product up to today.

The blood sugar sensor is based on an enzymatic reaction, that is it is a biosensor. Gaining an insight into biological electrochemistry is a powerful tool for modern technology. Using enzymes in detection to create a very sensitive and selective sensor is just one of the many possibilities that biomolecules offer to technology. Biofuel cells create energy out of glucose or lactate and can thus power an implanted diagnostic device inside a human body. Imitating the photosystem of plants leads to new developments in photovoltaics. DNA or protein chips allow a high density of recognition elements on an electronic circuit, turning it into a lab on chip that can quantitatively detect various viruses, bacteria, etc., with a single droplet of human blood serum, for example.

In the last 10 years electrochemical impedance spectroscopy has been opening new possibilities in corrosion and coating research as well as opened the path to more label free methods, which means no chemicals need to be added and the analyte needs no modification to create an electrochemical signal.

These are all modern electrochemical applications and additionally classic electrochemistry applications are still essential like electrolysis or galvanization. This very brief list of technologies, available because of knowledge in electrochemistry, shows how important it is to teach the basic concepts and applications of electrochemistry during the studies of chemistry, biochemistry, physics, biology, medicine, pharma, chemical engineering, and material sciences.

2.2 Goals

We believe that students should work with state-of-the-art technology and learn to use them as well as apply learned theories. PalmSens BV has always focused on small, portable, and economical devices. Our software was designed for users with different background knowledge, so also novice electrochemists can perform experiments without a long and complex introduction.

With this kit students will be able to learn how to operate a digital potentiostat, perform their own measurements, and process the results. The described theories, concepts, and applications should teach the basic concepts and real-life applications.

We would like to teach how parameters influence your measurements and why, how a kinetic analysis can be performed, how samples can be quantified, the standard addition method, the calibration curve method, and the construction of a biosensor.

2.3 Use

The material, texts, and protocols should give ideas and concepts for a teaching a lab course. We assume that you will still need to adjust some things, since students have very different levels of understanding and different lab courses have different goals. You can choose the protocols you like for your lab course. There is a Student's Guide (script) but this is basically an abbreviated version of this guide. We cannot compete with the textbooks and thus encourage you and your students to consider external literature (chapter 2.4). These books are also helpful if you want to teach deeper knowledge about certain topics, since this guide only provides the knowledge necessary to understand the experiments described here.

This manual is by default shipped together with a potentiostat and the required accessories. The instructions will be referring to the software PSTrace, although the experiments can also be performed with PalmSens' mobile app, PSTouch. Chemicals are not included.

Safety regulations differ from country to country and may change every year. We assume that the lab classes are supervised by staff members, who are informed about the local laws and regulations concerning safety and environmental protection. You are not allowed to upload or provide this guide to publicly accessible web space or distribute it in any other way to non-participants or instructors of your lab course.

2.4 Literature

Each person has a different way of explaining and learning. Usually, it is smart to give students some choice on which literature they can use and let them choose which book they prefer. For every lab day students should know what knowledge is expected from them and they would have to acquire it on their own, if the information provided in the script is not sufficient.

3.1 What is a potentiostat good for?

A voltmeter measures the potential difference between two points. To do so the circuit needs to be closed, but a very tiny current is usually flowing. This way you can see the potential difference between two points with almost no disturbance for the investigated system.

Knowing the potential between two points is useful but manipulating potentials is even better. This is what a power source does. In all households, batteries are the most common example of DC power supplies: a power supply having constant non-alternating potential. In electrochemical applications DC power supplies are used for galvanization (the deposition of metals on conducting materials, often other metals). Another well-known application is the electrolysis of compounds. A common industrial example is the chloralkaline process where salt (NaCl) and water (H_2O) are split into chlorine (Cl_2), hydrogen (H_2), and sodium hydroxide (NaOH).

The disadvantage is that you cannot investigate a single electrode and thus a single event. The current flows through the anode (electrode where oxidation happens) and the cathode (electrode where reduction takes place). Both these electrodes influence the measured current and the current limiting process cannot be determined. This is especially an issue in analytical chemistry. An electrochemical analysis that can be used easily with a power supply is the electrogravimetry. An electrode's weight is determined and all the metal in a defined sample volume is reduced, which leads to the precipitation of the metal on the electrode. The weight is measured again and thus the amount of metal in the sample volume will be determined. Although this method works fine, it has some disadvantages. The process takes time, e.g. 30 min plus drying and weighting for copper, nickel or lead oxide. In the given potential window only the analyte metal should be reduced. Hazardous side products may be produced. The solution needs to be heated and stirred to decrease the concentration polarization and to make the conversion of the analyte complete. The metal layer must stick to the electrode properly, otherwise a precise weighting of the electrode is not possible. To use other electroanalytical methods a potentiostat is needed.

A potentiostat uses three electrodes and a feedback loop to control the potential and measure the current flowing at just one of these electrodes, the working electrode. The potential will be measured to a fixed reference point and thus a lot of information about the event happening at the working electrode can be gathered.

The potentiostat controls
the potential of an electrode
**while measuring the current
flowing through that electrode.**

3.2 How Does a Potentiostat Work (in a nutshell)?

As mentioned before a potentiostat controls the potential of the working electrode and measures the current flowing through it. Why not just two electrodes? One of the reasons is that we cannot measure the potential of the working electrode against a fixed point when we have just two electrodes. Imagine a two-electrode system that consists of the already mentioned working electrode and the electrode, which potential should be our fixed reference point, the reference electrode. We apply a certain potential between these electrodes and an electrochemical reaction happens at the working electrode, but since the circuit needs to be closed and current needs to flow, a reaction that is inverse to the reaction at the working electrode must occur, that is if an oxidation occurs at the working electrode, a reduction must take place at the reference electrode.

If a current flows at a constant potential, an electrochemical reaction must happen according to Faraday's law:

$$Q = n \cdot z \cdot F \quad 3.1$$

This equation says that the charge Q flowing through an electrode is proportional to the amount n of a species that took or gave z electrons at the electrode. F is the Faraday constant and represents the charge of 1 mol electrons. The current I is the charge Q per time t flowing through the electrode:

$$I = Q/t \quad 3.2$$

The equations 3.1 and 3.2 combination shows that the current I flowing is connected to the reaction happening at the electrode via the amount n :

$$I = \frac{n \cdot z \cdot F}{t} \quad 3.3$$

Imagine now that the current is flowing at the reference electrode. At this electrode, a species' amount of n is converted. This conversion leads to a change of the surface or the concentration of the solution surrounding the electrode. The Nernst equation shows a clear correlation between the potential E of an electrode and its surrounding:

$$E = E^0 + \frac{RT}{zF} \ln \frac{a_{Ox}}{a_{Red}} \quad 3.4$$

E^0 is the standard potential of the redox couple (*Red* and *Ox*). R is the gas constant and T the temperature. The activity of the oxidized and reduced form of the species a_{Ox} and a_{Red} in the surrounding solution is not easy to predict. This often leads to a simplification of the equation:

$$E = E^0 + \frac{RT}{zF} \ln \frac{c_{Ox} f_{Ox}}{c_{Red} f_{Red}} = E^0 + \frac{RT}{zF} \ln \frac{c_{Ox}}{c_{Red}} + \frac{RT}{zF} \ln \frac{f_{Ox}}{f_{Red}} = E^{0'} + \frac{RT}{zF} \ln \frac{c_{Ox}}{c_{Red}} \quad 3.5$$

Usually, the distance between CE and WE is big enough so that the reactions do not influence each other, thus the counter reaction can be ignored, but sometimes (in small volumes, for example) it can be helpful to know which reaction happens at the counter electrode.

The potential is applied between reference and working electrode, while the current flows through working and counter electrode.

This way a constant reference point for the potential is maintained.

3.3 Electrodes

While the potentiostat is the heart of an electrochemical experiment, modern potentiostats need little effort to set up and operate. The average electrochemist will spend a lot more time with their electrodes. They need to be polished, maybe modified and sometimes it is rather challenging to fix them all in the right place. For this reason, we will first talk about the three different electrodes used with a potentiostat, before we take a closer look at the instrument itself again.

3.3.1 Working Electrode

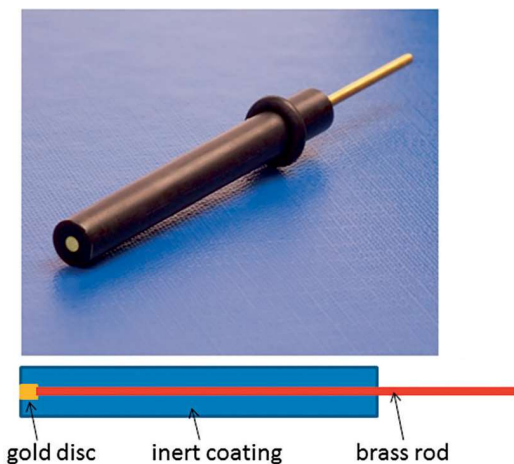


Figure 3.2: A gold disc working electrode in a Kel-F (Teflon) coat; photo and scheme.

The working electrode is the place where the reaction that we want to control or investigate happens. Therefore, this electrode should be carefully and reproducibly prepared. The most common working electrodes are disc electrodes. For example, a metal cylinder or a metal wire is surrounded by Teflon or PEEK and the cross section is exposed. The metal disc is connected to a

wire at the other end of the coating, so it can be connected (see Figure 3.2). Common materials for working electrodes are platinum and gold, as well as a variety of carbon phases. Due to its conductivity and reusability glassy carbon is the most popular among them.

To ensure a clean and smooth surface, the electrode is usually polished before usage. Very fine emery or sandpaper as well as slurries of aluminum oxide particles on cloth are used for mechanical polishing. Electropolishing is an alternative. This is used for surfaces that get contaminated very easily. The hydrophobic character of gold makes it often necessary to electropolish them. When residues need to be removed by electropolishing, a surface is cleaned by applying high potentials (see below chapter 4.3.4.3).

Rough surfaces will lead to high currents due to the charging of the interface, which will be explained in chapter 4.2.2.2. Dirty surfaces can show artifacts in the measurements or can cause that not the full active surface has access to the electrolyte. Cleaning an electrode is an important step in the electrode preparation. A blank electrode is often just the beginning of the preparation step. For many applications an electrode's surface needs a modification: to produce an ion-selective electrode, polymer films are put on their surface; to produce a biosensors, enzymes or other biomolecules (for example DNA) are immobilized at the electrode; to produce immunosensors, parts of the immune system are immobilized at the electrode and inorganic catalysts are also used for electrode modification.

A very interesting working electrode is the mercury electrode. Due to its liquid state mercury is used as a droplet electrode. At the end of a tube a mercury droplet is formed and used for the corresponding experiment. To clean the electrode the droplet is enlarged until it drops, and a new surface is prepared with clean mercury. This way, clean and easy reproducible surfaces are obtained, but due to its toxicity, mercury is not common in most laboratories. However, some experiments deliver the best results with mercury, so that the mercury electrode is still used nowadays.

The working electrode is the electrode where the investigated processes occur.

**It needs to be carefully prepared,
so that the surface is
reproducible and known.**

3.3.2 Reference Electrode

The reference electrode should deliver a constant potential. A current flowing through an electrode leads to an electrochemical reaction that will change the composition of the electrode's environment and thus the potential. Therefore, there should be as little current as possible flowing through the reference electrode.

4.1 Copper and Nickel Deposition

4.1.1 Goals

Most students already know the basics of electrochemical potentials and how they are applied in batteries or electrolysis. This experiment is meant to facilitate a transition from what is taught in most schools and the slightly more advanced level of potentiostatic experiments. Because galvanization for depositing metals or other protective layers is a widely used technique in industry as well, some basic knowledge of this important process should be gained. The experiment and its discussion should teach:

- A general idea about corrosion protection
- How can the different standard potentials be exploited for metal deposition?
- How do electrodeposition paints work?
- How does electrogravimetry work?

4.1.2 Introduction

4.1.2.1 Corrosion research and corrosion protection

Corrosion is the destruction of materials by chemical reactions with the environment. Replacement of corroded materials in buildings, bridges, or monuments and painting or galvanization of building elements is a huge investment into maintenance. The study “Corrosion Costs and Preventive Strategies in the United States” showed that in 1998 corrosion cost the U.S. 276 billion dollars. This is ca. 3.2 % of the US gross domestic product.¹ Painting the Eiffel tower costs ca. € 4 million every 7 years.²

Without a proper and closed layer of paint this monument would become unstable and break down.

Therefore, one of the most important fields in electrochemical research is corrosion. Lots of researchers investigate mechanisms of corrosive processes and possible new methods for corrosion protection. Companies check paints and lubricants for their corrosion protection capabilities and develop new methods for creating coatings or creating non-corrosive environments for machinery, for example flooding the entire gears with oil. The paint is usually a mixture of a polymer, color pigments, and various additives for adjusting the physical properties of the paint. These additives create smooth or rough surfaces or grant UV-light protection. The paint is usually dispersed or dissolved in some solvent (water or an organic solvent). The solvent evaporates after the paint has been applied and a polymer with the additives and pigments stays on the painted surface. The result is a physical barrier between the surface and its environment.

Electrodeposition paints are paints that are made insoluble by an electrochemical reaction. A conducting work piece is dipped into the paint bath and a potential is applied. The created reaction close to the work piece's surface will make the paint insoluble and thus a layer of paint precipitates on the metal surface. If the paint forms an insulating layer, the reaction will stop itself

1 Gerhardus H. Koch, Michiel P.H. Brongers, Neil G. Thompson, Y. Paul Virmani and Joe H. Payer. Corrosion Costs and Preventive Strategies in the United States – report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), September 2001

2 <http://www.toureiffel.paris/en/everything-about-the-tower/themed-files/97.html>

4.1.5 Results

This chapter should give the instructor an idea of what the data are expected to look like. Furthermore, we will briefly name some sources for deviations from the theoretical expectations. The experiments were performed with Staples paper clips (product number 19284). The setup with the set might look like this:



Figure 4.3: setup of the experiment

The results of this experiment basically consist of different appearances of the paper clip after the different depositions. A clear difference between the uncoated paper clip, the copper covered, and the nickel or nickel copper alloy covered parts should be visible.

If during the copper deposition the solution turns green or yellow, iron is released from the paper clip. It seems the potential is too high. A deep red rust (iron oxide) also indicates the release of iron. The observed currents should be negative after the capacitive current has decayed.

The potential of the paper clip's iron is sufficient to deposit copper, so in many cases a deposition just by dipping will be observed. The potential control will lead to thicker layers of copper. These grow faster and less regular than the thin layer deposited by the open circuit potential of the iron. The thicker layers appear less shiny because they are rougher. In industrial application an additive to grow thick smooth layers of copper is often added. The paper clip is expected to look like this after deposition:



Figure 4.4: steel paper clip covered with copper at the right part

4.2 The Cottrell Experiment and Diffusion Limitation

4.2.1 Goals

Electrochemically, the Cottrell Experiment is easy to perform, and the electrochemical process is easy to understand. However, the physical observations during the experiment are important for many electrochemical techniques and experiments. The importance of mass transport, especially diffusion, as limitation for a flowing current and the additional current flowing due to charging of the electrochemical double layer are basic principles and influence almost every electrochemical experiment. The experiment and its discussion should teach:

- What is capacitive current and what is its influence?
- How does mass transport limit the current during electrochemical experiments?
- What is the Cottrell equation?
- How can a Cottrell experiment be used for analysis?

4.2.2 Introduction

4.2.2.1 The Cottrell Experiment

Simple experiments often lead to intensive theoretical observations, when performed under real conditions. Suddenly temperature, pressure, etc. influence the outcome of the experiment. The Cottrell experiment is one of the most basic and well understood potential control experiments. The basic idea is to keep an electrode at a potential that won't lead to any reaction at the electrode and when a stable state is reached a potential step is made that will lead to a chemical reaction.

In detail this means the potential E of the electrode is before the potential step below the formal potential E^0 of an electrochemical active species. This species is present in the solution surrounding the electrode. The potential before the potential step is named E_1 in Figure 4.6. In the following pictures and explanations, it is assumed that the species is in its reduced form (Red). The concentration of Red is c_{Red}^* everywhere before the potential step, meanwhile the concentration of the oxidized form c_{Ox}^* is 0.

The potential step is raising the potential so that:

$$E_2 > E^0$$

4.2

According to the Nernst equation (see equation 3.6) the ratio Ox/Red will become bigger. Red is consumed by the electrode by accepting an electron, that is Red is oxidized, and the oxidized form (Ox) is produced (see Figure 4.6). If E_2 is significantly higher than E^0 , c_{Red} is 0 at the electrode surface and all Red close to the electrode is consumed.

4.3 Cyclic Voltammetry – the Most Used Technique

4.3.1 Goals

Moving from passive potentiometric experiments to potentiostatic experiments by controlling the potential was an important development. However, the step that followed towards potentiodynamic experiments may have been even more important for modern electrochemistry.

Potentiodynamic experiments made it easy to collect all the data needed for a plot of current I versus potential E . These plots are called a voltammogram and the technique used for measuring is called voltammetry. In a short period of time the cyclic voltammetry (CV) provides a lot of information and allows kinetic investigations. It is by far the most used technique by PalmSens customers. Experienced electrochemists read quite some information from the shape of a CV. The experiment and its discussion should teach:

- What is a cyclic voltammetry?
- Why does a cyclic voltammogram show a specific shape?
- What does the cyclic voltammogram say about reversibility?
- How can a cyclic voltammogram help to distinguish adsorbed and free diffusing species?
- How can a cyclic voltammogram be used to characterize catalysts?

4.3.2 Introduction

4.3.2.1 What is a Cyclic Voltammogram?

During a cyclic voltammogram the potential is controlled, and the current is measured. The potential is linear increasing or decreasing. The change of the potential per time is the scan rate v . As can be seen from the mathematical definition (see equation 4.12) this is the slope of the linear potential.

$$v = \frac{\partial E}{\partial t} \quad 4.12$$

At the start the potential is usually in a region where no electrochemical reaction is occurring. The linear sweep of the potential is usually chosen in such a way that the potential crosses the formal potential of the investigated species (see Figure 4.16). After reaching a set potential the slope of the linear potential is inverted, that is a decreasing becomes an increasing potential and vice versa. This potential is called the vertex potential. One cycle is finished when the potential reaches the starting potential again. It is possible to repeat this process several times. The intention behind multiple cycles is often to observe the stability of a system. Modern software usually offers the option to choose two vertex potentials and a start potential, that is the potential sweeps between the two vertex potentials and starts at a potential between these two.

4.4 Detection of Multiple Heavy Metals by Stripping Voltammetry

4.4.1 Goals

For many lab technicians, quantitative analysis is an everyday task. Monitoring processes, product quality, etc. are common tasks for electrochemical analysis. With raising awareness of pollution monitoring heavy metals in water reservoirs, pipes, rivers, etc. is getting more and more important. Heavy metals are very suitable for electrochemical detection and very low concentrations can be measured. Quantification limits in the range of parts per trillion (ppt) have been demonstrated. The experiment and its discussion should teach:

- Why care about heavy metals?
- How does stripping voltammetry work?
- How can multiple analytes be detected in one experiment?
- How to operate the analytical mode of PSTrace / PStouch?

4.4.2 Introduction

4.4.2.1 Why Care about Heavy Metals?

For several decades pollution has been a widely known issue. There is an increased public interest in unhealthy or outright toxic substances in resources we use for creating everyday goods or even consume ourselves, for example water, meat, milk, vegetables. Because of this, research focused on these topics brings a lot of funding opportunities.

Spoiled water is the cause of many illnesses and other health issues. Monitoring drinking water is an important task to keep people healthy. While for surface water bacteria are the main threat, in almost all urban areas water is consumed after flowing through pipelines. This or the direct pollution of ground water can lead to heavy metals in drinking water. Many heavy metals are biologically active and cause illnesses. A well-known example is lead poisoning.

Originally the term heavy metals referred to metals with a higher density than iron, but nowadays the term heavy metals is used in general as a term for all metals that are toxic for nature. Most heavy metals released into the food chain and water are due to human intervention. Most heavy metals are present in the earth's crust, but mining is bringing them to the surface. Acid rain caused by air pollution or by other exposed minerals dissolves the metals from the ore and carries it into rivers and plants. Sometimes waste containing heavy metal is disposed directly into rivers or oceans. All this had quite some impact on humans. The metal is not removed from the food chain but stays in it. And since the industrialization the heavy metal pollution has heavily increased.

Many examples of the negative consequences of exposure to heavy metals are known. Mining waste containing cadmium was disposed in a Japanese river in 1910. As a result, people eating the rice grown with river water got soft bones and suffered from kidney failures. The Mad Hatter from the book *Alice in Wonderland* goes back to the expression "mad as a hatter". The expression most likely derived from the negative effect of mercury used during manufacturing felt hats. Women drinking mercury-stained water, due to mining wastes, gave birth to mentally disabled children.

4.5 Detection of Glucose with a Self-Made Biosensor Based on Glucose Oxidase

4.5.1 Goals

Most electrochemical devices with low current ($< 1\text{ A}$) and potential ranges ($< 10\text{ V}$) are used for analytical methods. For this reason, several experiments concerning the detection of different analytes are included in this kit. For many lab technicians, quantitative analysis is an everyday task. Monitoring processes, product quality, etc. are tasks that are performed very often. New methods or improvement of the old ones promise cheaper or faster execution of the analysis.

Biosensors exploit biomolecules for sensing purposes. They have a high selectivity and sensitivity. They can be built for various illnesses or other analytes. Though biomolecules are often difficult to handle and need special care, the number of developed biosensors is increasing. The experiment and its discussion should teach:

- What is a biosensor?
- What are the basic principles?
- How can a biosensor be made?
- Why detect glucose?

4.5.2 Introduction

4.5.2.1 What is a Biosensor?

A biosensor uses a biological recognition element to convert a chemical signal into an electrical one. This very general concept is illustrated in Figure 4.46. This conversion can be achieved in many ways. Biological recognition elements can be enzymes or parts of immune systems. An enzyme is a biological catalyst. It speeds up reactions or makes them possible under given conditions; additionally, enzymes are very selective for certain reactions and only convert a specific substance or group of substances.

The immune system of a complex organism like a mammal produces antibodies as a reaction to biological material from outside the body. Antibodies bind to this biological material specifically. The transducer element of a biosensor converts the reaction at the recognition element into an electrical signal. A very common method is using an electrode as a transducer. As introduced in chapter 4.3.2.3 p. 54 a free diffusing redox mediator is able to transport electrons from a redox enzyme to the electrode, thus forming the transducer together with the electrode.

4.6 Detection of Hydrogen Peroxide with Self-made Prussian Blue Electrodes

4.6.1 Goals

Most electrochemical devices with low current ranges (< 1 A) and potential ranges (< 10 V) are used for analytical methods. For this reason, several experiments concerning the detection of different analytes are included in this kit. For many lab technicians, quantitative analysis is an everyday task. There is always a demand for new methods or improvement of old ones because less time or less costs for a test to monitor processes or product quality will save a big amount of money. Catalyzed reactions are often important for these kinds of sensors, to make them selective and to make their power consumption low. The experiment and its discussion should teach:

- What is Prussian Blue?
- Why are catalysts used for sensors?
- How to deposit Prussian Blue?
- What is a calibration curve?
- How to make a calibration curve?
- How to use a calibration curve for quantification?

4.6.2 Introduction

4.6.2.1 Why detect Hydrogen Peroxide?

Most likely hydrogen peroxide (H_2O_2) is best known for its use in hair bleach. It is the simplest peroxide (a compound with an oxygen-oxygen single bond). It is also a strong oxidizer. Due to its oxidizing properties, hydrogen peroxide is often used as a bleach or cleaning agent. It is used for bleaching hair, fabrics as well as teeth, disinfection of food packaging, medical equipment or to remove fungus. The artificial word “active oxygen” in advertisements for detergents usually indicates hydrogen peroxide mixtures. In many drugstores hydrogen peroxide solutions are available for removing blood stains or similar stains. The oxidizing capacity of hydrogen peroxide is so strong that it is considered a highly reactive oxygen species. Concentrated hydrogen peroxide, or “high-test peroxide”, is therefore used as a propellant in rocketry.

In fuel cells hydrogen peroxide is an unwanted side product. To achieve a high energy yield oxygen should be reduced directly to water consuming 4 electrons. If the reaction stops at hydrogen peroxide, only 2 electrons are accepted. Organisms also produce hydrogen peroxide naturally as a by-product of the oxidative metabolism. A well-known enzymatic reaction is the oxidation of glucose by glucose oxidase. The produced hydrogen peroxide can be used to detect the glucose indirectly. Oxidases use the normally present oxygen as an electron acceptor and thus produce hydrogen peroxide after oxidizing their substrate. Consequently, nearly all living things (specifically, all obligate and facultative aerobes) possess enzymes known as catalase peroxidases, which harmlessly and catalytically decompose low concentrations of hydrogen peroxide to water and oxygen.

Accordingly, hydrogen peroxide detection is useful for fuel cell catalyst research, for controlling the number of disinfectants used, for waste water control and as basis for a biosensor with a hydrogen peroxide producing enzyme.