THE ELECTROCHEMICAL HYDROXYLATION OF AROMATIC SUBSTRATES

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A dissertation submitted in partial fulfilment of the requirements for the

Masters Degree in Technology: Chemistry

In the Faculty of Applied Science at the
PORT ELIZABETH TECHNIKON

January 2002
Promoter: Prof. P.L.R. Loyson
ACKNOWLEDGEMENTS

- My promoter Prof. P.L.R Loyson for his help and guidance.

- To NRF for their financial assistance

- To my mother for all her help, support and guidance. Without her I would not be what and where I am today.

- Jacques and Nikki for reminding me that the problems encountered were not too big but the successes were.

- The staff of the Faculty of Applied Science (PE Technikon), and Shawn Gouws, Wilroy Bennen, Lee-Anne Willets and the rest of the gang for friendship, entertainment and advice concerning various matters.
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SUMMARY

The electrochemical hydroxylation of aromatic substrates was investigated in some detail, with the view to develop a method, which could produce dihydroxybenzenes in acceptable yields. Of particular interest was the selectivity and yield of the 1,4-dihydroxybenzenes. Two distinctly different methods were investigated in order to achieve this goal, acyloxylation and direct electrochemical hydroxylation.

Acyloxylation is the process where radical cations generated at the anode undergoes nucleophilic attack by acetate anions. The resulting aromatic acetates so produced can then be hydrolysed to the phenolic compounds. Two nucleophile systems were considered in the investigation, acetates (acetoxylation) and trifluoro-acetates (trifluoro-acetoxylation). These investigations were conducted under a variety of conditions using phenol and phenyl acetate as starting materials. From the results it was, however, concluded that the acetoxylation of these aromatic compounds occurs in unacceptable product and current yields. Trifluoro-acetoxylation on the other hand showed promise, but due to the nature and cost of the reagents it was deemed to be an impractical process.

Direct electrochemical hydroxylation: in which the radical cations produced at the anode undergoes nucleophilic attack by water producing the corresponding dihydroxybenzenes. These dihydroxybenzenes are then further oxidised to the benzoquinones, which then undergo reduction at the cathode in order to produce the corresponding dihydroxybenzene. In this process phenol, 2-tert-butylphenol and 2,6-di-tert-butylphenol were investigated as substrates. The results indicated that the yield towards the 1,4-dihydroxybenzenes increased as the degree of substitution on the ring increased.
Using product distribution diagrams it was found that the optimum electrode configuration for the electrolysis proved to be a lead dioxide anode and a nickel cathode.

During a fractional factorial design, in order to determine which of the variables effected the production of the 1,4-dihydroxybenzene, it was found that current density, substrate loading and co-solvent volume played a significant role in the production of 1,4-dihydroxybenzene from phenol.

The investigation proved that the direct electrochemical hydroxylation shows promise for the production of the dihydroxybenzenes, especially as the activation of the aromatic ring increases.
CHAPTER 1

INTRODUCTION

1.1 GENERAL

In some or other form chemicals have been used since the origin of civilization. Dyes, fragrances and medicinal products were extracted from plants, and animal fats were used for the production of soap and the treatment of leather. These activities were very localized, only serving the needs of the immediate population. But as the world developed and the industrial revolution began, it was realized that there was a need for better products and more effective production procedures. This resulted in the establishment of the chemical industry.¹

The first widespread commercial application of organic chemistry was the production of synthetic dyestuffs in the late 1850’s. This stimulated the industry over the following 30 – 40 years to such an extent as to have side industries develop, which did not necessarily specialize in dye-related technologies. By 1900 the interest in organic synthesis, generated by the dyestuff industry, was so pronounced that a number of organic products became commercially available.²

During the past century the organic chemical industry has developed rapidly. The major reason for this was competition. Companies tried to outwit each other so as to have larger profit margins, and countries waging war on each other needed to better equip their troops to ensure victory, for example the need for rubber for gas masks and vehicles.³

During the twentieth century chemistry has penetrated into everyday life and has made a major improvement on both our standard of living and life expectancy. Common chemicals are polymers (plastics, synthetic rubbers and fibres), pharmaceuticals and dyes. The world as we know it, would not have
been possible if it was not for the rapid development and progress made in the field of chemistry.

The chemical industry is of special importance to developing countries. When comparing the share the chemical industry has in the manufacturing industrial output, the output of a developing country like South Africa is twice that of a developed country like the UK, in fact 20 %\(^4\) compared to the 9 % of the UK.\(^2\)

As mentioned previously in this section, competition had a great effect on the development of the chemical industry, due to companies producing similar products competing with each other. Since the market value of the product is fixed, the company, which has the most cost-effective production procedure, using more efficient technologies, will prosper financially over the competitor. Thus the need exists to continually improve present technologies. In this way technologies are developed which are simpler and cheaper, so as to obtain higher profit margins. Thus research is constantly performed in order to improve yields and selectivities of reactions used in industry.\(^5\)

### 1.2 BRIEF HISTORY OF THE SOUTH AFRICAN CHEMICAL INDUSTRY

The South African chemical industry has a long history. Since the latter part of the nineteenth century chemicals have been produced for a variety of industries, the main one being the mining industry.\(^1\) As the country developed the requirements of other industries such as the farming industry resulted in a diversification of the South African chemical industry.\(^6\)

The chemical industry in South Africa stems from the mining industry and its need for chemicals. The discovery of diamonds (Kimberly, 1868), gold (Witwatersrand, 1886) and coalfields (Witbank and Vryheid), led to a rapid growth in the demand for explosives.\(^1\) By 1911 there were three separate companies making explosives using similar feedstocks and technologies in the production of similar explosives. The only factor that kept the companies running was the export market that resulted from the need for explosives during the First World War. Following the war, two of the companies
diversified into fertilizer production. This was due to the fierce competition in the explosives industry and the need for fertilizers expressed by the agricultural industry. More diversification followed, leading to the true start of the South African chemical industry. This diversification resulted in the production of both inorganic and organic chemicals:

- Inorganic: inorganic acids, fertilizers and a wide variety of mining chemicals such as calcium cyanide.
- Organic chemicals: ethanol, petrol, DDT and CFC's.

Since there is no oil and little natural gas reserves in South Africa, emphasis was placed on the coal reserves in order to supply organic feedstock and fuel. This resulted in research being done in order to gasify coal. The interest in the gasification and carbonisation of coal can be traced back to 1927, when a Government White Paper recommending the development of such processes was published.

The first process relating to this was when SATMAR (South African Torbanite Mining and Refining Company) was established in the early 1930’s. This was to mine oil shale and distil and refine the resulting oil in order to produce petrol. The interest in this field was extended and rights to the German Fischer-Tropsch process were acquired. As a result of this, the Government-sponsored South African Coal, Oil and Gas Corporation Ltd. (later to become known as South African Synthetic Oil Limited, SASOL), was established on 26 September 1950. The plant SASOL One produced medium octane petrol, LPG and a range of chemicals (higher boiling waxes and oils including diesel). Due to the increased isolation of South Africa as a result of sanctions imposed by the international community, the focus of this industry shifted. The shift was from the production of fuel to the establishment of a local chemical industry that could primarily be sustained from locally available raw materials derived from the oil from coal process, which was only achieved in the sixties. Further research was done and feedstock for rubber, fertilizer and secondary chemicals were produced. This development was further driven by the
establishment of plants that could aid in the achievement of this goal.\textsuperscript{9} Examples of these were:\textsuperscript{9}

- The establishment of the NATREF refinery in 1960, thought to be a collaboration of Total SA and the National Iranian Oil Company. The aim was to refine and crack imported petroleum to produce ethylene for plastics and pipeline gas.
- The establishment of two large oil-from-coal plants in Secunda during the early 1980’s to allow self-sufficiency in fuels.

The synfuel sector serves not only the local petroleum industry as fuel source but also became the major source of chemical feedstock and intermediates.\textsuperscript{10}

Since the 1990’s the largest South African chemical company proved to be SASOL. Since its inception it has been innovating and diversifying itself by placing high priority on research and development. By continuous improvement to the Fisher – Tropsch process, SASOL first developed their Synthol and later the SASOL Advanced Synthol process. The primary organic products obtained from the Advanced Synthol process are almost exclusively aliphatic and include olefins (ethylene, propylene, 1-pentene, 1-hexene and 1-octene) and oxygenates (alcohols, ketones and carboxylic acids). Aromatic compounds such as phenols, cresols and xylenols are obtained in small amounts as by-products from the gasification of coal.\textsuperscript{9}

\subsection{1.2.1 Current Trends}

More recently the South African chemical industry has been shaped by a variety of factors. Among these are changing environmental, legislative and labour conditions. All the above conditions can in some or other way be related to the changes that occurred in the country since 1994. The new government is more representative of the workers and reflects the needs and wishes of a broader society. This has affected the legislative, environmental and labour conditions under which companies have to operate, resulting in increased production costs but better environmental and occupational safety.\textsuperscript{11,12}
The adoption of Responsible Care,\textsuperscript{13} which effects the way in which a company operates, into the chemical community has also shaped it to a great extent. Responsible Care, which was initiated in Canada (1984), states that a company has an obligation to consider the way in which it approaches business and its role in society. By doing this, it should have a long-term commitment to the community in fields such as occupational safety and environmental protection and in so doing develop cleaner technologies. The opening-up of international chemical markets forced the South African chemical community to accept Responsible Care, because countries that have committed themselves to Responsible Care require that their trading partners also comply. The adoption of Responsible Care has eradicated the days when economic considerations alone determined the success of chemical production practices. The environmental considerations have today become an even larger influence on the success of the chemical products and production processes.

The admission of South Africa back into the world market also exposed the local chemical companies to competition from international chemical companies. This exposed the South African chemical industry to a variety of problems, most of these resulting from the isolation which the South African chemical industry underwent in the past. During the isolation, the South African chemical industry made an effort to protect the industry and to manufacture products geared for local use. This inward focus resulted in the construction of small-scale plants situated close to available raw material sources (oil-from-coal) and the largest domestic market (Gauteng). The size of a plant was geared to local demands and thus too small to competently compete economically with larger companies. The inland location of the plants increased costs due to raw material and product transportation costs to and from sea ports.\textsuperscript{6}

The above-mentioned factors forced the South African chemical industry to look closely at its available and viable options. The SASOL-AECI joint venture Polifin (1993) is an example of this investigation. The aim of this venture was
the production of monomers, polymers, cyanide, peroxide and chlor-alkali products, thus allowing the companies to compete economically in the world market.\textsuperscript{7}

The resulting exposure of the South African chemical industry to the world markets was both beneficial and detrimental, in that it forced companies to either “cut their losses” and concentrate on the more economical processes in their arsenal or to go under. Examples of the rationalization and mergers carried out by some South African chemical companies are:

- SASOL:\textsuperscript{9} Has at great expense undergone a variety of changes in order to improve their range of products as well as the quantity and quality of said products.
- AECI:\textsuperscript{7} Has moved away from ammonia and urea production by the sale of their interests in Polyfin to SASOL (1999), and the disposal of 50% of Kynoch. They are also in the process of developing a Dulux technical paints business together with PPG Industries of Pittsburg.
- Sentrachem:\textsuperscript{14} Has during the 1990’s been affected adversely by factors such as a prolonged drought, high interest rates, increasing international competition and devaluation in the Rand. This produced a vulnerable company, which in 1997 was successfully acquired by the Dow chemical company. Dow then carried out the following steps:
  - The acquisition of Hoechst SA’s interest in Safripol.
  - Restructuring of Agrihold into Dow Agrosciences, and moving its Middle-East-Africa headquarters from London to Johannesburg, thus showing a marked interest in the possibilities of the South African chemical industry.

Other strategies, which companies could follow in order to survive, are:

- The incorporation by medium to large chemical companies of competitors into its structure, in order to become larger and more competitive in an increasingly tough global market.
- Trimming of large company businesses and subsequently discarding non-core businesses resulting in the establishment of a large corporation
that trades in products resulting only from its core business while having interests in a number of markets.

- Globalisation: diversification by producers of commodity chemicals, resulting in the production of high value downstream products from their own feedstocks.

The South African chemical industry is the largest of its kind in Africa. It is of substantial economic importance to the country, contributing 5% to GDP and approximately 25% of its manufacturing sales.¹⁵ Whilst the industry is complex and diversified, the end products can be divided into the following:⁶

- Base chemicals: these include petrochemical building blocks such as ethylene, propylene, benzene, toluene and methanol. The production of these products is mainly centred on SASOL and their Sasol 1 and 2 installations.
- Intermediate chemicals: these include a variety of compounds such as solvents, phenols, plastics and rubber.
- Chemical end-products: these include processed plastics, paints, explosives and fertilizers.
- Speciality chemical end products: These products tend to be lower volume but higher added-value chemicals. These include pharmaceuticals, agro-chemicals, food-, fuel-, and plastics additives.

The first three categories are dominated by Sasol Chemical industries, AECI and Dow Sentrachem. There are however, a number of other companies which are active in these three sectors, they are Hoechst SA, Afrox, Bayer, Smithchem, Shell Chemicals, BASF, African Products, Engen Petroleum, ICI, Rohm and Haas and finally Omnia.⁶

The speciality chemical end-products field has a variety of producers and importers of these chemicals. These are: Chemserve, Fine Chemicals Corp, Norsicel, Henkel, Revertex, CH Chemicals and various companies in the Protea group.⁶
Although the South African chemical industry has changed much over the short period since its acceptance by the world, it is clear that the chemical industry has only begun its transformation. For the South African chemical industry to become and remain a major player in the world chemical industry, a variety of other changes will still be required.

1.2.2 Coal Chemicals vs. Oil Chemicals

Oil currently provides 90% of the chemical raw materials used for organic chemical. The production of petroleum products from oil is a well-established and mature industry. This caused chemical companies over the world to abandon their research into refining techniques, since the technology is available at a price, and rather shift their emphasis to downstream products.

Oil is responsible for 60% of the world’s fossil fuel consumption, but contains between 5% and 10% (v/v) of chemicals that can be used in the chemical industry. Since the world’s oil reserves are finite and the price of oil will never be as low as it was in the 90’s, it is not difficult to foresee that the world will, within the near future, be forced to shift its focus from oil to other feedstock such as natural gas and coal.

Coal can also be used to satisfy energy needs. But for coal (and natural gas) to be used as a feedstock for the chemical industry, it has to undergo major transformations. The feedstock attainable from the feed depends to a great extent on the specific transformation employed:

- Liquefaction: lower molecular weight and highly hydrogenated species are formed.
- Gasification: formation of gas mixtures rich in both carbon monoxide and hydrogen.

The refining of oil has as its basis distillation. The distillation fractions attainable from oils are shown in Scheme 1.1. The contrasting feedstock from the complex transformation of coal is shown in Scheme 1.2. It can be seen
that there is a drastic difference between the products of the coal and oil processes.

\textbf{Scheme 1.1: Distillation fractions from oil}^{16} 

The local South African feedstock are mainly derived from coal, putting the South African chemical industry in the advantageous position of having a large and abundant supply of this feedstock. The South African company Mossgas, operating in the Western Cape, has the ability to shift the market if it was not for licensing constraints. They are currently primarily producing liquid fuels along with industrial alcohols, liquid oxygen, liquid nitrogen and carbon dioxide from the natural gas deposits below the seabed in the area.\textsuperscript{17}
Scheme 1.2: Products attainable from coal processing
The area where local companies have a large advantage is the field of phenolic compounds, phenols, cresols, etc which can be obtained from coal tars. These tars are formed in the refining of coal, so there is a relatively large supply of these tars available in South Africa. The current work addresses just one of these opportunities, the hydroxylation of aromatic compounds, specifically phenolic compounds.

1.3 OVERVIEW ON STARTING MATERIALS

Phenol, (hydroxybenzene, carbolic acid, \( \text{C}_6\text{H}_5\text{OH} \ [108-95-2] \)), discovered in 1834 by F. Runge, is the parent substance of a homologous series of compounds with the hydroxy group bonded directly to the ring.\(^{18}\)

Phenol occurs as either a free component or as an addition product in natural products and organisms. Phenol is formed as a metabolic product and can be found in human urine, and can also be liberated from lignin upon hydrolysis. Larger amounts can be formed in the coking or low-temperature carbonisation of wood, brown coal, hard coal and in oil cracking. The largest sources of phenol are in the carbonisation of coal and in oil cracking. Phenol has been an important chemical in history: it was used, under the name carbolic acid, as a disinfectant in World War I. The use of phenol as a disinfectant did however decline since the war, due to the carbolic acid also being corrosive, thereby attacking tissue. Currently phenol is of major industrial importance in the world since it is a starting material for a variety of intermediates and finished products, illustrating the current trend in industry to value-added products.\(^{18}\)

Examples of substituted phenols used in these hydroxylation studies are 2-\textit{tert}-butylphenol and 2,6-di-\textit{tert}-butylphenol. These compounds are produced from the alkylation of phenol in the presence of catalysts. The nature of the process and the type of catalyst governs the product distribution. An example of one of the reactions is when sulfonated polystyrene-polydivinylbenzene ion exchange resin is used as the catalyst, forming mixtures of alkylated and di-alkylated phenols.\(^{19}\)
The products formed upon the hydroxylation of phenol and substituted phenols were mainly the corresponding dihydroxybenzenes and 4-substituted benzoquinones.

1.3.1 Properties

Phenol is a clear solid at room temperature and melts at 40.9 °C, crystallizing into colourless prisms. It is completely miscible with water at temperatures above 68.4 °C, whilst below this temperature its solubility decreases with temperature. Phenol is readily soluble in most organic solvents (aromatic hydrocarbons, alcohols, ketones, ethers, acids, halogenated hydrocarbons, etc.). Phenol is an acidic substance with a pKa value of 9.89. The reason for this acidity is the ability of the molecule to stabilize the negative charge formed upon proton loss through quinoid resonance structures. Because of this acidity phenols can form salts with aqueous alkali hydroxide solutions.\(^{18}\)

Phenol has a relatively high boiling point (181.75 °C) due to the hydrogen bond formation present between molecules. Phenol can readily undergo electrophilic substitution, the reason for this is again the contribution of the \(\sigma\)- and \(\pi\)-quinoid resonance structures. Under oxidative conditions phenols can readily form free radicals, which can then undergo dimerization or further oxidation to dihydroxybenzenes and quinones. Since phenol radicals are relatively stable they can be used as radical scavengers and oxidation inhibitors.\(^{18}\)

As mentioned in Section 1.3, the alkyl phenols used in the study were 2-\textit{tert}-butylphenol and 2,6-di-\textit{tert}-butylphenol. Both these compounds are phenolic in nature but the bulky alkyl groups present on these molecules have a pronounced effect on the properties of the substance. The boiling points of 2-\textit{tert}-butylphenol and 2,6-di-\textit{tert}-butylphenol are 224 and 253 °C respectively. The difference between the boiling points of these molecules and that of phenol can be explained when considering the nature of the substituents on the ring. The solubility of these molecules also differs from that of phenol in that they are a lot less soluble than phenol. This is again ascribed to the bulky
substituents, which decrease the polarity of the molecules, so the solubility of the molecules in polar solvents decreases and increases in non-polar solvents. Along with the decrease in solubility of these molecules, compared to phenol, is the decrease in acidity. This can be ascribed to the bulky alkyl groups adjacent to the hydroxy substituents, since the steric hindrance in the phenolate anion hinders solvation.\(^{19}\)

### 1.4 OVERVIEW ON PRODUCTS

#### 1.4.1 Introduction

Upon the hydroxylation of phenol, dihydroxybenzenes and \(p\)-benzoquinone are formed. All three isomers of the dihydroxybenzenes could be formed. These are hydroquinone \(^{123-31-9}\) (1,4-dihydroxybenzene, 1,4-benzenediol, \(p\)-dihydroxybenzene), catechol \(^{120-80-9}\) (1,2-dihydroxybenzene, 1,2-benzenediol, \(o\)-dihydroxybenzene) and resorcinol \(^{108-46-3}\) (1,3-dihydroxybenzene, 1,3-benzenediol, \(m\)-dihydroxybenzene). \(p\)-Benzoquinone \(^{106-51-4}\) (quinone, 1,4-benzoquinone, 1,4-benzenedione) is produced as the result of over-oxidation of the dihydroxybenzenes. Scheme 1.3 gives the structure of these compounds.\(^{20\cdot22}\)

**Scheme 1.3: Products**

![Scheme 1.3: Products](image)

- Hydroquinone is a white crystalline substance, which was first discovered in 1820 from the dry distillation of quinic acid. Then, in 1844, it was described by Woehler when he obtained it from the reduction of 1,4-benzoquinone.\(^{20\cdot22}\)
- Catechol is a slightly grey crystalline compound with a phenolic odour, and a sweet and bitter taste. It was first obtained in 1839 upon the dry distillation of catechin.$^{22}$

- Resorcinol is a crystalline compound with a faint pink tinge and faint aromatic odour. It was first obtained in 1864 by the alkali fusion of galbanum and asafoetida resins.$^{21,22}$

### 1.4.2 Properties

As shown in Table 1.1, the dihydroxybenzenes do not have similar physical properties. The reason for this can be explained through hydrogen bonding, within and between molecules.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Catechol</th>
<th>Resorcinol</th>
<th>Hydroquinone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>105 °C</td>
<td>110 °C</td>
<td>172 °C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>245 °C</td>
<td>277 °C</td>
<td>287 °C</td>
</tr>
</tbody>
</table>

Looking at both the melting and the boiling points, it can be seen that the increase in these properties is proportional to the separation between the hydroxy substituents in the molecule. This can be explained as follows: the closer the hydroxy groups are to each other, the greater the likelihood of hydrogen bonding within the molecule; hence there is a smaller amount of hydrogen bonding with surrounding molecules causing less attraction between molecules so there is less energy needed to separate these molecules from each other, resulting in the lower melting and boiling points.

There is a marked trend in the solubility of the dihydroxybenzene isomers. This is that the solubility of hydroquinone in any solvent is always different from that of catechol and resorcinol, which are always relatively close.$^{22}$

The dihydroxybenzenes are weak acids with two dissociation constants, one for the loss of each proton. Catechol differs from the other dihydroxybenzenes
in that it has the ability to complex most metal salts, due to the two adjacent 
hydroxy substituents.\textsuperscript{22}

In general, the physical properties of hydroquinone vary to a great extent from 
those of catechol and resorcinol whose properties are close to each other.

The dihydroxybenzenes undergo all the typical reactions of phenol. When 
comparing the oxidation potential of the dihydroxybenzenes to that of the 
corresponding phenols, it can be seen that it is lower than that for phenol. 
This is because there is greater electron density on the ring of 
dihydroxybenzenes. With the exception of resorcinol, the dihydroxybenzenes 
are easily oxidised to the corresponding benzoquinones.\textsuperscript{20,22}

1.4.3 Uses and applications of products

Dihydroxybenzenes are primarily used as intermediates for the production of 
a variety of value-added products.

- Hydroquinone: the uses of hydroquinone are varied.\textsuperscript{20,22}
  - Photography: The largest demand for hydroquinone is in this 
    industry. Here it is primarily used for black and white film, 
    lithography, photochemical machining, microfilm and X-ray film. A 
    wide array of derivatives are used, including sulphate salts of \( p \)-\( N \)-
    methyl-aminophenol and potassium 2,5-dihydroxy-
    benzenesulfonate.
  - Rubber industry: This is the second largest consumer of 
    hydroquinone and its derivatives. Here the derivatives are used as 
    antioxidants and antioxants. Examples of derivatives used in the 
    industry are \( N,N' \)-diaryl-\( p \)-phenylenediamines, dialkylated 
    hydroquinones, \( N \)-alkyl-\( p \)-aminophenols, dialkyl-\( p \)-phenylene-
    diamines and aralkyl-\( p \)-phenylene-diamines.
  - Polymer industry: Hydroquinone, hydroquinone monomethyl ether 
    and \( p \)-benzoquinone are used extensively in the vinyl polymer 
    industry to inhibit free radical polymerisation during processing and 
    storage. Hydroquinone, \( p \)-benzoquinone, 2-methylhydroquinone, 2-
tert-butylnydroquinone and 2,5-di-tert-butylnydroquinone are used as stabilisers in unsaturated polyester resins. Hydroquinone bis(2-hydroxyethyl)ether is used as a chain extender in the production of thermosetting urethane polymers.

- Food industry: examples of these derivatives include, 2-tert-butylnydroquinone and 2-tert-butyln-4-hydroquinone.
- Dyes and pigments: hydroquinone dimethyl ether is used as a starting material for a family of dyes, based on 2-amino- and 2-amino-5-chloro derivatives such as quinizarin.
- Agricultural chemicals: A variety of fungicides and herbicides are produced using hydroquinone as intermediate. Examples of these are Chloroneb (fungicide), which is produced from hydroquinone dimethyl ether, ethofumesate (herbicide), which is produced from p-benzoquinone, and fluazifop-butyl, which is based on the o-alkylation of hydroquinone with 2-halo-proprionic acid derivatives.
- Pharmaceuticals: Hydroquinone and several derivatives are used as skin depigmentation and bleaching agent in topical formulations.

The field is still expanding with new applications for hydroquinone and its derivatives being discovered rapidly. Examples of these applications are found in the fields of metal corrosion treatment and polymers (liquid crystals, new polymer and plastic formulations), since these new polymers exhibit good strengths, weathering ability, solvent resistance, flame retardance, and temperature stability.

- Resorcinol: The uses of resorcinol are limited.²¹,²²
  - Rubber industry: This is by far the largest consumer of resorcinol in the world. It is used in both the production of rubber and the reinforcement of rubber products. Here the resorcinol can be used as an adhesion agent or an additive to the rubber in order to modify its properties.
  - Adhesives: This is the second largest consumer of resorcinol in the world. Here the largest application is in the field of wood adhesives,
especially in the production of laminated wood beams. Here the resins and adhesives should be waterproof at room temperatures.

Additional uses of resorcinol in industry are in the fields of polymers (light stabilizers), pharmaceuticals (sun screen formulations and specialized applications like acne formulations) and the dye industry (fluorescein and eosin).

- **Catechol:** The uses of catechol are varied. The main use of catechol is as an intermediate in the production of other compounds used in the following industries:
  
  o **Pharmaceutical preparations:** Guaiacol, and guaiacol benzoates, carbonates, salicylates, sulphonates and glyceryl ethers are used as expectorants. Veratrole and sassafras are used as antisepptics.
  
  o **Food industry:** Veratrole is used as a meat additive as liquid smoking agents. *tert*-Butylcatechol is also used as an antioxidant for lard.
  
  o **Perfume industry:** Derivatives such as piperonal (cherry and vanilla) and eugenol (clove) are used as flavours.
  
  o **Agricultural industry:** Piperonal derivatives and arbofuran are also used as insecticides. Catechol phosphate is claimed to be a plant growth accelerator. Phosphoric and thiophosphoric esters of catechol are used as fungicides.
  
  o **Rubber industry:** Derivatives are also used in this industry: an example of this is the di-*o*-toluylguanidine salt of dicatechol-borate, which is used as a rubber accelerator.
  
  o **Polymer industry:** Stannous derivatives of catechol are employed as catalysts for polyurethane foams. Salts of *tert*-butylcatechol are used to stabilize poly(vinyl chloride) polymers. *tert*-Butylcatechol is used as a stabilizer or polymerisation inhibitor for styrene, butadiene and other reactive monomers.
  
  o **Paints and inks:** Guaiacol is used as an anti-oxidant and anti-skinning additive to paints, varnishes, enamels and printing inks.
1.4.4 Sources

Dihydroxybenzenes can be obtained from a variety of different sources, including both natural and synthetic. These sources will be mentioned and explained below.

1.4.4.1. Natural

The dihydroxybenzenes cannot be extracted from plants on a sufficient scale as to satisfy any industrial need for it. All of the dihydroxybenzenes are naturally occurring except for resorcinol.\(^{20-22}\)

1.4.4.2. Synthetic\(^{20-22}\)

The manufacturing procedures used on an industrial scale for the manufacture of dihydroxybenzenes are shown in Table 1.2 and described below.

Table 1.2: Industrial production procedures for dihydroxybenzenes

<table>
<thead>
<tr>
<th>Dihydroxybenzene</th>
<th>Process</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroquinone</td>
<td>Aniline oxidation</td>
<td>US, FRG, Japan, U.K., People’s Republic of China</td>
</tr>
<tr>
<td></td>
<td>Phenol hydroxylation</td>
<td>France, Italy, Japan</td>
</tr>
<tr>
<td></td>
<td>p-diisopropylbenzene oxidation</td>
<td>U.S., Japan</td>
</tr>
<tr>
<td>Resorcinol</td>
<td>Benzene sulfonation</td>
<td>U.S., Italy, FRG, U.K., Puerto Rico, Japan</td>
</tr>
<tr>
<td></td>
<td>m-diisopropylbenzene hydroperoxidation</td>
<td>Japan</td>
</tr>
<tr>
<td>Catechol</td>
<td>Phenol hydroxylation</td>
<td>France, Italy, Japan</td>
</tr>
<tr>
<td></td>
<td>Coal-tar distillation</td>
<td>U.K.</td>
</tr>
</tbody>
</table>
Oxidation of aniline: This is a three step process:

- Oxidation of aniline with manganese dioxide (20% excess, pyrolusite ore can be used as a source) in sulfuric acid (5°C). This produces benzoquinone and manganese sulfate.

\[
2 \text{NH}_2 + \text{MnO}_2 + 5 \text{H}_2\text{SO}_4 \rightarrow 2 \text{O} + (\text{NH}_4)_2\text{SO}_4 + 4 \text{MnSO}_4 + 4 \text{H}_2\text{O} \tag{1.1}
\]

- The benzoquinone is then separated from the reaction mixture by steam stripping.

- The separated benzoquinone is reduced to hydroquinone using an aqueous iron suspension (55 - 65°C), which produces hydroquinone. This is separated from the iron and iron oxide through filtration. An alternative method to this is catalytic hydrogenation. The resulting hydroquinone is separated by centrifuging and the resulting product is vacuum dried yielding 85% hydroquinone.

\[
\text{O} + \text{Fe} + \text{H}_2\text{O} \rightarrow \text{OH} + \text{FeO} \tag{1.2}
\]

Hydroxylation of phenol: A mixture of catechol and hydroquinone is obtained by hydroxylation of phenol with hydrogen peroxide in the presence of a catalyst. The ratio of catechol to hydroquinone can range from (3:1) to (0.1:1). It is reported that with the aid of shape-selective zeolites a selectivity of 99% can be obtained towards the hydroquinone.
A typical process involves the following steps:

- Dihydroxybenzenes are extracted with solvents and the oxidation mixture washed with water.
- The products are then separated from each other and the solvent through distillation.

Hydroperoxidation of \( p \)- and \( m \)-diisopropylbenzene: Benzene is alkylated with propene in the presence of a catalyst. The reaction products are isomerized to \( p \)- and \( m \)-diisopropylbenzene and oxidized to \( p \)- and \( m \)-diisopropylbenzene dihydroperoxide. An acid catalyst then cleaves these products in order to produce hydroquinone and resorcinol with an 80% yield. The reaction proceeds as follows:

- \( p \)- and \( m \)-diisopropylbenzene are produced by the Friedel-Crafts alkylation of benzene with propene, and followed by isomerization to the desired products.

The purified diisopropylbenzene is converted to the dihydroperoxide by air oxidation under slightly alkaline conditions at 80 – 90 °C. This dihydroperoxide is purified and separated from the reaction mixture by either extraction or crystallization.
The dihydroperoxide is cleaved through the Hock rearrangement by treatment of the dihydroperoxide solution with a 0.2 - 1.0% sulfuric acid catalyst at 60 – 80 °C. The corresponding dihydroxybenzene and acetone is then separated and purified through crystallization.

- Sulfonation of benzene: In this process benzene is sulfonated with sulfur trioxide in sulfuric acid. This reaction mixture is neutralized, alkali fused with sodium hydroxide and acidified with sulfuric acid in order to produce resorcinol. This process produces a considerable amount of waste since mixtures of sulfur trioxide and sulfuric acid are used, which needs to be neutralized with lime and then precipitated as gypsum and then landfilled. The process consists of three steps:

  o Sulfonation of benzene, by the use of sulfur trioxide in order to produce $m$-benzene disulphonic acid.
Neutralization of \( m \)-benzene disulphonic acid with a base like sodium sulfite, soda ash or sodium hydroxide to produce \( m \)-benzene di-sodium di-sulphonate.

\[
\text{SO}_3\text{H} \quad \text{Base} \quad \text{SO}_3\text{Na}
\]

Alkali fusion of the \( m \)-benzene di-sodium di-sulfonate with an excess of sodium hydroxide at 320 – 350 °C to produce di-sodium resorcinate and sodium sulfite.

\[
\text{SO}_3\text{Na} \quad \text{NaOH} \quad \text{ONa}
\]

The di-sodium resorcinate and sodium sulfite are treated with either a small quantity of water (which yields solid sodium sulfite containing some organic impurities) or a large quantity of water (which yields a saturated solution of the product). In both these processes the product is reacted with sulfur dioxide, sulfuric acid or hydrochloric acid. The dissolved product is then extracted with an organic solvent.

\[
\text{H}^+ \quad \text{ONa} \quad \text{OH}
\]

Currently there are a number of methods, which show promise for the industrial synthesis of the dihydroxybenzenes.
Hydroquinone:

- The carboxylate esters of aromatic diols can be prepared by the Bayer-Villiger oxidation of 4-hydroxy-substituted aromatic ketones with 97% conversion and selectivity.
- Can be produced by the microbiological oxidation of both benzene and phenol with very high selectivities.
- $p$-Benzoquinone is produced in selectivities greater than 90% by the air oxidation of phenol using a copper catalyst.
- Can be produced from benzene in the presence of Cu(I) chloride or titanium.
- $p$-Benzoquinone and hydroquinone can be obtained by reacting benzene with ozone in an aqueous medium.
- Can be produced by the hydroxylation of $p$-isopropylphenylphenol using 30% hydrogen peroxide under acidic condition.

Resorcinol:

- Can be produced by the hydrogenation of 1,3-dinitrobenzene using a process developed by Koppers and Mitsui.
- Can be produced using acetone and either methyl acrylate or acetonitrile, by the dehydrogenation of 1,3-cyclohexanediione formed, as developed by Hoechst.

Catechol:

- Can be prepared from cyclohexane derivatives. The cyclohexanone is chlorinated and then hydrolyzed to 2-hydroxycyclohexanone and 1,3-cyclohexanediione followed by dehydrogenation to catechol.
1.5 Need for an electrochemical investigation

Modern industrial practice is turning increasingly towards electrochemical synthetic procedures, especially for the production of fine chemicals, such as pharmaceuticals, agricultural chemicals and important chemical intermediates. This shift is driven mainly by environmental considerations and economic factors. It is therefore of interest to investigate possible electrochemical pathways for aromatic hydroxylation.
CHAPTER 2

ELECTROCHEMICAL ASPECTS

2.1 INDUSTRIAL ELECTROCHEMISTRY

2.1.1 General

The classification “industrial electrochemistry” covers a wide field of applications, which can be summarized as follows:\textsuperscript{23, 24}

- Organic electro-synthesis
- Inorganic electro-synthesis
- Extraction
- Finishing and processing of metals
- Material separations
- Water purification
- Effluent treatment
- Energy generation
- Corrosion
- Protection of metals
- Sensors and monitors

Considering the above applications, it is important to note that only organic electro-synthesis will be dealt with in this investigation.

When one consider possible processes for synthetic organic chemistry, electrochemistry is often neglected. This is because electrochemistry is often not considered as a viable synthesis technique. The reasons for this are as follows:\textsuperscript{25}

- Lack of education: few students are exposed to the principles and possibilities of electro-organic chemistry.
- Technical terminology: often, electrochemical terminology is complex and confusing.
- Type of equipment: specialized equipment is required.

In many cases, however as will be seen, it is possible to effect chemical reactions in good yields and selectivities using electrochemical means.\textsuperscript{26, 27}
2.1.2 Industrial considerations
For an industrial electrochemical process to be developed, the following guidelines should be followed:

General:\(^28\)
- Processes that have effective catalytic procedures should be avoided.
- Processes that result in products which are currently being phased out in industry, should not be considered.
- There is a definite advantage to manufacturing products with high molecular mass.
- Processes where more than 8 electrons are transferred per molecule should be avoided.
- The process being considered should yield high current efficiencies, yields and selectivities.

Along with the above, BASF, a large German company, also recommends the following:\(^29\)
- Electrode service life \(\geq 4000\)hr
- Membrane service life \(\geq 8000\)hr
- Current efficiency \(\geq 75\%\)
- Concentration of product in final electrolyte \(\geq 8\%\)
- Simple product isolation

2.1.3 Organic versus inorganic electro-synthesis
In comparison with inorganic electro-synthesis, organic electrochemical work suffers from the following limitations:\(^30\)
- Conductivity: It is normally an order of magnitude smaller for organic solutions. This results in the need for new cell designs in order to cope with this low conductivity.
- Solvent supporting electrolyte: In inorganic work the solvent-supporting electrolyte system is normally an inorganic salt dissolved in water. For organic solutions the solvent-supporting electrolyte system is normally
an organic or inorganic supporting electrolyte dissolved in an organic solvent.

- Product selectivity: The number of reactive sites on an organic molecule or ion is usually larger than for an inorganic molecule or ion, so the tendency to form by-products is more extensive in organic electro synthesis. This, along with the factors mentioned above results in more complicated product separation procedures.

2.2 HISTORY OF ORGANIC ELECTROCHEMISTRY

Electro-organic chemistry has been known since 1800, when it was first found that a potential difference between two electrodes could result in a chemical reaction. Achim Von Arnim discovered that when he dipped a voltaic pile into an alcoholic beverage (either wine or beer) and observed the formation of a sour smelling product, acetic acid.\(^{31}\)

Later, researchers like Michael Faraday, Hermann Kolbe and Otto Haber founded the field of electro-organic synthesis. Faraday was the first to determine the amount of charge necessary to convert a mole of substrate to a mole of product. This was, however, done with an inorganic copper salt. To Faraday’s disappointment, the discovery did not hold true when he changed to an organic substrate namely an acetate salt; with this substrate he only formed carbon dioxide and ethane\(^{32}\). In 1849 Kolbe used Faraday’s results as a basis for the work he did with long chain fatty acids, which resulted in carbon-carbon bond formation.\(^{33}\) Countries like Russia, India, Japan and Germany still use this technology \(^{34} \cdot 36\). Kolbe’s work was also used as a basis for other researchers. In 1891 they modified the Kolbe reaction and used the electrolysis of hemi-esters of dicarboxylic acids to produce di-esters having twice as many CH\(_2\) groups as the parent acid. This was the first real synthetic organic electrochemical reaction.

In the period between 1920 and 1940 a number of electrochemical reactions were adopted by industry. These included the reduction of nitrobenzene to benzidine and pyridine to piperidine.\(^{37}\) The first large-scale industrial
application of electro-organic synthesis was introduced by the Atlas Powder Co. (now ICI USA Inc.) in 1937. It was the cathodic reduction of glucose to manitol and sorbitol and this process produced 1400 metric tons per year. The process was used until 1948 when it was replaced by a more economically viable catalytic hydrogenation process.\textsuperscript{37, 38} The next large electro-organic process adopted by industry was in 1964, when the small upstart company Nalco, based in Freeport Texas, adopted a process where tetra-alkyl lead was produced at 1500 to 1800 t per year.\textsuperscript{37,39} Shortly after this, in 1965, Monsanto at Decator Alabama adopted a process for the electro-reductive coupling of acrylonitrile to adiponitrile.\textsuperscript{40 - 41}

The above-mentioned industrial electro-organic processes were made possible by advances in a number of electrochemistry fields. Two such fields were:\textsuperscript{32}

- Electrochemical analysis: techniques such as potentiostatic measurements, cyclic voltammetry and rotating disk electrodes made the understanding of reaction mechanisms possible.
- Electrochemical engineering: advances in cell design, electrode material and many other components used for electrochemical cells made it possible to develop and design better electrochemical reactors.

When considering the history of organic electrochemical processes, it can be seen that only reductive processes made it to an industrial scale; this was due to the highly corrosive environments involved during electrochemical oxidations. However the advances mentioned above made this now also possible. Examples of these advances are shown in Table 2.4. The publication of a comprehensive literature also helped in the understanding of the field. These publications included books like Organische Elektrochemie by F.R. Fichter\textsuperscript{42}, Electro-organic Synthesis, 1800-1975 by Sherlock Swann JR\textsuperscript{43} and Organic Electrochemistry by Manuel M. Baizer.\textsuperscript{44}
2.3 Current industrial electro-organic processes

The scale of electro-organic processes varies widely, with one very large one and about a hundred smaller ones. The Monsanto process mentioned in Section 2.2 for the production of adiponitrile is running at a total capacity of more than 200000 t per year. Generally the production of a commercial electrochemical process is around 100t per year or lower. There are currently more than a 100 processes running at this scale over the world. It is expected that advances in the field of electrochemical engineering, such as minimization in cell cost, electricity consumption and optimisation of product selectivity, will pave the way for further expansion of the smaller electrochemical processes.

Tables 2.1 to 2.4 illustrate the most important industrial electrochemical processes in operation, classified according to reaction type. All the information in these Tables is extracted from Robert Jansson Chemical Engineering News.45

Table 2.1 Cathodic coupling

<table>
<thead>
<tr>
<th>Type</th>
<th>No</th>
<th>Starting material</th>
<th>Product</th>
<th>Statusa</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=C</td>
<td>1</td>
<td>Acrylonitrile</td>
<td>Adiponitrile</td>
<td>C</td>
<td>Monsanto</td>
</tr>
<tr>
<td>C=O</td>
<td>2</td>
<td>Formaldehyde</td>
<td>Ethylene glycol</td>
<td>B/P</td>
<td>Electrosyn</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Acetone</td>
<td>Pinacol</td>
<td>P</td>
<td>BASF, Bayer</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Acetylpyridine</td>
<td>A pinacol</td>
<td>B/P</td>
<td>Ciba</td>
</tr>
</tbody>
</table>

a: B – bench-scale development of significance, P – pilot-plant development, C – Commercial process
Table 2.2  Anodic coupling

<table>
<thead>
<tr>
<th>Type</th>
<th>No</th>
<th>Starting material</th>
<th>Product</th>
<th>Status</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kolbe</td>
<td>1</td>
<td>Adipic hemiesters</td>
<td>Sebacic diesters</td>
<td>P/C</td>
<td>BASF, USSR, Asahi Chemical</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Monomethyl suberate</td>
<td>Tetradecanedioic ester</td>
<td>C</td>
<td>Soda Aromatic (Japan)</td>
</tr>
</tbody>
</table>

a : P – pilot-plant development, C – Commercial process

Table 2.3  Cathodic hydrogenation of carbon containing multiple bonds

<table>
<thead>
<tr>
<th>Type</th>
<th>No</th>
<th>Starting material</th>
<th>Product</th>
<th>Status</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=C</td>
<td>1</td>
<td>Maleic acid</td>
<td>Succinic acid</td>
<td>C</td>
<td>CERCI</td>
</tr>
<tr>
<td>C=C</td>
<td>2</td>
<td>Benzene</td>
<td>1,2-Dihydrobenzene</td>
<td>P</td>
<td>Exxon, Monsanto</td>
</tr>
<tr>
<td>C≡N</td>
<td>3</td>
<td>Tetra-hydrocarbazole</td>
<td>Carbazoline</td>
<td>C</td>
<td>BASF</td>
</tr>
<tr>
<td>C=O</td>
<td>4</td>
<td>Glucose</td>
<td>Sorbitol/manitol</td>
<td>C</td>
<td>Atlas Powder</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Carbon dioxide</td>
<td>Oxalic acid</td>
<td>B</td>
<td>DECHHEMA</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Oxalic acid</td>
<td>Glyoxylic acid</td>
<td>C</td>
<td>Rhone Poulenc, Steeley Chemicals</td>
</tr>
<tr>
<td>COOH</td>
<td>7</td>
<td>Anthranilic acid</td>
<td>o-Aminobenzyl alchol</td>
<td>P/C</td>
<td>BASF</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>salicylic acid</td>
<td>Salicylaldehyde</td>
<td>F</td>
<td>USSR, CERCI</td>
</tr>
<tr>
<td>NO₂</td>
<td>9</td>
<td>Nitrobenzene</td>
<td>Aniline</td>
<td>C</td>
<td>CERCI</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>o-Nitrotoluene</td>
<td>o-Toluidine</td>
<td>C</td>
<td>CERCI</td>
</tr>
</tbody>
</table>

a : B – bench-scale development of significance, P – pilot-plant development, C – Commercial process, F – former processes
## Table 2.4  Anodic functionalization (oxidation)

<table>
<thead>
<tr>
<th>Type</th>
<th>No</th>
<th>Starting material</th>
<th>Product</th>
<th>Status&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation (2 F)</td>
<td>1</td>
<td>Butane</td>
<td>Methyl ethyl ketone</td>
<td>P</td>
<td>Exxon</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Ethyl oxalate</td>
<td>Ethyl isocyanate</td>
<td>B</td>
<td>Royal Dutch Shell</td>
</tr>
<tr>
<td>Oxidation (4 F)</td>
<td>3</td>
<td>Isobutanol</td>
<td>Isobutyric acid</td>
<td>P/C</td>
<td>USSR</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Toluene</td>
<td>Benzaldehyde (redox e.g. Ce&lt;sup&gt;4+&lt;/sup&gt;)</td>
<td>P</td>
<td>CERCI</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>p-Xylene</td>
<td>Tolualdehyde (redox e.g. Ce&lt;sup&gt;4+&lt;/sup&gt;)</td>
<td>P</td>
<td>CERCI</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>p-Methoxy toluene</td>
<td>p-Methoxy benzaldehyde (via methoxylation)</td>
<td>C</td>
<td>BASF</td>
</tr>
<tr>
<td>Oxidation (6 F)</td>
<td>7</td>
<td>p-Nitrotoluene</td>
<td>p-Nitrobenzoic acid</td>
<td>C</td>
<td>CERCI</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Benzene</td>
<td>Quinone</td>
<td>P</td>
<td>Braunkohlen, ECRC</td>
</tr>
<tr>
<td>Hydroxylation</td>
<td>9</td>
<td>Benzene</td>
<td>Hydroquinone</td>
<td>P</td>
<td>Union Rheinisch</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Naphthalene</td>
<td>$\infty$-Naphthol (via acetoxylation)</td>
<td>P/C</td>
<td>BASF</td>
</tr>
</tbody>
</table>

<sup>a</sup>: B – bench-scale development of significance, P – pilot-plant development, C – Commercial process
Molecules can be coupled to synthesize products. The most important industrial example of this type of reaction is the Monsanto process mentioned above and shown as number 1 in Table 2.1. Cathodic coupling is summarized in Table 2.1 and anodic coupling in Table 2.2.

Reduction reactions, involving cathodic hydrogenation of carbon compounds, containing multiple bonds, are shown in Table 2.3. Oxidation reactions, describing anodic conversion of functional groups, are shown in Table 2.4.

\[
\text{R-OH} \xrightarrow{4F} \text{R-COOH} \quad (2.1)
\]

\[
\text{Ar} \xrightarrow{4F} \text{Ar-} \quad (2.2)
\]

\[
\text{Ar} \xrightarrow{6F} \text{Ar-COOH} \quad (2.3)
\]

\[
\text{Ar} \xrightarrow{6F} \quad (2.4)
\]

In Equations 2.1 to 2.4 R is an alkyl group and Ar the aryl group, whilst F is the amount of faradays per mole for the particular reaction, which is the same as the number of electrons per molecule required.
2.4 PRACTICE OF ELECTROCHEMICAL SYNTHESIS

In this section the practical aspects of electrochemistry over conventional chemical methods will be discussed, along with the various approaches to perform electrochemical reactions.

2.4.1 Electrochemical versus conventional chemical methods

Every successful chemical reaction involving oxidation or reduction, should have an electrochemical equivalent, whilst the opposite of this statement should also be true. At present this is not the case, the reason being that in many cases suitable chemical redox reagents have not yet been discovered. In electrochemistry, the conditions can be as forcing or as mild as required; this is normally governed by the potential at which the working electrode operates.

Electrochemistry has several advantages and disadvantages when compared to conventional chemical techniques. These are as follows:

- Reactor setup: Electrochemical reactors are more expensive than stirred tank reactors. On the other hand electrochemical reactors lend themselves better to automation; this is due to easier control of the electrical parameters.
- Utilities: A larger amount of electricity is needed in electrochemistry than conventional chemistry. The difference can be as small as an order of magnitude or even higher.
- Environmentally: Electrochemistry is viewed as a clean method. This is because there is improved management of potential pollutants, as well as possible minimization of toxic and hazardous reagents. This is achieved by the regeneration of redox reagents, (as in indirect oxidation using Ce⁴⁺) resulting in minimization of waste.
- Safety: Electrochemistry affords the ability to localise the generation of extreme conditions to only the cell, thus minimizing the risks involved in plant operations. Examples of this are the in-situ generation of hydrogen peroxide and lithium aluminium hydride. The reactions are also operated under milder conditions (temperature and pressure).
Reaction: Electrochemistry affords better control over reaction rate. In many cases it also reduces the number of reaction steps and allows novel chemical transformations to be performed. The electrochemical production of quinone from benzene is an example of a decrease in the number of reaction steps required when compared to conventional methods. The reactions are shown in Equations 2.5 to 2.8 below.

**Electrochemical process**

\[
\text{C}_6\text{H}_6 - 6e^- - 6\text{H}^+ + 2\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_4\text{O}_2 \quad (2.5)
\]

**Conventional process**

i) The oxidation and nitration of benzene to nitrobenzene (Equation 2.6):

\[
\text{C}_6\text{H}_6 + \text{HNO}_3 \rightarrow \text{C}_6\text{H}_4\text{NO}_2 \quad (2.6)
\]

ii) Reduction of nitrobenzene to aniline (Equation 2.7):

\[
\text{C}_6\text{H}_4\text{NO}_2 + [\text{H}] \rightarrow \text{C}_6\text{H}_4\text{NH}_2 \quad (2.7)
\]
iii) Oxidation of aniline to quinone with chromic acid (Equation 2.5):

\[
\text{NH}_2 \quad \xrightarrow{\text{H}_2\text{CrO}_4} \quad \text{O} \quad \text{O}
\]

- Product quality \( R^\text{R} \): There is normally an improvement in product quality. This is due to the fact that the selectivity of the electrochemical reactions is normally high and there is less and, more specifically, a smaller variety of impurities present in electrochemical processes as compared to the conventional methods.

- Convenience in work-up \( R^\text{R} \): The reactions generally yield fewer and less varied impurities due to the improved selectivities. Separation of chemical oxidants or reductants is also eliminated from the work-up procedure if allowance is made for the supporting electrolyte. All these factors contribute to processes which are more convenient to work up.

- Cost \( R^\text{R} \): Neglecting the initial cost of equipment, it is normally cheaper to run a electrochemical process than a conventional one. This is possible since the reagents used are electrons and electrons are normally considerably cheaper than chemical reagents, especially in a country where electricity is very cheap. \( R^\text{R} \)

Considering these factors it is possible to conceive a process where it will be more economical to perform the reaction electrochemically than it will be to perform it using conventional methods.

2.4.2 Direct versus Indirect Electron transfer

The main difference between these two electrochemical procedures is with regards to the mechanism of electron transfer.\(^{23, 28, 32, 37, 47}\)
• Direct electrochemistry: The transfer of the electrons takes place heterogeneously across the electrode / solution interface.

• Indirect electrochemistry: The electron transfer takes place between a mediator and a substrate. The electron transfer can be either hetero- or homogeneous, since the nature of the mediator can differ.

2.4.2.1 Direct electron transfer

Since the electron transfer takes place heterogeneously across the electrode solution interface, it is easy to determine the potential at which the substrate undergoes an electrochemical reaction. This is determined through electrochemical analysis such as cyclic voltammetry.

The mechanism of direct electron transfer is explained below:

• Migration of the substrate to the electrode surface

• Adsorption of the substrate on the electrode surface

• Electron transfer between the electrode and the substrate, forming a radical

• Either, reaction of the generated radical followed by desorption of the product or desorption of the radical followed by further reaction to a product.

Tables 2.1 – 2.4 gives many examples of direct electron transfer processes.

2.4.2.2 Indirect electron transfer

In this process a mediator is used which selectively oxidises or reduces the substrate to the target compound. This mediator is then regenerated electrochemically either in-cell, or ex-cell after separation of the organic phase.

An example is the conversion of anthracene to anthraquinone via electrogenerated chromic acid. A concentrated solution of
chromium(III) in aqueous sulphuric acid is partly oxidized to chromic acid at a PbO\textsubscript{2} anode (Equation 2.9):

\[
2 \text{Cr}^{3+} + 7 \text{H}_2\text{O} + 6 \text{e}^- \rightarrow \text{Cr}_2\text{O}_7^{2-} + 14\text{H}^+ \tag{2.9}
\]

and the dichromate is then reacted with anthracene (Equation 2.10):

\[
\begin{array}{c}
\text{Anthracene} + 8\text{H}^+ + \text{Cr}_2\text{O}_7^{2-} \\
\rightarrow \text{Anthraquinone} + 2\text{Cr}^{3+} + 5\text{H}_2\text{O}
\end{array} \tag{2.10}
\]

This reaction takes place in a separate reactor, and the above process has been carried out for over 50 years. Recent improvements have been introduced where the electrolysis is performed in a membrane cell and the chemical step is carried out by allowing the chromic acid to trickle through a column of solid anthracene.

Another example is the use of Ce\textsuperscript{4+} as mediator in the selective oxidation of various toluenes to the respective benzaldehyde, as shown in Table 2.4 (entries 4, 5). Here the Ce\textsuperscript{3+}, formed upon oxidation of the toluene, is regenerated electrochemically to form Ce\textsuperscript{4+} and recycled in the reactor.\textsuperscript{51}

Mediators can be either inorganic or organic in nature, and operate homogeneously (Ce\textsuperscript{4+}) or heterogeneously, when the mediator is bound to the electrode (MnO\textsubscript{2}, PbO\textsubscript{2}).\textsuperscript{47}

There are several advantages of indirect electron transfer:

- The redox catalyst can have a high solubility in water, allowing electrochemistry to be carried out at high current densities in an aqueous electrolyte.
- Multiphase procedures can lead to straightforward product isolation.
• Since the redox reagent is recycled, the problems of using toxic reagents are reduced and large volumes of unwanted solid or solution effluent are not produced.

2.4.3 Constant current and constant potential electrolysis

Electrochemical reactions can be carried out using one of two procedures: constant current and constant potential electrolysis.\textsuperscript{30, 52}

• Constant potential electrolysis: This reaction is carried out as the name suggests. The potential of the working electrode is kept constant with respect to a reference electrode. As the reaction proceeds the cell current gradually decreases.

• Constant current electrolysis: The current is kept constant throughout the reaction, whilst the potential of the electrolysis system changes gradually as the reaction proceeds.

In constant potential and constant current electrolysis the amount of charge sent through the reaction mixture can be determined using Equation 2.11 and 2.12 respectively.\textsuperscript{52}

\[ Q = \int_{0}^{\infty} I dt = nFN \]  
\[ Q = \int_{0}^{\infty} I dt = It = nFN \]  

Referring to Equations 2.11 and 2.12 the symbols can be explained as follows:

• Q is the quantity of electricity (in coulombs passed through the cell))
• I is the current (Ampere).
• n is the total number of electrons involved per molecule.
• t is time (seconds).
• F is the Faraday constant; it is the charge needed (96500 coulombs) per mole of substrate to effect the electrochemical reaction, assuming there is a one electron change.
• N is the number of moles of substrate initially present.
These two processes have several advantages and disadvantages when compared to each other. These are as follows: \(^{30}\)

- Complexity of equipment: The electronic equipment to both effect and monitor the electrolysis in constant current electrolysis is much less complicated than that needed for constant potential electrolysis.
- Selectivity: Constant potential electrolysis is much more selective than constant current electrolysis. With proper understanding of the specific reaction being investigated, the selectivity of constant current electrolysis can approach that of constant potential electrolysis.

Taking the above into account, it is not difficult to see why most of the electrolysis procedures carried out in industry today are done using constant current electrolysis.

### 2.4.4 Divided versus undivided

Electrolysis procedures, whether direct or indirect, can be carried out in the simplest way using one of two methods: undivided (one compartment) or divided (two compartments). These are explained below: \(^{30, 32}\)

- Undivided: Here there is no separation between the anode (oxidation) and the cathode (reduction), i.e. the two electrodes are immersed in the same solution.
- Divided: Here there is a physical separation (micro-porous divider) between the anolyte and the catholyte. This prevents products, formed at one electrode, from migrating to the other where it can undergo additional reactions.

There are several advantages and disadvantages of using divided and undivided processes in electrochemical synthesis. These are mentioned below: \(^{30, 32}\)

- Cell design: This is much less complicated in undivided processes than it is in divided processes. The separator used in the divided cell can also cause problems: the cell resistance is increased and this problem could
be magnified if fouling of the separator occurs. When scaling-up, it is known that an undivided reactor is cheaper than a divided reactor by an order of magnitude.

- Reactions: Divided cells prevent the occurrence of side reactions, which can occur at the counter electrode, which can interfere with the reaction in question. The divided cell does, however, facilitate the possibility of performing paired synthesis, where two distinctly separate reactions could be carried in the same reactor at the same time.

The separators used in divided electrolysis can be of two kinds: 30, 32

- Inert physical separation: These separators normally consist of sintered glass or micro-porous polypropylene and only prevent substantial mixing of the anolyte and the catholyte.

- Ion exchange separators: These separators consist of polymers, which have functional groups bonded to the polymer itself; an example of this is Nafion. These separators prevent the mixing of the anolyte and the catholyte solutions. The flow of charge is facilitated by ion exchange reactions, which take place between the solution and the membranes.

As mentioned above, it is known that industry would prefer the construction of undivided cells above that of divided cells, purely because of financial reasoning.

2.5 REACTION TYPES ENCOUNTERED DURING ELECTROLYSIS OF AROMATIC HYDROCARBONS

A variety of reactions can take place upon electrolysis of a solution containing aromatic substrates. These reactions are facilitated through electron transfer and are possible if there is a potential difference between the two electrodes. Two types of reactions can take place, which can be explained using molecular orbital theory: 32

- Oxidation (anodic): the loss of electrons from the highest occupied molecular orbital (HOMO).
- Reduction (cathodic): Acceptance of electrons into the lowest unoccupied molecular orbital (LUMO).

This section will concentrate on electrochemical oxidation. This is because the majority of work done in this investigation covers electrochemical oxidation. The most common reactions encountered during the electrochemical oxidation of aromatic substrates are as follows:

- Side chain substitution (Equation 2.13).\(^{53}\)

\[
\text{R-H} \quad + \text{Nu} \quad \xrightarrow{\text{H}^+, \text{-}2\text{e}^-} \quad \text{R-Nu}
\]  

(Equation 2.13)

- Nuclear substitution (Equation 2.14).\(^{54}\)

\[
\text{R} \quad + \text{Nu} \quad \xrightarrow{-2\text{e}^-} \quad \text{R-Nu}
\]  

(Equation 2.14)

- Nuclear substitution and addition (Equation 2.15).\(^{55}\)

\[
\text{R} \quad + 2\text{Nu} \quad \xrightarrow{-2\text{e}^-} \quad \text{R-Nu}_2
\]  

(Equation 2.15)
Factors which affect the type of reaction which aromatic substrates undergo, can be divided into the following main sections: 30, 32, 37, 56-59

- Structure and nature of the substrate which produces the radical ion: The substituents on the molecule will affect the route the reaction follows; substituents which are electron donating (-OH) will make the molecule more susceptible to oxidation whereas electron accepting substituents (-NO₂) will have the opposite effect. Substituents which are conjugated with the ring or possess non-bonded electron pairs will aid in the stabilization of charges formed on the molecule. The reason for this is resonance stabilization.

- Environment in which the substrate and resulting radical ion finds itself: This includes variables such as:
  - Electrodes: Electrodes affect both the formation of the radical and the follow-up reactions of the radical. This is done through adsorption of the substrate onto the electrode surface in a specific orientation. This orientation can then affect factors such as the regioselectivity of the reaction, resulting in the promotion of one reaction above another on electrodes.
  - Solvent and supporting electrolyte: These factors affect the reaction to a great extent. They can either take part in the reaction (nucleophile or electrophile) or they can aid in both the chemical and electrochemical steps of the reaction. The following properties of solvents and electrolytes are important in affecting the reaction mechanism:
    - Proton availability: This is an important factor in governing the route and rate of the reaction, since most electrochemical
reactions are affected by either the gain or loss of protons. This results in the classification of solvents according to the proton availability:

- Protic: Proton rich (water)
- Aprotic: Lack of protons (acetonitrile)
- Semi-protic: Availability of protons to an extent (mixture of water and acetonitrile in varying ratios).

✧ Conductivity and dielectric constant: These two factors are closely related. The dielectric constant is a measure of the ability of the solvent to dissolve compounds and the dissolved compounds can conduct electricity. The conductivity of the reaction mixture can affect the reaction.

✧ Viscosity: This influences the mass transport mechanism in the reaction mixture, thus possibly affecting the route of the reaction, since electrochemical reactions take place between the radical and other constituents of the solution. If these components cannot reach each other, the radical formed during the electrolysis will react with itself or the substrate so producing dimers and polymers.

Temperature: The temperature of the reaction mixture can also have an effect on the reaction, since it affects the stabilities of the different participants in the reaction as well as the conductivity and the mass transport of the solution.
2.5.1 General reactions of radical cations

Radical cations are formed upon oxidation of aromatic substrates as shown in Equation 2.17.\textsuperscript{53, 54, 55, 58}

\[ R \quad \overset{-e^-}{\longrightarrow} \quad \overset{+}{R} \quad \text{(2.17)} \]

As mentioned in Section 2.5, the factors influencing the stability of this radical cation will govern the route the reaction follows.

The reactions shown in Section 2.5 are possible because of the reactivity of this radical cation in different situations.\textsuperscript{60}

- Radical cations derived from saturated systems will preferentially lose a proton to yield a radical as shown in Equation 2.18:

\[ \text{RH}^+ \quad + \quad \text{B}_2 \quad \longrightarrow \quad \text{R}' \quad + \quad \text{BH} \quad \text{(2.18)} \]

- Radical cations derived from unsaturated systems can react via Equations 2.19, 2.20 and 2.21.

\[ \text{RH}^+ \quad + \quad \text{Nu}^- \quad \longrightarrow \quad \text{HR}^- \quad \longrightarrow \quad \text{Nu} \quad \text{(2.19)} \]

\[ \text{RH}^+ \quad + \quad \text{B}_2 \quad \longrightarrow \quad \text{R}' \quad + \quad \text{BH} \quad \text{(2.20)} \]

\[ \text{RH}^+ \quad + \quad \text{RH}^+ \quad \longrightarrow \quad \text{HR}^+ \quad \cdots \quad \text{HR}^+ \quad \text{(2.21)} \]

- Radical cations can be oxidised further to di-cations at the anode as shown in Equations 2.22.

\[ \text{RH}^+ \quad - \quad e^- \quad \longrightarrow \quad \text{RH}^{2+} \quad \text{(2.22)} \]
The reaction with the nucleophile (Equation 2.19) and the base (Equation 2.20) predominate over the coupling reaction (Equation 2.21), which is relatively rare.\textsuperscript{60}

Deprotonation of the radical cation depends on the reaction mechanism. But normally occurs just after the first oxidation step.

Due to the wide variety of reactions, which radical cations can undergo, there is the possibility of forming complex mixtures of products during anodic reactions.

2.6 Reaction types applied to phenol

It is generally accepted that the first step in the electrochemical oxidation of aromatic compounds involves the removal of an electron from the substrate in order to produce a radical cation as shown in Equation 2.23.\textsuperscript{58} The formation of this radical cation is important to explain the electrochemical behaviour of phenol because phenol will not react with water, but the radical cation of phenol will. This is umpolung, where an electron rich species (phenol) is converted to an electron deficient species (radical cation).\textsuperscript{58}

\[
\begin{array}{c}
\text{OH} \\
\text{Ph} \\
\rightarrow \quad \text{Ph}^+ \\
\text{OH}
\end{array}
\]  

(2.23)

Phenolic compounds are easily oxidised.\textsuperscript{58} This is because the hydroxyl group is electron donating and the loss of electrons can be stabilized. The hydroxyl group has non-bonded electron pairs on the oxygen, which can take part in the resonance stabilization of the molecule\textsuperscript{59}. Using these resonance forms, predictions can be made on possible reaction pathways the molecule might undergo.
The stabilization of the radical cation is achieved through the delocalisation of both the positive charge and radical through the conjugated system.

2.6.1 Side chain substitution

The most important prerequisite for the side chain substitution of the aromatic substrate is the presence of $\alpha$-hydrogens. Since none of these hydrogens are present on phenol, side chain substitution cannot take place.

2.6.2 Nuclear substitution

This reaction normally takes place when:

- Strong nucleophiles are present.
- The ring is not highly alkylated.

The process is shown in Scheme 2.1 and can be explained as follow:

I. The substrate loses an electron in order to produce a radical cation.

II. The radical cation then loses a proton in order to produce a radical.

III. The radical then loses an additional electron in order to produce a cation.

IV. This cation then undergoes attack by a nucleophile in order to produce the nucleophilic-substituted product.

Scheme 2.1: Nuclear substitution
2.6.3 Nuclear substitution and addition\textsuperscript{56}

This reaction takes place under the same conditions as nuclear substitution, but can predominate under certain conditions mentioned below:

- In an environment where protons are not easily lost.
- Very strong nucleophiles are present.
- The ring is not sterically hindered.

The process is shown in Scheme 2.2 and can be explained as follow:

I. The substrate loses an electron in order to produce a radical cation.
II. The radical cation is attacked by a nucleophile.
III. The radical loses an additional electron in order to produce a cation.
IV. This cation is then again attacked by a nucleophile in order to produce the product.

Scheme 2.2: Nuclear substitution and addition

2.6.4 Dimerization\textsuperscript{56}

This type of reaction takes place when:

- There is no nucleophile present in the reaction medium.
- The mass transfer of the reaction mixture is not good enough to replenish the depleted concentration of the nucleophile present in the vicinity of the radical cation.
Under these conditions the substrate itself can act as a nucleophile towards the cationic radicals, resulting in the formation of dimers and polymers.

Two possibilities can occur in the case of phenolic compounds:

- Nuclear dimerization as shown in Scheme 2.3.

**Scheme 2.3: Nuclear dimerization**

- Side chain dimerization as shown in Schemes 2.4 and 2.5.

**Scheme 2.4: Side chain dimerization (side chain, nuclear)**

**Scheme 2.5: Side chain dimerization (side chain, side chain)**
A variety of dimers can be formed when phenolic compounds are electrolysed. An indication of the identity of the dimers formed can be gained when looking at the possible resonance structures attainable for the radical and radical cation.

### 2.7 POSSIBLE PATHWAYS TOWARDS HYDROXYLATED PHENOLS

During a literature survey a variety of technologies were found which can be used to effect electrochemical hydroxylation of aromatic compounds. These methods will be briefly mentioned below. More emphasis will be placed on the technologies thought to be viable and possible using the equipment available.

#### 2.7.1 Indirect procedures using inorganic ions

The following technologies, based on the electrochemistry of inorganic ions, could be used to hydroxylate aromatic substrates:

- **Inorganic peroxides**: Among these are potassium peroxydiphosphate, sodium perborate, potassium peroxydisulphate and hydrogen peroxide. To organic chemists they are well known as stoichiometric oxidants but the fact that they can be regenerated using electrochemical means is relatively unknown. The most important example here is the electrogenerated fentons reagent.

- **Catalysis regeneration**: Acetoxylation can be done using catalysis. An example of this is the use of cobalt acetate in order to acetoxylate aromatic substrates. This catalyst can be regenerated electrochemically.

- **Inorganic metal mediators**: Metal ions such as V(II) and Cr(II) were found to be able to hydroxylate phenol in the presence of oxygen. These processes do, however, suffer from low current efficiencies, and product outputs.

These indirect processes were not investigated. The reason for this was that the necessary equipment needed to compensate for the inherent problems
associated with indirect electrochemistry, such as low current efficiencies and a low product to reagent volume ratio, were not available.

### 2.7.2 Indirect procedures based on acyloxylation

This is a broad classification for processes in which the nucleophiles are acetate anions. The reaction proceeds through the oxidation (anodic) of the aromatic substrate, followed by nucleophilic attack to form the aromatic acetate. Two reactions were investigated: acetoxylation, where the nucleophile is an acetate,\(^{71, 72}\) and trifluoro-acetoxylation,\(^{73}\) where the nucleophile is a trifluoro-acetate. The reaction is shown in Scheme 2.6. After the reaction, the acyloxylated products are hydrolysed to the corresponding phenolic compound, with the release of the corresponding carboxylic acid, according to Equation 2.24.

**Scheme 2.6: Acyloxylation**

- **Acetoxylation:** \(R_1 = \text{OH and } R_2 = \text{CH}_3\)
- **Trifluoro-acetoxylation:** \(R_1 = \text{OH and } R_2 = \text{CF}_3\)

The mechanism (Scheme 2.6) for the production of the acetate is an ECEC mechanism:

1. **E:** The anodic oxidation of the aromatic substrate at the electrode surface in order to produce the radical cation, followed by resonance stabilization of this radical. The extent to which the oxidation occurs
depends on the oxidation potential of the substrate. The lower the oxidation potential the greater the extent of the reaction.

II. C: The loss of a proton from the cationic radical in order to produce a radical, followed by resonance stabilization. The location and the rate at which this proton is lost depend on the acidity of the reaction environment in which the cationic radical finds itself.

III. E: The loss of an electron from the radical in order to produce the organic cation, followed by resonance stabilization of this cation.

IV. C: Nucleophilic attack of the ester anion on the cation in order to form the neutral aromatic ester.

\[ \text{R}_1 \text{OH + R}_2 \text{CO}_2^- \rightarrow \text{R}_1 \text{OH} + \text{R}_2 \text{COOH} \]  \hspace{1cm} (2.24)

\( R_1 = \text{OH and } R_2 = \text{CH}_3 \text{ or CF}_3 \)

2.7.2.1 Kolbe reaction\(^7\)\(^4\)

This is an anodic process in which an acetate anion is oxidised to carbon dioxide and a radical. This process is shown Equation 2.25. The radical can then take part in a variety of reactions.

\[ \text{RCOO}^- - e^- \rightarrow \text{CO}_2 + \text{R}' \]  \hspace{1cm} (2.25)

During acyloxylation reactions, the Kolbe process is an unwanted side reaction, which results in by-product formation, decreased current efficiency and accountabilities.
2.7.3 Direct electrochemical hydroxylation

The proposed mechanism, involving the direct electrochemical oxidation of the phenolic substrate, is shown in Schemes 2.7 and 2.8 below. When considering the mechanism it can be seen that it is an ECEC, mechanism. The end result of the oxidation is the production of the benzoquinone.

Scheme 2.7: Oxidation to benzoquinone

R₁ and R₂ can be virtually anything but in this investigation it was H or C(CH₃)₃.

I. E: Anodic oxidation of the aromatic substrate at the electrode surface in order to produce the radical cation, followed by resonance
stabilization of this radical. The extent to which this occurs depends on the oxidation potential of the phenolic compound. The lower the oxidation potential the greater the extent of the reaction.

II. C: The loss of a proton from the radical cation in order to produce the radical, followed by resonance stabilization of this radical. The location from which this proton is lost depends on the acidity of the phenolic group. This is a rapid reaction due to the acidity of the phenolic radical cation, since the pKa value is in the range of 9.98 for unsubstituted phenol.\textsuperscript{74}

III. E: The loss of an electron from the radical in order to produce the organic cation, followed by resonance stabilization of this cation.

IV. C: Nucleophilic attack of water on the cation, resulting in a highly unstable structure, which is then rapidly rearranged, with the loss of a proton.

V. E: Anodic oxidation of the hydroxy substituted compound at the electrode surface in order to produce the radical cation, followed by resonance stabilization of this radical.

VI. C: The loss of a proton from the radical cation in order to produce the radical, followed by resonance stabilization of this radical. The location from which this proton is lost depends on the acidity of the phenolic group. This is a rapid reaction due to the acidity of the phenolic radical cation, since the pKa value is in the range of 9.98 for unsubstituted phenol.\textsuperscript{74}

VII. E: The loss of an electron from the radical in order to produce the organic cation, followed by resonance stabilization of this cation.

VIII. C: Nucleophilic attack of water on the cation, resulting in a highly unstable structure, which is then rapidly rearranged, with the loss of a proton in order to produce the hydroxy substituted compound.

IX. This molecule then loses water in order to produce the benzoquinone.

\(\rho\)-Benzoquinone is the predominating isomer. This can be explained through the relative stabilities of the isomeric benzoquinones, as well as the directing effect of the hydroxyl group already present on the ring.
This reaction can also take place in a basic solution; if this is the case, the mechanism follows the CECE mechanism, where the initial C reaction is the loss of the acidic proton on the hydroxy group.

**Scheme 2.8: Reduction to hydroquinone**

R₁ and R₂ can be virtually anything but in this investigation it was H or C(CH₃)₃

I. **E:** A one electron reduction of the benzoquinone at the cathode in order to produce the radical anion. This radical can then be resonance stabilized. The ease with which this occurs depends on the reduction potential of the molecule.

II. **C:** The addition of a proton to the radical anion followed by electron rearrangement within the molecule in order to produce the aromatic radical.

III. **E:** The gain of an additional electron to the molecule so as to form an anion, which is resonance stabilized. In a protic media, this species will be short lived, due to the high proton affinity of the anion.

IV. **C:** The anion will then rapidly accept a proton from almost any source in order to produce the hydroquinone.
2.8 Outline of study

The objective of the investigation is to study the anodic hydroxylation of phenol, 2-tert-butylphenol and 2,6-di-tert-butylphenol with the aim of maximizing the electrochemical production of the corresponding hydroquinones.

The investigation will be limited to the anodic oxidation of substrates that can be easily produced from phenol and substituted phenols.
CHAPTER 3

EXPERIMENTAL

3.1 MATERIALS

3.1.1 Reagents for synthesis

All reagents used in the electrochemical synthesis procedures, together with their sources and respective grades, are listed in Table 3.1 and were used as received.

Table 3.1: Reagent for synthesis

<table>
<thead>
<tr>
<th>CHEMICAL NAME</th>
<th>CHEMICAL FORMULA</th>
<th>SOURCE</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,6-Di-tert-butylphenol</td>
<td>(C₄H₉)₂C₆H₅OH</td>
<td>Fluka</td>
<td>AR</td>
</tr>
<tr>
<td>2-tert-Butylphenol</td>
<td>C₄H₉C₆H₅OH</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Acetic Acid, Sodium salt</td>
<td>CH₃COONa</td>
<td>Saarchem</td>
<td>Ar</td>
</tr>
<tr>
<td>Acetic Anhydride</td>
<td>(CH₃CO)₂O</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>CH₃CN</td>
<td>BDH</td>
<td>HPLC</td>
</tr>
<tr>
<td>Catechol</td>
<td>C₆H₄(OH)₂</td>
<td>BDH</td>
<td>CP</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>CH₃CH₂OCOCH₃</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Glacial Acetic Acid</td>
<td>CH₃COOH</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Hydroquinone</td>
<td>C₆H₄(OH)₂</td>
<td>BDH</td>
<td>AR</td>
</tr>
<tr>
<td>Phenol</td>
<td>C₆H₅OH</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Phenyl Acetate</td>
<td>C₆H₅OCOCH₃</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>p-Toluene sulphonic acid</td>
<td>C₇H₁₀O₄S</td>
<td>Acros</td>
<td>AR</td>
</tr>
<tr>
<td>Resorcinol</td>
<td>C₆H₄(OH)₂</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>NaCl</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>NaOH</td>
<td>BDH</td>
<td>CP</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>H₂SO₄</td>
<td>Skymchem</td>
<td>CP</td>
</tr>
<tr>
<td>Tetraethylammonium p-toluenesulphonate</td>
<td>(C₂H₅)₄N(O₃SC₆H₄CH₃</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
</tbody>
</table>
### CHEMICAL NAME | CHEMICAL FORMULA | SOURCE | GRADE  
---|---|---|---
Trifluoroacetic Acid | CF₃COOH | Aldrich | AR  
Trifluoroacetic Acid, Sodium salt | CF₃COONa | Aldrich | AR  
Trifluoroacetic Anhydride | (CF₃CO)₂O | Merck | AR  
Water | H₂O | BHT DSA-30 water system | 12 μS.cm⁻¹  
Magnesium sulphate (anhydrous) | MgSO₄ | Saarchem | CP  

A = Ar = Analytical Reagent, CP = Chemically Pure, HPLC = HPLC grade

#### 3.1.2 Reagents for analysis

##### 3.1.2.1 Reagents for electro-analytical studies

All the reagents used in the electro-analytical studies were of analytical grade, and are listed in Table 3.2. The preparation of compounds used for electro-analytical standards are described in Section 3.2.

#### Table 3.2: Reagents for electro-analytical procedures

| CHEMICAL NAME | CHEMICAL FORMULA | SOURCE | GRADE  
---|---|---|---
1,2-Di-acetoxybenzene | (CH₃COO)₂C₆H₄ | Synthesis | 99 %  
1,3-Di-acetoxybenzene | (CH₃COO)₂C₆H₄ | Synthesis | 98%  
1,4-Di-acetoxybenzene | (CH₃COO)₂C₆H₄ | Synthesis | 99 %  
2,6-Di-tert-butylbenzoquinone | (C₄H₉)₂C₆H₂O₂ | Synthesis | 99 %  
2,6-Di-tert-butylhydroquinone | (C₄H₉)₂C₆H₂(OH)₂ | Synthesis | 98 %  
2,6-Di-tert-butylphenol | (C₄H₉)₂C₆H₂OH | Aldrich | AR  
2-tert-Butylbenzoquinone | (C₄H₉)C₆H₃O₂ | Synthesis | 99 %  
2-tert-Butylhydroquinone | (C₄H₉)C₆H₃(OH)₂ | Synthesis | 98 %  
2-tert-Butylphenol | (C₄H₉)C₆H₄OH | Aldrich | AR
<table>
<thead>
<tr>
<th>CHEMICAL NAME</th>
<th>CHEMICAL FORMULA</th>
<th>SOURCE</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>CH₃COOH</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Acetic acid, Sodium salt</td>
<td>CH₃COONa</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Acetic Anhydride</td>
<td>(CH₃CO)₂O</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>CH₃CN</td>
<td>BDH</td>
<td>HPLC</td>
</tr>
<tr>
<td>Benzoquinone</td>
<td>(C₆H₄)O₂</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Catechol</td>
<td>C₆H₄ (OH)₂</td>
<td>BDH</td>
<td>CP</td>
</tr>
<tr>
<td>Hydroquinone</td>
<td>C₆H₄ (OH)₂</td>
<td>BDH</td>
<td>AR</td>
</tr>
<tr>
<td>Phenol</td>
<td>C₆H₅OH</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Phenyl Acetate</td>
<td>C₆H₅OCOCH₃</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Resorcinol</td>
<td>C₆H₄ (OH)₂</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Sulfuric Acid</td>
<td>H₂SO₄</td>
<td>Skychem</td>
<td>CP</td>
</tr>
<tr>
<td>Trifluoroacetic Acid</td>
<td>CF₃COOH</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Trifluoroacetic Acid, Sodium salt</td>
<td>CF₃COONa</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Trifluoroacetic Anhydride</td>
<td>(CF₃CO)₂O</td>
<td>Merck</td>
<td>AR</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>BHT DSA-30 water system</td>
<td>12 μS.cm⁻¹</td>
</tr>
</tbody>
</table>

A – Ar = Analytical Reagent, CP = Chemically Pure, HPLC = HPLC grade

### 3.1.2.2 Reagents for GLC studies

All the reagents used in the GLC studies were of analytical grade, and are listed in Table 3.3. The preparation of compounds used for electro-analytical standards are described in Section 3.4.1.
Table 3.3: Reagents used for GLC analysis

<table>
<thead>
<tr>
<th>CHEMICAL NAME</th>
<th>CHEMICAL FORMULA</th>
<th>SOURCE</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2-Di-acetoxybenzene</td>
<td>(CH₃COO)₂C₆H₄</td>
<td>Synthesis</td>
<td>99 %</td>
</tr>
<tr>
<td>1,3-Di-acetoxybenzene</td>
<td>(CH₃COO)₂C₆H₄</td>
<td>Synthesis</td>
<td>98 %</td>
</tr>
<tr>
<td>1,4-Di-acetoxybenzene</td>
<td>(CH₃COO)₂C₆H₄</td>
<td>Synthesis</td>
<td>99 %</td>
</tr>
<tr>
<td>Benzoquinone</td>
<td>(C₆H₄)O₂</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>CH₃CH₂OCOCH₃</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₃OH</td>
<td>BDH</td>
<td>HPLC</td>
</tr>
<tr>
<td>Phenol</td>
<td>C₆H₅OH</td>
<td>Saarchem</td>
<td>AR</td>
</tr>
<tr>
<td>Phenyl Acetate</td>
<td>C₆H₅OCOCH₃</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>p-Iso-propyl benzaldehyde</td>
<td>(C₃H₇)C₆H₄CHO</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
</tbody>
</table>

A – Ar = Analytical Reagent, HPLC = HPLC grade

3.1.2.3 Reagents for HPLC studies

All the reagents used in the HPLC studies were of analytical grade, and are listed in Table 3.4. The preparation of compounds used for electro-analytical standards are described in Section 3.4.2.

Table 3.4: Reagents for HPLC analysis

<table>
<thead>
<tr>
<th>CHEMICAL NAME</th>
<th>CHEMICAL FORMULA</th>
<th>SOURCE</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,6-Di-tert-butylbenzoquinone</td>
<td>(C₄H₉)₂C₆H₂O₂</td>
<td>Synthesis</td>
<td>99 %</td>
</tr>
<tr>
<td>2,6-Di-tert-butylhydroquinone</td>
<td>(C₄H₉)₂C₆H₂(OH)₂</td>
<td>Synthesis</td>
<td>98 %</td>
</tr>
<tr>
<td>2,6-Di-tert-butylphenol</td>
<td>(C₄H₉)₂C₆H₃OH</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>2-tert-Butylbenzoquinone</td>
<td>(C₄H₉)C₆H₃O₂</td>
<td>Synthesis</td>
<td>99 %</td>
</tr>
<tr>
<td>2-tert-Butylhydroquinone</td>
<td>(C₄H₉)C₆H₃(OH)₂</td>
<td>Synthesis</td>
<td>98 %</td>
</tr>
<tr>
<td>2-tert-Butylphenol</td>
<td>(C₄H₉)C₆H₄OH</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>CH₃CN</td>
<td>BDH</td>
<td>HPLC</td>
</tr>
<tr>
<td>Benzoquinone</td>
<td>(C₆H₄)O₂</td>
<td>Aldrich</td>
<td>AR</td>
</tr>
<tr>
<td>Catechol</td>
<td>C₆H₄(OH)₂</td>
<td>BDH</td>
<td>CP</td>
</tr>
<tr>
<td>Hydroquinone</td>
<td>C₆H₄(OH)₂</td>
<td>BDH</td>
<td>AR</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₃OH</td>
<td>BDH</td>
<td>HPLC</td>
</tr>
</tbody>
</table>
### Table 3.5: Electrode materials

<table>
<thead>
<tr>
<th>Designation Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-1</td>
<td>Nickel flag</td>
</tr>
<tr>
<td>PB-1</td>
<td>Lead dioxide on titanium mesh (5 cm²).</td>
</tr>
<tr>
<td>PT-1</td>
<td>Platinum flag electrode (5 cm², sealed in glass tube).</td>
</tr>
<tr>
<td>PT-2</td>
<td>Platinum flag electrode (5 cm², sealed in glass tube).</td>
</tr>
</tbody>
</table>

3.1.2.4 Electrode material

The electrode materials used in the electrochemical reactions were obtained from Electrosynthesis Company Incorporated, Lancaster, NY, USA and are listed in Table 3.5 below.

3.2 Synthetic procedures

3.2.1 Synthesis of di-acetoxybenzenes

The corresponding dihydroxybenzene (3.5g; 32 mmol) was weighed into a 150 cm³ round-bottom flask containing 45 cm³ of an aqueous sodium hydroxide solution (10% m/v; 113 mmol). This resulted in a color change depending on which isomer was used. To this 45 g of ice was added in order to keep the reaction temperature close to 0 °C. The reaction was then
vigorously stirred while acetic anhydride (8 cm$^3$; 85 mmol) was quickly added. After the progress of 5 minutes, the stirring was stopped and the reaction left to reach room temperature.

The separation and purification of the standards depends on which di-acetoxybenzene was produced.

1,2- and 1,4-Di-acetoxybenzene: These products are both white solids at room temperature. The solid product is filtered and washed with three 50 cm$^3$ portions of water. The remaining solid is then recrystallized from a water / ethanol solution, dried and stored in a vacuum desiccator.

1,3-Di-acetoxybenzene: This product is a translucent liquid at room temperature. The 1,3-di-acetoxybenzene is separated form the aqueous solution by decantation and purified by washing three times with 50 cm$^3$ of water. The 1,3 di-acetoxybenzene is then dissolved in 50 cm$^3$ of ethyl acetate and dried over 5 g of anhydrous magnesium sulphate. After this, the ethyl acetate is distilled off and the remaining 1,3 di-acetoxybenzene stored in a desiccator.

The identification and purity determinations of the standards were done using two techniques, GC-MS and DSC. The MS traces for 1,2 -, 1,4 - and 1,3-di-acetoxybenzene indicated that the products were successfully synthesized. The DSC and GC-MS area percentages indicated that the compounds were of acceptable purity and the melting points confirmed this. These results are shown in Table 3.6. The chromatogram, MS trace and DSC results are shown in the addendum.
Table 3. 6: Di-acetate product identification

<table>
<thead>
<tr>
<th>Isomer</th>
<th>Melting point</th>
<th>MS trace</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2-Di-acetoxybenzene</td>
<td>64 °C</td>
<td>m/z 221 (M(^+)) , m/z 193 (M(^+) - C(CH(_3)_3) , m/z 177 (M(^+) - (CH(_3)_3CCOO)</td>
<td>99 %</td>
</tr>
<tr>
<td>1,3-Di-acetoxybenzene</td>
<td>Liquid at 25 °C</td>
<td>m/z 221 (M(^+)) , m/z 193 (M(^+) - C(CH(_3)_3) , m/z 177 (M(^+) - (CH(_3)_3CCOO)</td>
<td>98 %</td>
</tr>
<tr>
<td>1,4-Di-acetoxybenzene</td>
<td>123 °C</td>
<td>m/z 221 (M(^+)) , m/z 193 (M(^+) - C(CH(_3)_3) , m/z 177 (M(^+) - (CH(_3)_3CCOO)</td>
<td>99 %</td>
</tr>
</tbody>
</table>

3.2.2 Synthesis of 2,6-di-tert-butylhydroquinone

2,6-Di-tert-butylhydroquinone was produced from the corresponding phenol through electrochemical oxidation of the phenol to the benzoquinone, followed by electrochemical reduction of the benzoquinone in a divided cell. This divided cell was equipped with a sintered glass separator. The anode was a lead dioxide electrode and the cathode a platinum electrode.

2,6-Di-tert-butylphenol (1.815 g; 8.8 mmol) was weighed into the anodic compartment of a divided cell reactor, which contained acetonitrile (53 cm\(^3\); 1015 mmol). To this an aqueous sulfuric acid solution (5 % v/v; 21 mmol) was added. After the addition of a similar solvent system to the cathodic compartment, the solution was stirred at 1000 rpm at room temperature. The electrolysis was started at 800 mA and run to twice the theoretical amount of charge (8 F). After oxidation, the lead dioxide electrode was exchanged with a nickel electrode and the polarity of the cell changed in order for the nickel electrode to become cathodic. The electrolysis was then carried out in a similar fashion as above. After electrolysis, the reaction mixture was poured into a separating funnel. This was extracted three times with 50 cm\(^3\) portions of ethyl acetate. The organic portion was washed with 50 cm\(^3\) of a saturated sodium bicarbonate solution followed by three portions of 50 cm\(^3\) water. The
organic phase was dried over anhydrous magnesium sulphate and the ethyl acetate distilled. The resulting hydroquinone was stored in the dark in a vacuum desiccator. The identification and purity determinations of the standards were done using two techniques, GCMS and DSC. The purity was found to be in excess of 99%. The compound showed the characteristic MS traces; m/z 166 (M+), m/z 149 (M+ - OH), m/z 109 (M+ - C(CH₃)₃). The DSC determination showed that the standard had a melting point of 96 °C, which corresponds to values available in literature. The chromatogram, MS trace and DSC results are as shown in the addendum.

3.2.3 Synthesis of tert-butylated benzoquinones

The same method was used in order to produce both 2-tert-butylbenzoquinone and 2,6-di-tert-butylbenzoquinone. These benzoquinones were produced from the corresponding hydroquinones through electrochemical oxidation in a divided cell. This divided cell was equipped with a sintered glass separator. The anode was a lead dioxide electrode and the cathode a platinum electrode.

The 2-tert-butylhydroquinone (1.46 g; 8.8 mmol) or 2,6-di-tert-butylhydroquinone (1.96 g; 8.8 mmol) was weighed into the anodic compartment of a divided cell reactor which contained acetonitrile (53 cm³; 1015 mmol). To this, an aqueous sulfuric acid solution (5 % v/v; 21 mmol) was added. After the addition of a similar solvent system to the anodic compartment, the solution was stirred at 1000 rpm at room temperature. The electrolysis was started at 800 mA and run to twice the theoretical amount of charge (8 F). After electrolysis, the reaction mixture was poured into a separating funnel. This was extracted three times with 50 cm³ portions of ethyl acetate. The resulting organic portion was washed with 50 cm³ of a saturated sodium bicarbonate solution followed by three portions of 50 cm³ water. The resulting organic portion was dried over anhydrous magnesium sulphate and the ethyl acetate distilled. The resulting benzoquinone was stored in the dark in a vacuum desiccator. The identification and purity determinations of the standards were done using two techniques, GC-MS and DSC. The MS traces
for 2-tert-butylbenzoquinone and 2,6-di-tert-butylbenzoquinone indicated that the products were successfully synthesized. The DSC and GCMS area percentages indicated that the compounds were of acceptable purity and the melting points confirm this. These results are shown in Table 3.7. The chromatogram, MS trace and DSC results are as shown in the addendum.

Table 3.7: Benzoquinone product identification

<table>
<thead>
<tr>
<th>Product</th>
<th>Melting point</th>
<th>MS trace</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-tert-butylbenzoquinone</td>
<td>76 °C</td>
<td>m/z 164 (M⁺), m/z 107 (M⁺ - C(CH₃)₃)</td>
<td>99 %</td>
</tr>
<tr>
<td>2,6-di-tert-butylbenzoquinone</td>
<td>69 °C</td>
<td>m/z 220 (M⁺), m/z 163 (M⁺ - C(CH₃)₃), m/z 106 (M⁺ - 2 C(CH₃)₃)</td>
<td>98 %</td>
</tr>
</tbody>
</table>

3.3 Experimental procedures

3.3.1 Apparatus for electrochemical oxidation procedures

The electrochemical cell shown in Figure 3.1 consists of a double-walled reactor flask, 150 cm³ in volume, equipped with a heating jacket, which was connected to a circulator in order to affect either heating or cooling. The top of the reaction flask was designed with quikfit adapters for the insertion of a variety of apparatus, including electrodes, thermometers, drying tubes and condensers. One of the quikfit adapters in the reactor lid was always left open to the atmosphere, either through a condenser or a drying tube, in order to prevent a pressure build-up in the reactor due to gas formation in the reactor.
3.3.2 Anodic oxidation using the electrochemical cell

The supporting electrolyte and substrate were weighed by difference into the electrochemical cell and the appropriate solvent was directly added to the reactor. The reactor lid, into which the appropriate fittings such as electrodes, thermometers, drying tubes were added, was then sealed onto the reactor. A Labcon circulator controlled the temperature, in order to keep the reaction temperature constant at a preset level throughout the electrolysis. Various temperatures were investigated. The electrolysis was conducted under constant current conditions in order to achieve the required current density and controlled by an Amel Instruments 2051 General Purpose Potentiostat.

After completion of the electrolysis, the electrodes were removed from the reaction mixture; a 0.5 cm$^3$ aliquot sample was taken for analysis and to this a known amount of internal standard was added for internal standard quantification.
Acetoxylation: Following the addition of a known volume of \( p \)-iso-propyl benzaldehyde in solution, the sample was injected into the gas chromatograph.

Hydroxylation: Following the addition of a known amount of \( p \)-nitrophenol solution, the sample was injected into the liquid chromatograph.

The usual work-up procedure (extraction of the reaction mixture with an organic solvent) was avoided for the following reasons:

- The substrates, reaction intermediates and products were only partly extracted from the reaction medium into the organic solvents, which resulted in large errors in analysis.
- The extraction procedure was very wasteful, leading to the consumption of large amounts of additional reagents.
- The extraction procedure was also very time consuming.

### 3.4 Analytical techniques

Several analytical procedures were employed for the analysis of substrates, intermediates, products and supporting electrolytes. Each analytical technique will be described separately.

#### 3.4.1 Capillary Gas Chromatography

GLC analyses were carried out using a Varian 3800 Gas Chromatograph equipped with a Sepalcowax 10 capillary column (60 m x 0.32 mm i.d. 0.25 microns film thickness) and a flame ionisation detector. Data were acquired from the detector by means of an IBM compatible personal computer equipped with Star chromatography software. The carrier gas (\( N_2 \)) flow rate was 1.88 cm\(^3\) min\(^{-1}\), with a column head pressure of 0.42 kg cm\(^{-3}\). The injector was operated in a split mode with a split ratio of 1 : 100 with an injector volume of 1 \( \mu \)l. Samples were injected with the aid of a Hamilton 10 \( \mu \)l GC syringe. Typical conditions for GC analysis are given in Table 3.8. An internal standard method, with \( p \)-isopropyl benzaldehyde as standard, was used for
the analysis of individual components from the phenol and phenyl acetate reaction mixtures. Response factors for the compounds of interest were determined by means of a four-level calibration using standard solutions containing known amounts of the analytes and internal standards.

Table 3. 8: Capillary GC conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Temperature/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial column temperature</td>
<td>130 °C</td>
</tr>
<tr>
<td>Initial column hold time</td>
<td>10 min</td>
</tr>
<tr>
<td>Heating rate</td>
<td>5 °C min⁻¹</td>
</tr>
<tr>
<td>Mid column temperature</td>
<td>190 °C</td>
</tr>
<tr>
<td>Mid column hold time</td>
<td>0 min</td>
</tr>
<tr>
<td>Final column temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Final column hold time</td>
<td>10 min</td>
</tr>
<tr>
<td>Heating rate</td>
<td>15 °C min⁻¹</td>
</tr>
<tr>
<td>Injector temperature</td>
<td>150 - 250 °C</td>
</tr>
<tr>
<td>Detector temperature</td>
<td>280 °C</td>
</tr>
</tbody>
</table>

3.4.2 High Pressure Liquid Chromatography

HPLC analyses were carried out on a Hewlett Packard 1100 series HPLC chromatograph with a dual pump system, equipped with a variable UV – Visible detector and an auto sampler unit. Data was acquired with a Hewlett Packard Vectra personal computer loaded with HP Chemstation for LC software. All solvents were HPLC grade and were degassed prior to analysis with a Millipore vacuum-degassing unit. A 3.9 x 300 mm Waters μBondapak C₁₈ (serial no. W90211G041) column was used for the analysis of the reaction samples.

As different substrates were used in the reactions, analysis of the mixtures required different LC conditions. These settings are summarized in Tables 3.9 - 3.11. An internal standard method, with p-nitrophenol as standard, was used for the analysis of individual components of the phenol, 2-tert-butylphenol and 2,6-di-tert-butylphenol reaction mixtures. Response factors for the compounds
of interest were determined by means of a five-level calibration using standard solutions containing known amounts of the analytes and internal standards.

Table 3. 9: HPLC conditions (phenol reaction mixtures)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Volume</td>
<td>10 µl</td>
</tr>
<tr>
<td>Columns</td>
<td>μBondpak C&lt;sub&gt;18&lt;/sub&gt; 3.9 x 300 mm (Waters)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>280 nm</td>
</tr>
<tr>
<td>Flow Rates</td>
<td>1 cm&lt;sup&gt;3&lt;/sup&gt; min&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mobile Phases</td>
<td>30% MeOH : 70% H&lt;sub&gt;2&lt;/sub&gt;O buffered to pH = 3 with H&lt;sub&gt;3&lt;/sub&gt;PO&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>Internal Standard</td>
<td>4-nitrophenol</td>
</tr>
</tbody>
</table>

Table 3. 10: HPLC conditions (2-<i>tert</i>-butylphenol reaction mixtures)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Volume</td>
<td>1 µl</td>
</tr>
<tr>
<td>Columns</td>
<td>μBondpak C&lt;sub&gt;18&lt;/sub&gt; 3.9 x 300 mm (Waters)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>220 nm</td>
</tr>
<tr>
<td>Flow Rates</td>
<td>1 cm&lt;sup&gt;3&lt;/sup&gt; min&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mobile Phases</td>
<td>55% MeCN : 45% H&lt;sub&gt;2&lt;/sub&gt;O buffered to pH = 3 with H&lt;sub&gt;3&lt;/sub&gt;PO&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>Internal Standard</td>
<td>4-nitrophenol</td>
</tr>
</tbody>
</table>

Table 3. 11: HPLC conditions (2,6-di-<i>tert</i>-butylphenol reaction mixtures)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Volume</td>
<td>1 µl</td>
</tr>
<tr>
<td>Columns</td>
<td>μBondpak C&lt;sub&gt;18&lt;/sub&gt; 3.9 x 300 mm (Waters)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>220 nm</td>
</tr>
<tr>
<td>Flow Rates</td>
<td>1 cm&lt;sup&gt;3&lt;/sup&gt; min&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mobile Phases</td>
<td>55% MeCN : 45% H&lt;sub&gt;2&lt;/sub&gt;O buffered to pH = 3 with H&lt;sub&gt;3&lt;/sub&gt;PO&lt;sub&gt;4&lt;/sub&gt;</td>
</tr>
<tr>
<td>Internal Standard</td>
<td>4-nitrophenol</td>
</tr>
</tbody>
</table>
3.4.3 Cyclic Voltammetry
CV studies were performed on a BAS CV50 cyclic voltammetry system. A Gateway 2000 personal computer, running CV50 software, was used for both instrumental control and data acquisition. The electrochemical cell was equipped with platinum or glassy carbon working electrodes, a platinum wire auxiliary electrode and an Ag/AgCl reference electrode. The potential of the working electrode was scanned over a potential range of 0 – 2.5 V at a scan rate of 100 mV s^{-1} and a sensitivity of 1 mA V^{-1}. Cyclic voltammograms were recorded for the substrates, intermediates and final products, so as to determine their oxidation potentials. The solvent / supporting electrolyte system used for the reactions was used as the analysis medium.

3.4.4 Linear Scanning Voltammetry
LSV runs were done on a EG&E Princeton Applied Research Potentiostat / Galvanostat Model 263A connected to a personal computer using Headstart Creative Electrochemistry Software version 1.70 software for both instrumental control and acquisition of data. The electrochemical cell was similar to that used in the electrochemical oxidations. The electrochemical cell was equipped with a variety of working and auxiliary electrodes and an Ag/AgCl reference electrode. The potential of the working electrode was scanned over a potential range of 0 – 2.0 V at a scan rate of 100 mV s^{-1}. The linear sweep voltammograms were recorded for the substrates so as to determine their oxidation potentials. The solvent / supporting electrolyte system and electrodes used for the reactions, were used for the analysis.

3.4.5 Gas Chromatography - Mass spectrometry
GC-MS analysis was used mainly for qualitative analysis. Use was made of a Hewlett Packard 5890 series II Gas Chromatograph connected to a 5972 series mass selective detector. Separation was achieved with the aid of a 30m x 0.25mm i.d. HP-5 MS (Chrompack) column. Helium was used as the carrier gas, with a flow rate of 1.83 cm^3 min^{-1} and a column head pressure of 1.15 kg cm^{-3}. Data acquisition and manipulation were carried out with HP
Enhanced HP G1034C Chemstation Software using a personal computer. Use was made of both on-column and split / splitless injection modes using the respective GC syringes (supplied by Hamilton) for each injection mode. Other important chromatographic conditions used are summarised in Table 3.12.

<table>
<thead>
<tr>
<th>Initial column temperature</th>
<th>50 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial column hold time</td>
<td>5 min</td>
</tr>
<tr>
<td>Heating rate</td>
<td>10 °C min⁻¹</td>
</tr>
<tr>
<td>Mid column temperature</td>
<td>100 °C</td>
</tr>
<tr>
<td>Mid column hold time</td>
<td>5 min</td>
</tr>
<tr>
<td>Final column temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Final column hold time</td>
<td>10 min</td>
</tr>
<tr>
<td>Heating rate</td>
<td>10 °C min⁻¹</td>
</tr>
<tr>
<td>Injector temperature</td>
<td>280 °C</td>
</tr>
<tr>
<td>Detector temperature</td>
<td>300 °C</td>
</tr>
<tr>
<td>Detector solvent delay</td>
<td>2 min</td>
</tr>
</tbody>
</table>

### 3.4.6 Differential Scanning Calorimetry

A Mettler Toledo DSC 820 was used to determine the purity and melting point of the synthesised standards as well as their decomposition temperatures. The sample was placed in an aluminium sample pan (working range up to 400 °C) and sealed in a press. Data were analysed on a Mecer premium-X personal computer with the aid of Mettler STAre software.

### 3.4.7 UV/Visible Spectrophotometry

The optimum UV absorbance wavelength of HPLC standards was determined with the aid of a Beckman DU® 7500 double beam UV / Visible spectrophotometer with Beckman DU series 7000 software. Data transfer and further manipulation of data was achieved with the aid of a personal
computer, data transfer cable and PC Plus software. A quartz sample cell (cuvette) was used with methanol or acetonitrile as solvent.

3.4.8 pH determination

Use was made of an Inolab level 1 digital pH meter with a WTW Sentix single glass pH electrode (serial no C000304091) to adjust the pH of the aqueous phase (pH=3) for use in HPLC analysis.

3.4.9 Conductivity studies

Conductivity and resistance measurements were performed on a Metrohm 660 conductivity meter equipped with two platinum black electrodes. The cell constant (calculated to be 0.798 \( \Omega^{-1} \text{cm}^{-1} \)) was determined from a 0.1 M KCl solution.

The acetic acid used as solvent for the conductivity / resistance measurements, was analysed as is, with the addition of acetic anhydride (in order to act as a water scavenger). The supporting electrolytes were dried in a vacuum oven overnight at 80 °C. The supporting electrolytes were then stored in a vacuum desiccator until needed. The conductivities of four different supporting electrolytes were measured at concentrations ranging from 0.10 - 1.00 M. These supporting electrolytes were sodium acetate, sodium perchlorate, potassium fluoride and sulfuric acid.
CHAPTER 4

ELECTROCHEMICAL ACYLOXYLATION

4.1 Introduction

In this section electrochemical acyloxylation of phenol and phenyl acetate is examined, in order to evaluate the industrial feasibility of forming di-acetates, which could then readily be hydrolized to the corresponding dihydroxybenzenes, as shown in Scheme 4.1.

Scheme 4. 1: General scheme for acyloxylation and hydrolysis

Acetoxylation: \( R = -\text{CH}_3 \)
Trifluoro-acetoxylation: \( R = -\text{CF}_3 \)

The objective of the work was to produce selectively either 1,2- or 1,4-dihydroxybenzenes.

Phenol was taken as starting material since it is readily available industrially and has one hydroxyl group attached to the ring already. Phenyl acetate was selected since it already contained one acetate group on the ring, and due to
its higher oxidation potential, would suffer less side reactions than the more easily oxidised phenol.

The investigation was carried out by studying the reaction variables which affect product distribution. The most important variables include reaction temperature, supporting electrolyte, supporting electrolyte concentration, electrode material, current density and the nature of the solvent.

Both acetoxylation and trifluoro-acetoxylation of these compounds was investigated.

4.1.1 Definitions

The following terms were used in the discussion of results:

\[
Conversion(\%) = \frac{\text{(moles of substrate consumed)}}{\text{(moles of substrate charged)}} \times 100 \quad (4.1)
\]

\[
Yield \ of \ product = \frac{\text{(moles of specific product formed)}}{\text{(moles of substrate charged)}} \times 100 \quad (4.2)
\]

\[
Selectivity \ of \ product = \frac{\text{(moles of specific product formed)}}{\text{(moles of all products formed)}} \times 100 \quad (4.3)
\]

\[
Accountability(\%) = \frac{\text{(moles of products and substrate after reaction)}}{\text{(moles of substrate charged)}} \times 100 \quad (4.4)
\]

\[
Current \ Efficiency = \frac{\text{moles of product \times no. of electrons per molecule}}{\text{moles of electrons charged}} \quad (4.5)
\]
4.2 Acetoxylation

4.2.1 Introduction

Acetoxylation involves the introduction of an acetate group onto a compound. This can be done electrochemically through an ECEC mechanism as discussed in Section 2.7.2. The balanced electrochemical reaction for acetoxylation of phenol or phenyl acetate is shown in Equation 4.6.

\[
R = -\text{OH or } -\text{OAc}
\]

\[
\text{Phenol} + \text{OAc}^- \rightarrow \text{Phenyl acetate} + 2e^- + H^+ \quad (4.6)
\]

The product so obtained can be readily hydrolysed to indirectly produce the dihydroxybenzenes, as shown in the final part of the reaction in Scheme 4.1.

4.2.2 Oxidation potential

The first step in an electrochemical investigation is the determination of the oxidation potential of the compounds being investigated. This can be done using a variety of experimental techniques. Among these are Linear Sweep Voltammetry and Cyclic Voltammetry. In both these techniques the potential of a working electrode, immersed in a solution containing the substrate, is varied and the resultant current is measured. In Linear Sweep Voltammetry the potential is increased linearly in one direction, whilst in Cyclic Voltammetry the potential is varied first in one direction then in the other. Substrates to be studied are not the only ones to be considered; solvents and supporting electrolytes are present as well. It is important to know also how these other constituents of the medium will react under the applied potential.

If the oxidation potential of the medium is lower than that of the substrate in question, the likelihood of the substrate undergoing reaction is small, unless
the reaction of the substrate is in some way dependent on the reaction of the medium.

Oxidation potentials are usually measured as $E_{1/2}$ in LSV, or $E_{pa}$ in CV. $E_{pa}$ represents the oxidation potential measured at the anodic peak in a Cyclic Voltammogram whereas $E_{1/2}$ is the potential at half the plateau height in a Linear Scanning Voltammogram. The reason why both analysis techniques were used, was that LSV can be done under the same reaction conditions (i.e. using the same electrodes) as the reaction set-up, whereas, in contrast, the CV technique uses microelectrodes which differ from those used during the reaction. CV is also capable of yielding information about the reversibility of a reaction.

Table 4.1 shows the results for the oxidation potential for phenol, phenyl acetate and isomeric di-acetates under reaction conditions of 1 mol dm$^{-3}$ NaOAC / HOAc

<table>
<thead>
<tr>
<th>Analysis technique</th>
<th>Substrate</th>
<th>Working electrode</th>
<th>Ox. Pot. Electrolyte$^a$</th>
<th>Ox. Pot. Substrate$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>Phenol</td>
<td>Pt</td>
<td>1915 mV</td>
<td>1089 mV</td>
</tr>
<tr>
<td>CV</td>
<td>Phenol</td>
<td>C</td>
<td>1666 mV</td>
<td>1055 mV</td>
</tr>
<tr>
<td>LSV</td>
<td>Phenol</td>
<td>Pt</td>
<td>1878 mV</td>
<td>1075 mV</td>
</tr>
<tr>
<td>LSV</td>
<td>Phenol</td>
<td>C</td>
<td>1623 mV</td>
<td>1042 mV</td>
</tr>
<tr>
<td>CV</td>
<td>Phenyl Acetate</td>
<td>Pt</td>
<td>1915 mV</td>
<td>1312 mV</td>
</tr>
<tr>
<td>CV</td>
<td>Phenyl Acetate</td>
<td>C</td>
<td>1666 mV</td>
<td>1349 mV</td>
</tr>
<tr>
<td>LSV</td>
<td>Phenyl Acetate</td>
<td>Pt</td>
<td>1878 mV</td>
<td>1298 mV</td>
</tr>
<tr>
<td>LSV</td>
<td>Phenyl Acetate</td>
<td>C</td>
<td>1623 mV</td>
<td>1273 mV</td>
</tr>
<tr>
<td>CV</td>
<td>1,2-di-acetoxy benzene</td>
<td>Pt</td>
<td>1915 mV</td>
<td>Not observed</td>
</tr>
<tr>
<td>CV</td>
<td>1,2-di-acetoxy benzene</td>
<td>C</td>
<td>1666 mV</td>
<td>Not observed</td>
</tr>
</tbody>
</table>
The oxidation potentials are the $E_{pa}$ and $E_{1/2}$ values obtained from CV and LSV runs as shown in the addendum.

These CV and LSV results correlate with those shown in the literature, when taking into consideration that experimental differences can affect the measured oxidation potentials.

From the results shown in Table 4.1 a variety of observations can be made:

- **Electrode material**: The results indicate that the electrode material did not have a significant effect on the oxidation potential of the organic compounds. The electrode material did however have a major effect on the oxidation potential of the supporting electrolyte. The results indicate that carbon catalyses the electrochemical oxidation of acetate (Kolbe reaction), thus effectively lowering the oxidation potential of the acetate. This can have a great effect on the electrochemical reaction, if the oxidation potential of the compounds under investigation is close to that of supporting electrolyte.

- **Organic substrates**: The oxidation potentials of the substrates and products for the electrochemical acetoxylation of aromatic substrates are of major importance. From an electrochemical point of view, the compound with the lower oxidation potential will be oxidised...
preferentially to others with higher oxidation potentials. Considering the oxidation potentials of the di-acetates, it is noted that the 1,2- and 1,4-di-acetoxybenzenes are stable towards oxidation, since no oxidation peak was obtained for them under the experimental conditions. The 1,3-diacetoxybenzene, however, is readily oxidised. From an electrochemical point of view it can then be concluded that the 1,3-diacetoxybenzene is the only di-acetate isomer that will be unstable under reaction conditions, resulting in further oxidation of this di-acetate.

From an electrochemical point of view it can also be concluded that phenol will be a better substrate for the production of the di-acetates, since its oxidation potential is lower than that of phenyl acetate, assuming no side reactions take place.

The reason for the increased oxidation potential of phenyl acetate, as compared to that of phenol, can be related to the higher electron affinity of the acetate substituents as compared to that of the hydroxyl substitute. The acetate substituents is slightly electron withdrawing and this causes a decrease in the electron density on the aromatic ring resulting in the need for greater energy in order to remove a electron from the HOMO.

Having two such electron withdrawing groups present on the ring, as is the case with the isomeric diacetates, will result in an even higher oxidation potential, as observed. For the particular case of 1,3-diacetoxybenzene, the lower oxidation potential might be caused by the directing effect of the acetate groups. In 1,3-diacetoxybenzene the two acetate groups form a reactive site at the same position on the ring localization the negative charge density at the same position, near the diacetates groups. With 1,2- and 1,4-di-acetoxybenzene the negative charge density is spread around the ring. Since the charge density is localized to a greater extent for 1,3-diacetoxybenzene than for the other isomers, the 1,3-diacetoxybenzene will be more susceptible to oxidation so decreasing the oxidation potential.
• CV versus LSV: It can be seen that there is a slight discrepancy in the oxidation potentials obtained from CV and LSV. The explanation for this difference is that the factors which can effect the oxidation potential of the analyte (electrode material, electrode area and scan rate) differ between the two techniques.

4.2.3 Conductivity Studies

The conductivity studies were carried out on the same solvents and supporting electrolytes as used in the oxidation studies. Figure 4.1 shows the conductivities for the supporting electrolytes NaClO₄, KF and NaOAc as a function of concentration of the supporting electrolyte in acetic acid.

As can be seen, the order of conductivities for the various supporting electrolytes is as follows: NaClO₄ >>> NaOAc > KF. From a conductivity point of view the data indicates that NaClO₄ is the best supporting electrolyte.
4.2.4 Reaction studies

Experiments were carried out in order to identify and then quantify the products produced during the electrochemical acetoxylation of the substrates. The variables investigated are shown in Table 4.2

Table 4.2: Variables for acetoxylation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Phenol (0.05 – 0.5 mol L(^{-1})), Phenyl acetate (0.05 – 0.5 mol L(^{-1}))</td>
</tr>
<tr>
<td>Electrodes: Anode</td>
<td>Platinum, Graphite</td>
</tr>
<tr>
<td>Electrodes: Cathode</td>
<td>Platinum</td>
</tr>
<tr>
<td>Constant current</td>
<td>50 – 150 mA</td>
</tr>
<tr>
<td>Constant potential</td>
<td>Phenol (1200 mV), Phenyl acetate (1400 mV)</td>
</tr>
<tr>
<td>Supporting electrolyte</td>
<td>Sodium perchlorate, Sodium acetate and Potassium fluoride</td>
</tr>
<tr>
<td>Solvent</td>
<td>Acetic acid</td>
</tr>
<tr>
<td>Additive</td>
<td>Acetic anhydride</td>
</tr>
<tr>
<td>Temperature</td>
<td>25 – 65 °C</td>
</tr>
</tbody>
</table>

4.2.5 Qualitative analysis

- Phenol: The results for these reactions showed that no acetoxylation took place, since there was a complete absence of the di-acetoxybenzenes and acetoxy-phenols in the reaction mixture as confirmed by GCMS. This was the case for all the reaction conditions. A variety of other products were, however, found in small quantities. These included 2,2'-di-hydroxybiphenyl, 4,4'-di-hydroxybiphenyl, cresol, xylenol, phenyl ether and polymeric products.
- Phenyl acetate: The results for these reactions showed that acetoxylation took place here, indicated by the presence of small amounts of the acetoxylated products. It is interesting to note that the acetoxylated products were only formed under galvanostatic conditions.
A variety of other products were present albeit in small amounts as well. Kolbe products were found when carbon was used as anode material. When potassium fluoride was used as supporting electrolyte it was noted that some fluorinated products were produced. The use of sulphuric acid did not yield any Kolbe or acetoxylated products; only tarry substances, were produced.

4.2.6 Quantitative studies

- Phenol: From the above it was seen that phenol did not yield any acetoxylated products. It was thus decided to discontinue the acetoxylation investigation on phenol.

- Phenyl acetate: From Section 4.2.5 it was seen that phenyl acetate yielded acetoxylated products only under galvanostatic conditions. It was thus decided to continue the investigation under galvanostatic conditions only, with currents ranging from 50 – 150 mA and the passage of current was continued until 4 F of charge (twice the theoretical amount) had passed through the cell. Only platinum was used as electrode in these further experiments; the electrolyte concentration was kept constant at 0.5 M, and the temperature of the reaction mixture was held at 30 °C, since higher temperature caused the formation of benzoquinone.

Unfortunately the results obtained during the evaluation of the GC analysis method indicated that the method could not give accurate results. The reason for this was the thermal decomposition of the di-acetate standards on the injector insert (HPLC analysis could also not be carried out on the samples since the only separation method available used an acidic aqueous medium). The GC results could, however, show reaction trends. From these trends it could be seen that the acetoxylation did not yield very good results. Table 4.3 shows some results obtained in this further study.
Table 4.3: Results for acetoxylation of phenyl acetate using a platinum anode

<table>
<thead>
<tr>
<th>Sup Elec</th>
<th>Current Dens</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A m⁻²</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>KF</td>
<td>7.5</td>
<td>72</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>KF</td>
<td>2.5</td>
<td>80</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>NaClO₄</td>
<td>7.5</td>
<td>65</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>NaClO₄</td>
<td>2.5</td>
<td>72</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>NaOAc</td>
<td>7.5</td>
<td>70</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>NaOAc</td>
<td>2.5</td>
<td>81</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Sup Elec (supporting electrolyte), Elec Conc (electrolyte concentration), Current Dens (current density), A (Accountability), B (yield 1,2-di-acetoxybenzene), C (yield 1,3-di-acetoxybenzene), D (yield 1,4-di-acetoxybenzene) and E (current efficiency).

A large amount of benzoquinone was also produced, especially in the case of sodium perchlorate, where this formation has been included in the calculation for C.E. The benzoquinone possibly arises as a side product of the oxidation of phenyl acetate.

Considering the results, it can be said that the acetoxylation of phenyl acetate proceeds at a slow rate with low current efficiencies. The following observations can be further noted:

- **Isomer distribution**: No 1,3-di-acetoxybenzene was produced, only 1,2- and 1,4-di-acetoxybenzene. The ratios in which these isomers are produced is noteworthy. The ratios of isomers produced, differ from supporting electrolyte to supporting electrolyte. The results indicate that potassium fluoride promotes the production of 1,2-di-acetoxybenzene above 1,4-di-acetoxybenzene, whereas sodium perchlorate and sodium acetate promote the opposite.

- **Current efficiency**: The current efficiency for the sodium perchlorate reactions is higher than for the other supporting electrolytes.

- **Current density**: The results indicate that current density was a important factor resulting in higher current efficiencies at lower current densities.
4.2.7 Discussion of results

The results, obtained for the electrolysis of phenol and phenyl acetate in these solutions, are further discussed below:

- Phenol: Since phenol is not acetoxylated under the experimental conditions used, other reactions are taking place when phenol is the substrate. Two factors, associated with the phenol structure, could lead to further electrochemical pathways:
  - Presence of the acidic hydrogen in the hydroxyl group. This may cause deprotonation leading to the phenolate ion and radical in a CE mechanism, as shown in Scheme 4.2. This type of reaction leads to radicals which will react with each other and other radicals. However the pKa value of phenol is 9.89\(^\text{18}\) which indicates that it is a very weak acid and therefore the CE mechanism in the presence of acetic acid should not take place.

\begin{scheme}
\textbf{Scheme 4. 2: Radical formation (CE mechanism)}
\end{scheme}

- Ease of oxidation leading to different radicals. Since the oxidation potential of phenol is low, it is easily oxidized to both the phenolate and the nuclear radicals. Radical formation based on the EC mechanism is shown in Scheme 4.3
The following electrochemical reactions involving these radicals explain the formation of the products identified during phenol oxidation:

- **2,2'-di-hydroxybiphenyl**: the dimerization of nuclear radicals with each other or nuclear radical cations with phenol at the ortho position. (Scheme 2.3).
- **4,4'-di-hydroxybiphenyl**: the dimerization of nuclear radicals with each other or nuclear radical cations with phenol at the para position. (Scheme 2.3).
- **Phenyl ethers**: the coupling of the phenolate radicals with nuclear radicals (Scheme 2.4)
- **Polymeric products**: the further oxidation and coupling of the substrate and products mentioned above with each other.
The poor performance of phenol, based on the above characteristics, encouraged the use of phenyl acetate as substrate, since here the electron withdrawing nature of the acetate group would stabilize the radicals formed; also the absence of any acidic hydrogens bonded directly to the oxygen would force only the formation of the nuclear radical.

- Phenyl acetate: A variety of observations were made in Section 4.2.6 These will now be discussed further below:
  - Isomer distribution: It was found that only 1,2-di-acetoxybenzene and 1,4-di-acetoxybenzene were produced, and no 1,3-di-acetoxybenzene was present in the reaction mixture. It was also found that the supporting electrolyte played a major role in the isomer distribution ratio.
  - Absence of 1,3-di-acetoxybenzene: This can be explained by looking at the electronic configuration of an activated aromatic species and the oxidation potential of the 1,3-di-acetoxybenzene. Knowing that the o- and p- positions are capable of stabilizing the carbo-cation formed before nucleophilic attack to a greater extent than the m- position, it follows that the o- and p-di-acetoxy isomers will be formed preferentially over the m- isomer. Even if the m-isomer is produced, its oxidation potential is low enough for the compound to be further oxidised to unknown by-products.
  - Isomer ratio: It was observed that sodium acetate and sodium perchlorate yielded more 1,4-di-acetoxybenzene than 1,2-di-acetoxybenzene whilst potassium fluoride yielded more of the 1,2-isomer than the 1,4-isomer. This is an interesting observation and can be explained as follows. The only variable between these reactions is the supporting electrolyte. Potassium fluoride consists of a strong base F-, since it is the anion of a weak acid (pKa = 3.17). Since the solvent acetic acid (pKa = 4.75), in which the reaction is carried out, is a weak acid, this base would be capable of abstracting the proton from acetic acid especially in such a high
F⁻ concentration. This abstraction of the proton from acetic acid allows for the formation of free acetate in solution, which could then act as the nucleophile in the reaction. When considering the acetoxylation mechanism (Section 2.7.2) it is known that the process occurs through an ECE mechanism, and that the loss of a nuclear proton is the chemical step. The position from which the proton is lost governs which acetate isomer is produced; since the F⁻ in solution can aid in the loss of a proton, it is capable of affecting regeo-selectivity in the reaction favouring the 1,2 di-acetoxybenzene.

The isomer distribution of the other two supporting electrolytes is consistent with that explained through the cation stabilization and steric hindrance, since two acetate groups next to each other would cause steric hindrance.

- Current efficiency: It was found that the current efficiency for the reactions performed with sodium perchlorate is higher than for those performed with potassium fluoride and sodium acetate. The reason for this is fairly obvious; sodium perchlorate is the only reaction system where there is no free acetate present in the system. This effectively eliminates the oxidation of the acetate to the Kolbe radicals and carbon dioxide and in so doing allows a larger amount of the current to affect the oxidation of the substrate. This is not the case for potassium fluoride and sodium acetate where the Kolbe reaction still occurs, decreasing the current efficiency of the reaction.

The only source of acetate in the sodium perchlorate electrolyte medium is therefore from the ionisation of acetic acid. Since acetic acid is a weak acid, only a little acetate will be present in equilibrium. The results therefore show that acetoxylation takes place even if the concentration of acetate is low, under these conditions.
• Accountability: It is observed that there is a decrease in accountability going from potassium fluoride and sodium acetate to sodium perchlorate. This can again be explained through the supporting electrolyte effects on the reaction system.

- Potassium fluoride: this system has free acetate in solution but the concentration of the acetate is low. Since there is such a low concentration of the acetate present the Kolbe reaction is suppressed and the products resulting from the Kolbe reaction are decreased. However, the high concentration of the F\(^-\) ions will cause fluorination to take place, as was observed during the GCMS analysis. The formation of these fluorinated compounds cause the accountability to drop.

- Sodium acetate: since there is a high concentration of free acetate in solution, the Kolbe reaction is promoted, leading to typical products produced by the Kolbe reaction e.g. cresols and xylenols.

- Sodium perchlorate: It is known that there is a lack of free acetate present in solution, since the only source of acetate ions in this mixture is from the acetic acid solvent (a weak acid), this is good from a Kolbe reaction point of view, since the current efficiencies will be increased, but bad for accountability, since the production of the di-acetoxybenzenes depend on a reaction between the cation and an acetate nucleophile and the amount of free acetate is small. This results in the reaction of radical cations with other nucleophiles in the reaction mixture so producing by-products that decrease accountability.

In conclusion it can be stated that the hydroxylation of the selected aromatic compounds through acetoxylation might at best be a moderately successful method. This correlates with the results shown in literature. The problem associated with this process is not the hydrolysis of the di-acetates but the production of the di-acetates. The hydrolysis studies indicated that the acid
and base catalysed- hydrolysis proceeded faster and more efficiently under the application of ultrasound than heat. It was thus recommended that the investigation be concluded and other alternatives investigated.

4.3 Trifluoro-acetoxylation

In this process the nucleophile is trifluoro-acetate. The aromatic trifluoro-acetates formed upon reaction are then capable of being hydrolysed to the corresponding phenol and trifluoro-acetic acid.

4.3.1. Introduction

The introduction of the trifluoro-acetate ion, $\text{CF}_3\text{COO}^-$ into the aromatic ring will cause resistance towards further oxidation of the substituted aromatic compound, due to the very large electron withdrawing nature of the trifluoro-acetate group. In effect, the oxidation potential of the trifluoro-substituted compound should be high and therefore less likely to undergo further electrochemical oxidation reactions.

Subsequent hydrolysis should then produce the dihydroxybenzenes. This reaction is shown in the second last part of Scheme 4.1.

4.3.2. Reaction studies

Due to the hazardous nature of trifluoro-acetic acid, electrochemical studies such as CV, LSV and conductivity work could not be carried out. Electrochemical reactions were, however, performed on a limited scale in order to qualitatively identify products of the reaction. The experimental variables are shown in Table 4.4.
Table 4.4: Reaction conditions for trifluoro-acetoxylation

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Phenol (0.05 – 0.5 M), Phenyl acetate (0.05 – 0.5 M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodes: Anode</td>
<td>Platinum, Graphite</td>
</tr>
<tr>
<td>Cathode</td>
<td>Platinum</td>
</tr>
<tr>
<td>Constant current electrolysis</td>
<td>50 – 250 mA</td>
</tr>
<tr>
<td>Supporting electrolyte</td>
<td>Sodium trifluoro-acetate (0.5 – 1.0 M),</td>
</tr>
<tr>
<td>Solvent</td>
<td>Trifluoro-acetic acid, Acetonitrile</td>
</tr>
<tr>
<td>Additive</td>
<td>Trifluoro-acetic anhydride</td>
</tr>
<tr>
<td>Temperature</td>
<td>Ambient</td>
</tr>
</tbody>
</table>

4.3.3. Qualitative observations

- **Phenol**: The results for these reactions show that trifluoro-acetoxylation took place since the presence of all three di-trifluoro-acetoxy benzenes was detected using GCMS. This was not the case for all the reaction conditions investigated. Only the use of acetonitrile as a solvent allowed for the production of said products. It was also interesting to note that a large amount of phenyl trifluoro-acetate was produced. The formation of this compound will be discussed in Section 4.3.5.

- **Phenyl acetate**: The results for these reactions show that trifluoro acetoxylation took place; this is indicated by the presence of di-trifluoro acetoxylated benzenes and trifluoro-acetoxylated phenyl acetate as observed with GCMS. It is interesting to note that the trifluoro-acetoxylated products were only formed under galvanostatic conditions in an acetonitrile medium.

4.3.4. Quantitative studies

No trifluoro-substituted standards were available, so no quantitative analysis could be carried out; however, the GCMS results, indicated that the amounts of products formed were relatively low.
4.3.5. Discussion of results

From the qualitative studies it was found that the following factors had an effect on the trifluoro-acetoxylation of the aromatic substrates.

- **Additive:** The trifluoro-acetic anhydride was used to eliminate any water present in the system. If there was any water present it would immediately add to the ring so resulting in the formation of a phenolic compound, which will have a lower oxidation potential than any of the other species present in the system. The oxidation of this hydroxylated species will then yield by-products. This by-product formation would then result in a decrease in the current efficiency and accountability of the reaction.

- **Solvent systems:**
  - **Trifluoro-acetic acid:** The problem with this solvent is that it has a very low dielectric constant, resulting in a low solubility of the supporting electrolyte (sodium trifluoro-acetate) in the solution. This results in a reaction mixture, which has a low conductivity, so the supporting electrolyte stays in its ion pair configuration, thus limiting the amount of free trifluoro-acetate that can add to the aromatic substrate.
  - **Acetonitrile (dry):** Due to the problems that were experienced using trifluoro-acetic acid as a solvent, a decision was made to switch to a solvent, which has both a higher dielectric constant and a higher solubility for the sodium trifluoro-acetate. The change to acetonitrile had a drastic beneficial effect on the trifluoro-acetoxylation reaction.

- **Anode material:** The two materials that were investigated were graphite and platinum. There was no notable difference between the results obtained with platinum and graphite. Since the supporting electrolytes used in the reaction had an oxidation potential much higher than that of the substrates, the catalytic effect of the carbon anode towards the Kolbe reaction had no effect on electrolysis.
• **Solvent and supporting electrolyte system:**
  • **Trifluoro-acetic acid and sodium trifluoro-acetate:** In this system no aromatic esters were formed. It was however noted that there was a thick polymeric coating on the anode (both platinum and carbon). This is because the substrates (phenol, phenyl acetate) are better nucleophiles than the trifluoro-acetate in this medium, resulting in the addition of the substrates to each other so forming polymeric chains.

• **Acetonitrile / Sodium trifluoro-acetate:**
  • **Phenyl Acetate:** The results obtained for these reactions indicate that trifluoro-acetoxylation occurs to a large extent in this medium. This could be ascribed to the increase in conductivity of the solution resulting from the increase of the free trifluoro-acetate present. The results obtained indicate that all three of the trifluoro-acetoxy substituted phenyl acetates are present in varying ratios. It was also found that some di-trifluoro-acetoxy and mono-trifluoro-acetoxy compounds were formed: this can be explained by transesterification.

Since there are esters as well as strong carboxylic acids present in solution two types of transesterification reactions can occur:
  • **Acidolysis:** This is where there is an exchange between the carboxylic acid constituent of the ester and the free carboxylic acid in solution. This reaction takes place between the trifluoro-acetic acid (obtained from the reaction of trifluoro-acetic anhydride with water) present in solution with the acetate group on the phenyl acetates, giving rise to mono substituted phenyl acetates, as shown in Equation 4.7.
- **Ester-Ester exchange**: This is where an exchange reaction takes place between the two carboxylic acid constituents on two different esters. So there could be an exchange of the trifluoro-acetate group on one ester with the acetate group of another, as shown in Equation 4.8.

![Equation 4.7]

- **Phenol**: The results obtained for these reactions indicate that trifluoro-acetoxylation occurs to a large extent in this medium. The results indicate that all three of the di-trifluoro-acetoxy benzenes are formed in varying ratios. It was also found that there was only a small amount of phenol left in the reaction mixture, but there was a large amount of phenyl trifluoro-acetate. This is explained by the reaction of the trifluoro-acetic anhydride with the phenol yielding the phenyl trifluoro-acetate according to Equation 4.9.

![Equation 4.9]
4.4 Conclusive remarks

It has been shown that electrochemical acyloxylation of phenol and phenyl acetate, in order to indirectly form the dihydroxybenzenes, is not industrially viable under the experimental conditions investigated. The drawbacks of these methods include the low product yields, toxicity of the reagents and the high cost of reagents.

There is, however, a scientific paper\textsuperscript{73}, which shows that electrochemical trifluoro-acetoxylation of selected aromatic ring structures can occur with high yields, producing indirectly the dihydroxybenzenes upon hydrolysis. However the compounds selected have activated aromatic ring structures. Examples are naphthalene’s and 4-\textit{tert}-butylphenylacetate. In comparison with these compounds, phenol and phenyl acetate are deactivating for nucleophilic substitution, and therefore may not have sufficient electron density on the ring to facilitate easy trifluoro-acetoxylation. Results obtained, however, showed that trifluoro-acetoxylation did take place to a certain extent with these two substrates.
CHAPTER 5

ELECTROCHEMICAL HYDROXYLATION

5.1 Introduction

In this section the electrochemical hydroxylation of phenols to the corresponding 1,4-dihydroxybenzenes will be investigated. Using direct electrochemical oxidation of phenols to the benzoquinones (Scheme 5.1), followed by the reduction of the benzoquinones to the corresponding hydroquinone (Scheme 5.2).

Scheme 5.1: Oxidation to benzoquinone

\[
\begin{align*}
R_1\text{-}R_2\text{OH} & \xrightarrow{-e^-} R_1\text{-}R_2\text{H} \xrightarrow{-H^+} R_1\text{-}R_2\text{OH} \\
& \xrightarrow{-e^-} R_1\text{-}R_2\text{H} \xrightarrow{H_2O} R_1\text{-}R_2\text{OH} \\
& \xrightarrow{-H^+} R_1\text{-}R_2\text{OH} \\
& \xrightarrow{-e^-} R_1\text{-}R_2\text{OH} \\
& \xrightarrow{-H^+} R_1\text{-}R_2\text{OH} \\
& \xrightarrow{-e^-} R_1\text{-}R_2\text{OH} \\
\end{align*}
\]
R₁ and R₂ can be virtually anything but in this investigation it was H or C(CH₃)₃

Scheme 5.2: Reduction to hydroquinone

R₁ and R₂ can be virtually anything but in this investigation it was H or C(CH₃)₃

The objective of this work is to selectively produce the 1,4-dihydroxy benzenes from the corresponding phenols, with acceptable current efficiencies, accountabilities, yields and isomer purity.

The method for the electrochemical oxidation of phenols to the corresponding benzoquinone, followed by reduction of the benzoquinone to the hydroquinone, has been well known for quite some time.⁷⁵-⁸⁰ When considering the methods for the production of 1,4-dihydroxybenzene, it can be seen that all the methods follow similar procedures. All the reactions are carried out using sulfuric acid as the supporting electrolyte and water as solvent. The only differences between these methods are the electrode materials and the additives. The additives are all inorganic in nature such as (Cu, Cr).

Considering the literature, ⁷⁵-⁸⁰ it was decided not to follow the conventional methods, since they have been well investigated and do not yield exceptional results, but rather to apply a method, which has, not to our knowledge, been used in the oxidation of phenol. This oxidation of phenol is based on a
method,\textsuperscript{81} which describes the electrochemical oxidation of 2-aryl- the corresponding benzoquinone, followed by reduction to the corresponding hydroquinone.

This method describes a process similar to that known for the electrochemical oxidation of phenol, with one exception: use is made of an organic co-solvent (acetonitrile). The reason for the addition of the co-solvent to the original process was to change the properties of the solution to such an extent as to increase the solubility of the aqueous phase towards the organic substrate, which has a low solubility in the aqueous sulphuric acid solution.

Phenol was taken as starting material since it is readily available industrially, and the product resulting from the reaction (hydroquinone) is of economic importance. The tert-butylated phenols were also selected, because of the industrial importance of the corresponding hydroquinones and benzoquinones as anti-oxidants. It is also important to note that there are industrial processes available for the butylation of phenol and the de-butylation of the corresponding benzoquinones and hydroquinones. This allows the choice of one of two routes; first the production of the benzoquinone and hydroquinone from the corresponding phenol, or secondly the oxidation of the butylated phenol to the corresponding hydroquinones and benzoquinones followed by de-butylation.

The investigation was carried out, using constant current electrolysis, by studying the reaction variables, which affect product distributions: yield, current efficiency and accountability. The variables include: reaction temperature, supporting electrolyte identity, supporting electrolyte concentration, electrode material, current density and the nature of the solvent. These investigations were carried out with the aid of product distribution diagrams.
5.2 Oxidation potential

As mentioned previously in Section 4.2.2, the first step in an electrochemical investigation is the determination of the oxidation potential of the compounds being investigated. This was done using Cyclic Voltammetry, where the potential of a working electrode, immersed in a solution containing the analyte, is varied first in one direction then in the other. Analytes are not the only electro-active species in solution; others include solvents and supporting electrolytes. It is important to know how the other constituents of the medium will react under applied potential.

In this process it was found that the oxidation potential of the medium was above 2000 mV, higher than that of any of the substrates. From an electrochemical point of view it can then be concluded that the oxidation of the substrate can take place, without interference from the medium.

Oxidation potentials are usually measured as $E_{pa}$ in CV. $E_{pa}$ represents the oxidation potential measured at the anodic peak in a Cyclic Voltammogram.

Table 5.1 shows the results obtained during the investigation of the oxidation potential of phenols, hydroquinones and benzoquinones, under reaction conditions of 8ml 22 % $\text{H}_2\text{SO}_4$, 18 ml acetonitrile and 0.05 g analyte.
Table 5. 5: CV oxidation potentials

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Working electrode</th>
<th>Oxidation. Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenol</td>
<td>Pt</td>
<td>1348</td>
</tr>
<tr>
<td>Phenol</td>
<td>C</td>
<td>1348</td>
</tr>
<tr>
<td>1,4-dihydroxybenzene</td>
<td>Pt</td>
<td>964</td>
</tr>
<tr>
<td>1,4-dihydroxybenzene</td>
<td>C</td>
<td>962</td>
</tr>
<tr>
<td>p-Benzoquinone</td>
<td>Pt</td>
<td>Not observed</td>
</tr>
<tr>
<td>p-Benzoquinone</td>
<td>C</td>
<td>Not observed</td>
</tr>
<tr>
<td>2-tert-butylphenol</td>
<td>Pt</td>
<td>1305</td>
</tr>
<tr>
<td>2-tert-butylphenol</td>
<td>C</td>
<td>1351</td>
</tr>
<tr>
<td>2-tert-butylhydroquinone</td>
<td>Pt</td>
<td>754</td>
</tr>
<tr>
<td>2-tert-butylhydroquinone</td>
<td>C</td>
<td>816</td>
</tr>
<tr>
<td>2-tert-butylbenzoquinone</td>
<td>Pt</td>
<td>Not observed</td>
</tr>
<tr>
<td>2-tert-butylbenzoquinone</td>
<td>C</td>
<td>Not observed</td>
</tr>
<tr>
<td>2,6-di-tert-butylphenol</td>
<td>Pt</td>
<td>1182</td>
</tr>
<tr>
<td>2,6-di-tert-butylphenol</td>
<td>C</td>
<td>1357</td>
</tr>
<tr>
<td>2,6-di-tert-butylhydroquinone</td>
<td>Pt</td>
<td>728.5</td>
</tr>
<tr>
<td>2,6-di-tert-butylhydroquinone</td>
<td>C</td>
<td>816</td>
</tr>
<tr>
<td>2,6-di-tert-butylbenzoquinone</td>
<td>Pt</td>
<td>Not observed</td>
</tr>
<tr>
<td>2,6-di-tert-butylbenzoquinone</td>
<td>C</td>
<td>Not observed</td>
</tr>
</tbody>
</table>

Oxidation potentials measured using a Ag / AgCl (3 mol dm$^{-3}$) reference electrode.

These CV results show the generally acceptable trend, which states, the greater the activation of the aromatic ring the lower it’s oxidation potential.

From the results shown in Table 5.1 a number of observations can be made:

- Electrode material: generally the use of platinum leads to lower oxidation potential than carbon, with the difference between the values for platinum and carbon becoming greater as the degree of substitution of the phenol increases.
- Organic substrates: From an electrochemical point of view, the compound with the lower oxidation potential will be oxidised preferentially to others
with higher oxidation potentials. It is seen from Table 5.1 that the particular hydroquinone, which would be the target compound, has a lower oxidation potential than the corresponding phenol, whilst the further oxidized product (the benzoquinone, here the intermediate) is stable towards further oxidation. This therefore implies that, during oxidation at the anode, the phenol will be oxidized first to the respective hydroquinone or hydroquinone-like species, which, being vulnerable towards oxidation, will immediately be oxidized further to the corresponding benzoquinone, which should therefore accumulate at the anode in the cell.

However, the particular benzoquinone is in reversible electrochemical equilibrium with its hydroquinone, as shown in Equation 5.1.

\[
\text{R}_1 = \text{H or tert-butyl group} \\
\text{R}_2 = \text{H or tert-butyl group}
\]

At the cathode (the other electrode), therefore, this benzoquinone can be reduced to reform the hydroquinone. This reduction reaction will be superimposed on the normal cathode reduction reaction in acidic media, namely the reduction of protons to hydrogen gas, as per Equation 5.2.

\[
2 \text{H}^+ + 2e^- \overset{\text{H}_2 (g)}{\rightleftharpoons} \quad (5.2)
\]

It is noted from Equation (5.1) that the reduction of the benzoquinone requires protons, and that protons will therefore be consumed during the process; however, the re-oxidation of the hydroquinone to the benzoquinone resupplies these protons.
Considering the oxidation potentials of the phenols and hydroquinones on platinum in Table 5.1, one would expect a decrease in the potential upon substituting first one tert-butyl group onto the ring, and then another, since this group increases the electron density on the ring and therefore makes it easier for the compound to be oxidised. This is indeed found to be the case for the hydroquinones and phenols.

### 5.3 Reaction studies on phenol

The reactions were performed in order to determine the optimum conditions for the production of hydroquinones from the corresponding phenols through the investigation of reaction conditions. These reaction studies were performed as described in Section 3.3.2.

#### 5.3.1 Definitions

In this work, terms were used as defined in Equations 4.1 to 4.5.

#### 5.3.2 Product distribution diagrams of phenol

The electrolysis data will be presented in the form of graphs plotting mole % on the Y-axis and charge per mole (F) on the X-axis. These graphs will show the following: the percentage unreacted substrate, the yield (mole %) of the hydroquinone and benzoquinone formed, the sum of all constituents of interest in the solution (phenol, hydroquinone and benzoquinone) and the current efficiency as a function of charge per mole (F), which can be related to time since the electrolysis is conducted under controlled current.

It should be kept in mind that 4 F are required to convert the particular phenol to the benzoquinone, and 2 F to convert the benzoquinone back to the product, the hydroquinone. However, in an electrochemical cell, the cathodic reaction at one electrode takes place at the same time as the anodic reaction at the anode, the other electrode; also the target compound cannot be produced before the benzoquinone has been formed. So it can be said that 4
F is required to convert one mole of the particular phenol to the corresponding hydroquinone, since hydroquinone is produced via benzoquinone.

The sum total of the identified products formed in the reaction as a function of charge per mole, F, is a measure of the accountability of the reaction.

These reactions were conducted in order to ascertain what happens during the electrochemical oxidation of phenols to hydroquinones, as well as to determine which electrode material and electrode combination yielded optimum results.

The general reaction conditions for the product distribution reactions are shown in Table 5.2.

**Table 5.2: Reaction conditions during product distribution investigation**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>35 °C</td>
</tr>
<tr>
<td>Substrate concentration</td>
<td>0.33 mol L⁻¹</td>
</tr>
<tr>
<td>Sulfuric acid concentration</td>
<td>22 %</td>
</tr>
<tr>
<td>Acid volume</td>
<td>8 cm³</td>
</tr>
<tr>
<td>Solvent volume (acetonitrile)</td>
<td>24 cm³</td>
</tr>
<tr>
<td>Current density</td>
<td>2000 A m⁻²</td>
</tr>
</tbody>
</table>

Figures 5.3 to 5.6 show the oxidation of phenol using the conditions mentioned in Table 5.2, and further variables investigated as mentioned in the captions.
Figure 5.3: Product distribution diagram (anode: lead dioxide, cathode: platinum)

Figure 5.4: Product distribution diagram (anode: lead dioxide, cathode: nickel)
Figure 5.5: Product distribution diagram (anode: platinum, cathode: nickel)

Figure 5.6: Product distribution diagram (anode: platinum, cathode: platinum)
With reference to these figures, the following observations can be made:

- **Phenol:** The rate and extent at which phenol is oxidized varies depending on the electrode materials used. It can be seen that for the reactions conducted with the aid of the lead dioxide anode the rate of phenol oxidation is approximately constant up to 8 F whereupon the rate rapidly decreases. When platinum was investigated as anode material it was found that this rate change also occurs but at another constant point (7F). When comparing the mole % at which this inflection occurs in Figures 5.3 to 5.6 it is apparent that the inflection point is much lower for platinum than for lead dioxide. This indicates that the oxidation of phenol occurs to a greater extent and at a faster rate on the platinum anode as compared to that on the lead dioxide anode.

When considering the cathode materials investigated, it was found that for Ni the mole % at which this rate change occurs was comparable to those cases in which platinum was used as the cathodic material and it was seen that this change occurred at approximately 12 mole % (except when lead dioxide was used as the anode).

- **Benzoquinone:** The extent to which the intermediate benzoquinone is produced varies depending on the electrode materials investigated. It can be seen that the amount of benzoquinone formed reaches a maximum, then slowly decreases. For the reactions conducted with the aid of the lead dioxide anode the maximum is reached at 8 F and for the reactions where platinum was used as an anode the maximum occurs at 7 F. The mole % values of the benzoquinones does however differ drastically with the mole % values for the lead dioxide anode being under 5 % and those for the platinum anode being above 20 %.

When considering the cathode materials investigated it was seen that the amounts of benzoquinone produced did not vary significantly.
- **Hydroquinone formation:** The extent to which hydroquinone is produced varies depending on the electrode materials investigated. It can be seen that the amount of hydroquinone reaches a maximum, then slowly decreases. For the reactions conducted with the aid of the lead dioxide anode this maximum is reached at 8 F and for platinum as an anode it was 10 F. The mole % values for the hydroquinone maximum do however differ: for the lead dioxide anode being above 40 %, and for the platinum anode it was below 25 %.

When considering the cathode materials investigated it was seen that the amounts of hydroquinone produced varied, with the nickel cathode always yielding the highest mole % values, this is shown in Table 5.3.

<table>
<thead>
<tr>
<th>Anode</th>
<th>Cathode</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead dioxide</td>
<td>nickel</td>
<td>44%</td>
</tr>
<tr>
<td>Lead dioxide</td>
<td>platinum</td>
<td>40 %</td>
</tr>
<tr>
<td>Platinum</td>
<td>nickel</td>
<td>24%</td>
</tr>
<tr>
<td>Platinum</td>
<td>platinum</td>
<td>15 %</td>
</tr>
</tbody>
</table>

- **Catechol formation:** The extent to which catechol is produced varies depending on the electrode materials investigated. It can be seen that the amount of catechol reaches a maximum, then slowly decreases. For the reactions conducted using the lead dioxide as anode, the maximum is reached at 8 F and for platinum as anode it was 6 F. The mole % values of the catechol maximum do not differ when changing cathode materials but does however differ slightly when changing anode materials, this is shown in Table 5.4.
Table 5.4: Catechol yields versus electrode materials

<table>
<thead>
<tr>
<th>Anode</th>
<th>Cathode</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead dioxide</td>
<td>nickel</td>
<td>4.4%</td>
</tr>
<tr>
<td>Lead dioxide</td>
<td>platinum</td>
<td>4.4%</td>
</tr>
<tr>
<td>Platinum</td>
<td>nickel</td>
<td>3%</td>
</tr>
<tr>
<td>Platinum</td>
<td>platinum</td>
<td>3%</td>
</tr>
</tbody>
</table>

- **Current efficiencies:** The current efficiencies for the reactions done with the aid of different electrodes show significant variation with a change in anode material but no change for a variation in cathode material. For the reactions using lead dioxide as an anode, it can be seen that the current efficiency reaches a maximum at 4 F then slowly decreases, but with platinum as anode material the curve continually decreases. It can also be seen that in general the current efficiency is 10% higher for reactions conducted with lead dioxide than reactions conducted with platinum as anodes.

- **Accountability:** The accountability of the reactions also proved to be affected by electrode material. In all the reactions performed the accountability gradually decreases. The gradient of the line, which is an indication of the rate of product loss, does not vary when changing cathode material but does vary with the change in anode material, with the lead dioxide anode yielding superior accountabilities in each case.

5.3.3 Discussion of phenol oxidation

From the above results it can be seen that the rate of phenolic oxidation occurs faster and to a greater extent on a platinum anode than on a lead dioxide anode. The problem is, however, that the oxidation of the phenol on the platinum anode is less selective towards benzoquinone, than at the lead dioxide electrode; this can be observed from the differences in accountability between the two reactions.
It is also interesting to note that the point of inflection of the phenolic oxidation corresponds to the peak values for benzoquinone. This indicates that the benzoquinone is produced directly from the oxidation of phenol at that stage in the reaction.

The hydroquinone maximum for the reactions in which lead dioxide is used as an anode corresponds to the phenol inflection and the benzoquinone maximum. This indicates that the process in which the hydroquinone is produced i.e. benzoquinone reduction, runs parallel to the reaction for benzoquinone formation. From the product yields and current densities it can be seen that the nickel cathode as compared to the platinum cathode promotes the reduction of the benzoquinone to hydroquinone.

From the above it can thus be said that the use of a lead dioxide anode and a nickel cathode is the best electrode-pair choice for the production of the hydroquinone. These conditions should also be applicable for the substituted hydroquinones.

5.4 Reaction studies on substituted phenols

5.4.1 2-Tert-butylphenol product distribution investigation

Figures 5.7 and 5.8 show the oxidation of 2-tert-butylphenol using the conditions mentioned in Table 5.2, with the aid of a lead dioxide anode and a nickel cathode. These two figures are derived from the same set of data, but for the sake of clarity the x-axis in Figure 5.7 was expanded in Figure 5.8 so as to cover the 0 – 6 F range, in order to study the disappearance of the phenol.. The accuracy of the data is slightly suspect since a second layer developed upon cooling in the system, which made sampling difficult.
Figure 5.7: Product distribution diagram for 2-tert-butylphenol

Figure 5.8: Modified product distribution diagram for 2-tert-butylphenol
With reference to these figures, the following observations can be made:

- **2-tert-Butylphenol**: The consumption of the 2-tert-butylphenol in the reaction occurs at a faster rate than is the case with phenol: this is shown by the charge per mole value (6 F) at which the substituted phenol reaches a concentration close to zero, compared to 8 F at which phenol reaches a constant concentration. This is in line with the lower oxidation potential of the substituted phenol.

- **2-tert-Butylbenzoquinone**: It can be seen that the amount of 2-tert-butylbenzoquinone formed reaches a maximum, then slowly decreases. It is also shown that the maximum amount of 2-tert-butylbenzoquinone produced occurs at a charge per mole value of 9 F and a mole percent value of 53 % compared to phenol, which has a value of 8 F at 3.9 %.

- **2-tert-butylhydroquinone formation**: It can be seen that the amount of 2-tert-butylhydroquinone formed reaches a maximum, then slowly decreases. The maximum amount of 2-tert-butylhydroquinone produced, occurs at a charge per mole value of between 4 F and 6 F at a mole percent value of 50 %, compared to phenol which has a value of 8 F at 43 %

- **Current efficiency**: The current efficiency value for the electrochemical production of 2-tert-butylhydroquinone shows first a slight increase, followed by a gradual decrease. The current efficiency for the production of 2-tert-butylhydroquinone at 4 F was found to be 32 % compared to that of phenol which was 33 % at 4 F.

- **Accountability**: The accountability for the oxidation of 2-tert-butylphenol follows a gradual decrease up to 5 F followed by a increase to 8 F. In comparison, phenol just shows a continues drop in the accountability for the reaction.

### 5.4.2 2,6-Di-tert-butylphenol product distribution investigation

Figures 5.9 and 5.10 show the oxidation of 2,6-di-tert-butylphenol using the conditions mentioned in Table 5.2, with the aid of a lead dioxide anode and a platinum cathode. These two figures are derived from the same set of data,
but for the sake of clarity the x–axis in Figure 5.9 is expanded to Figure 5.10 so as to cover the 0 4 F range, where the phenol is consumed. The accuracy of the data is slightly suspect since a second layer developed upon cooling in the system, which made sampling difficult.

Figure 5.9: Product distribution diagram for 2,6-di-tert-butylphenol
With reference to these figures, the following observations can be made:

- **2,6-di-tert-butylphenol**: The consumption of the 2,6-di-tert-butylphenol in the reaction occurs at a faster rate than is the case with phenol and 2-tert-butylphenol: this is shown by the charge per mole value (4 F) at which 2,6-di-tert-butylphenol reaches a concentration close to zero compared to 6 F and 8 F for 2-tert-butylphenol and phenol respectively. This is in line with the very low oxidation potential of this compound.

- **2,6-di-tert-butylbenzoquinone**: It is shown that the amount of 2,6-di-tert-butylbenzoquinone formed reaches a maximum, then slowly decreases. The maximum amount of 2,6-di-tert-butylbenzoquinone produced, occurs at a charge per mole value of 6 F and a mole percent value of 43 % compared to 6 F, 50 % and 8 F, 3.9 % for 2-tert-butylphenol and phenol respectively.

- **2,6-di-tert-butylhydroquinone formation**: It can be seen that the amount of 2-tert-butylhydroquinone formed has an almost stepwise trend, moving from 0 % at 0 F up to 75 % at 3 F, then down to 63 % at 6 F and finally up to close to 100 % at 9 F. As observed, the other two phenols did not show a similar trend. This will be discussed more fully later in this section, but it was seen that the optimum values for the
formation of 2-\textit{tert}-butylhydroquinone was 50\% between 4 and 6 F, and for hydroquinone itself it was 44\% at 8 F.

- **Current efficiencies:** The current efficiencies value for the electrochemical production of 2,6-di-\textit{tert}-butylhydroquinone shows a gradual decrease from the start. The current efficiency for the production of 2,6-di-\textit{tert}-butylhydroquinone at 4 F was found to be 32\%, which was similar to the values achieved for both 2-\textit{tert}-butylhydroquinone and hydroquinone.

- **Accountability:** The accountability for the oxidation of 2,5-di-\textit{tert}-butylphenol shows a slight increase moving from 100\% to about 110\%. This discrepancy is due to sampling error mentioned earlier in this section.

### 5.4.3 Discussion

- In comparison to phenol, the substituted phenols are more readily oxidized. This has been shown to be due to their lower oxidation potential, which decreases with the degree of substitution.

- Also the corresponding hydroquinones are produced in greater yield, with the di-substituted phenol performing better than the mono-substituted one. At the point where the particular phenol has virtually disappeared, the mono-substituted phenol gave 50\% of the corresponding hydroquinone, whilst the di-substituted phenol gave 62\%.

- What is interesting, however, is the pronounced cyclic form of the curve for the hydroquinone formation for the di-substituted phenol, as shown in Figure 5.9. This cyclic nature is starting to develop also in Figure 5.7 for the mono-substituted phenol, and would be more noticeable if the experiment would have carried on for longer.

This cyclic form for the formation of the 2,5-di-\textit{tert}-butylhydroquinone in Figure 5.9 can be explained by considering the mechanism of phenol oxidation. The particular phenol is oxidised to the corresponding benzoquinone at the anode, and this benzoquinone can then be reduced to the particular hydroquinone at the cathode. This hydroquinone can then be re-oxidised at the anode, due to
the reversible electrochemical equilibrium mentioned in Equation 5.1. Keeping this mechanism in mind, the cyclic hydroquinone formation curve in Figure 5.9 can be explained as follows:

- **0 to 3 F:** As the phenol is oxidised and its concentration decreases, the benzoquinone is produced at the anode which is then reduced at the cathode to form the hydroquinone. This accounts for the decrease in the phenols concentration and the increase in the hydroquinones and benzoquinones concentrations.

- **3 to 6 F:** Here the depletion of the phenol has occurred to such an extent that its oxidation is no longer the dominant reaction at the anode. The oxidation of the hydroquinone present in the medium is now the predominating anodic reaction. This results in a decrease in the hydroquinone concentration and an increase in the benzoquinone concentration.

- **6 to 10 F:** Now the equilibrium reaction steps in, since the benzoquinone concentration has increased to a point where its reduction starts occurring faster than the hydroquinones oxidation. The hydroquinone concentration increases while the benzoquinones concentration decreases. At 9F it is possible to see the start of another such cycle.

### 5.5 Conclusion

The increased rates of reaction, accountabilities, yield of hydroquinones and of benzoquinones when moving from phenol to 2-tert-butylphenol and ultimately 2,6-di-tert-butylphenol can be explained using the effect the tertiary butyl group has on the substrate. Since the tertiary butyl group is electron donating, it decreases the oxidation potential of the substrate, so increasing the rate of reaction. The increased accountabilities, and yields can be explained through the increased selectivity the tertiary butyl group lend, to the substrate. This increased selectivity is caused through the stabilization of the radical cation formed upon oxidation. Since the tertiary butyl group is electron donating and contains a tertiary carbon, it is capable of stabilising both the positive charge and the radical of the radical cation and its reaction products. This stabilization could allow the radical, cation or radical cation to migrate
from the electrode surface into the bulk of the solution where it can undergo nucleophilic attack, rather than undergo polymerisation which would be the result if the species was to stay in the vicinity of the electrode.

This Chapter has shown that fairly good yields of the substituted hydroquinones can be produced from the corresponding phenols using electrochemical methods, in particular constant current electrolysis using lead dioxide anode and nickel as cathode.

Further optimisation work could be carried out in order to improve the yield, and especially the current efficiency, which has been low in all cases.

The optimisation for phenol will be explored in the next chapter.
CHAPTER 6
MULTIVARIATE INVESTIGATION OF THE ELECTROCHEMICAL HYDROXYLATION OF PHENOL

6.1 Introduction
Organic synthesis is an important area in chemical research. New synthetic methods are invented at an ever-increasing rate, which open new pathways to produce interesting chemical compounds. It is therefore necessary to explore the reaction conditions to determine how they should be adjusted to obtain optimal results. To this end, it is necessary to determine the scope and limitations of the reaction. This in turn calls for more experimentation. Chemical phenomena are rarely the result of single causes. Instead, a number of factors are likely to be involved and, unfortunately their influences will depend on still other factors. In order to be able to take such interactions into account, it is necessary to use multivariate methods, which allow all pertinent factors to be considered simultaneously, both for designing experiments and for analysing the results.

6.2 Identification of reaction variables
In this section the electrochemical hydroxylation of phenol to hydroquinone is investigated by means of multivariable methods. A set of known variables was chosen, each variable having a low and high value. These values are represented as +1 and −1 in the experimental design.

The following experimental variables were selected for investigation:
- Temperature: variation in the temperature will affect the kinetics of all steps in the electrode process; examples of these are solubility of compounds, conductivity of electrolytic solution and the rate of reactions.
• Substrate loading: This will be varied in order to investigate the amount of phenol needed in order to optimise the yield to hydroquinone. A higher mass will require more coulombs, or more time to be converted to the hydroquinone. But a higher amount of phenol can also cause side reactions to occur. An example of this is the dimerization of phenolic compounds.

• Acid concentration: Variations in the sulfuric acid concentration can affect the hydroxylation mechanism from both a chemical and an electrochemical point of view.
  o Chemical: from Scheme 2.3 and 2.4 it can be seen that proton loss plays a important role in the mechanism, it can then be concluded that the acid concentration can effect the hydroxylation mechanism.
  o Electrochemical: since protons can be reduced at the cathode to hydrogen gas, this reaction could have an effect on the reduction of the benzoquinone to the hydroquinone.

• Acid volume: The acid volume and acid concentration complement each other. The acid solution is made up in water, so this factor is also an indication of the amount of water in the reaction. Variations in the amount of water present in the reaction mixture can affect both the hydroxylation mechanism from both a chemical and an electrochemical point of view:
  o Chemical: from Scheme 2.3 it can be seen that water acts as a nucleophile in the mechanism, and it can then be concluded that the acid volume can effect the hydroxylation mechanism.
  o Electrochemical: since water can be oxidised at the anode to oxygen gas, this reaction could have an effect on the oxidation of phenol to benzoquinone.

• Solvent volume: The acetonitrile volume has an effect on the reaction mixture, since it affects the properties, which can affect both the chemical and electrochemical mechanism.

• Current density: This is defined as the ratio of current supplied to the area of an electrode, and can be related to electron density, or charge density on the electrode. A higher current density means that more
current is passed through the system, which will cause greater oxidation as compared to a lower current density.

In this section the electrochemical hydroxylation of phenol will be investigated so as to determine which factors affect the hydroquinone yield, the hydroquinone catechol ratio, accountability and current efficiency, by means of multivariable methods. Those variables which prove to be significant in affecting the above responses, will be identified by statistical methods, and a model for the determination of the optimum conditions will be determined.

6.3 Determination of experimental domain

The experimental conditions chosen for the five variables selected for this study are given in Table 6.1.

Table 6.1: Experimental variables settings – electrochemical hydroxylation of phenol

<table>
<thead>
<tr>
<th>Coded</th>
<th>Variable</th>
<th>Unit</th>
<th>Low Value</th>
<th>High Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Temp</td>
<td>ºC</td>
<td>35.0</td>
<td>45.0</td>
</tr>
<tr>
<td>B</td>
<td>Phenol</td>
<td>g</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>C</td>
<td>Acid Conc</td>
<td>%</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>D</td>
<td>Acid Vol</td>
<td>ml</td>
<td>6.00</td>
<td>8.00</td>
</tr>
<tr>
<td>E</td>
<td>Solvent</td>
<td>ml</td>
<td>18.00</td>
<td>24.00</td>
</tr>
<tr>
<td>F</td>
<td>Current</td>
<td>mA</td>
<td>800.0</td>
<td>1200.0</td>
</tr>
</tbody>
</table>

**Fixed variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of stirring</td>
<td>rpm</td>
<td>1000</td>
</tr>
<tr>
<td>Supporting electrolyte</td>
<td></td>
<td>H₂SO₄</td>
</tr>
<tr>
<td>Anodic material</td>
<td></td>
<td>PbO₂</td>
</tr>
<tr>
<td>Cathodic material</td>
<td></td>
<td>Ni</td>
</tr>
</tbody>
</table>
6.4 Design and responses

Since 6 variables are to be investigated at two levels, a total of $2^6$, or 64, different experiments are required to investigate all six variables at two levels. The design is capable of providing 64 independent statistics. In an initial study such as this one, not all of the information is necessary, or even useful. For this reasons a fractional factorial design consisting of only 16 experiments, was carried out. In this design, it is assumed that two-factor, or higher interactions are small compared to the effect of the main factors. By equating additional factors to such interactions, the number of experimental runs required may be reduced significantly.

For the present study, a $2^{6-2}$ (or quarter-fraction) fractional factorial design was selected, by equating a fifth factor (E) to the interaction ABC in a full $2^4$ factorial design in factors A,B,C and D (Table 5.5), and a sixth factor (F) to the BCD interaction. The three design generators, will therefore be $I = ABCE$, $I = ADEF$ and $I = BCDF$. Equating additional factors to higher order interactions has the effect of confounding main and interaction effects. The confounding (aliases) of the design may be obtained by multiplying each effect with each of the design generators in turn. The aliases of all the main effects in the present $2^{6-2}$ fractional factorial design are shown in Table 6.2.

Table 6.2: The possible aliases in the design

<table>
<thead>
<tr>
<th>Effect</th>
<th>Aliases</th>
</tr>
</thead>
<tbody>
<tr>
<td>[A]</td>
<td>A + BCE + DEF</td>
</tr>
<tr>
<td>[B]</td>
<td>B + ACE + CDF</td>
</tr>
<tr>
<td>[C]</td>
<td>C + ABE + BDF</td>
</tr>
<tr>
<td>[D]</td>
<td>D + AEF + BCF</td>
</tr>
<tr>
<td>[E]</td>
<td>E + ABC + ADF</td>
</tr>
<tr>
<td>[F]</td>
<td>F + ADE + BCD</td>
</tr>
</tbody>
</table>

The response variables selected for the optimization procedure were: yield (hydroquinone), ratio (hydroquinone / catechol), accountability and current efficiency.
The full design-matrix used together with the experimental responses obtained, is shown in Table 6.3.

Table 6.3: Experimental design matrix with responses

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>% Yield HQ</th>
<th>% ratio HQ:CAT</th>
<th>% Acc</th>
<th>% CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-0.988</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>58.2</td>
<td>44.6</td>
<td>84.7</td>
<td>38.8</td>
</tr>
<tr>
<td></td>
<td>(35)</td>
<td>(0.5031)</td>
<td>(16)</td>
<td>(6)</td>
<td>(24)</td>
<td>(1200)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1</td>
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<td>33.2</td>
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<td>(22)</td>
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<td>(24)</td>
<td>(1200)</td>
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<td></td>
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<td>1</td>
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<td>85.9</td>
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<td>(16)</td>
<td>(6)</td>
<td>(18)</td>
<td>(1200)</td>
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<td></td>
<td></td>
<td></td>
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<td>-0.986</td>
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<td>1</td>
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<td>(6)</td>
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<td>(800)</td>
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<td>(22)</td>
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<td>(18)</td>
<td>(800)</td>
<td></td>
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</tr>
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<td>-1</td>
<td>-1</td>
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<td>57.1</td>
<td>36.6</td>
<td>87.9</td>
<td>38.0</td>
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<td>(6)</td>
<td>(18)</td>
<td>(1200)</td>
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<td>50.7</td>
<td>83.0</td>
<td>36.8</td>
</tr>
<tr>
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<td>(22)</td>
<td>(8)</td>
<td>(24)</td>
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<td></td>
<td></td>
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<td>-1</td>
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<td>-1</td>
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<td>25.3</td>
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<td>(24)</td>
<td>(800)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The factor levels shown in Table 6.3 were coded using Equation 6.1.

\[ X_i = \frac{(x_i - x_c)}{s_x} \]  

(6.1)

where:  
- \( X_i \) = Coded value of variable \( x_i \),  
- \( x_i \) = natural value of variable \( x_i \) at a factorial point,  
- \( x_c \) = natural value of variable \( x_i \) at the design centre, and  
- \( s_x \) = step size in the natural values of variable \( x_i \).

The experiments were carried out using the procedure as described in Section 3.3.2.

6.5 Statistical analysis

6.5.1 Calculation of response surface model and effects

There are a number of methods available for the calculation of the effects and the response surface model. The method of linear least squares regression will be used in order to achieve this. Since it is known that the effect is twice
the corresponding coefficients value the response surface model will be calculated first using. Equation 6.2.

\[ R = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_{12} x_1 x_2 \]
\[ + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{15} x_1 x_5 + \beta_{16} x_1 x_6 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 \]
\[ + \beta_{25} x_2 x_5 + \beta_{26} x_2 x_6 + \beta_{34} x_3 x_4 \]  \quad (6.2)

where

- \( R \) = experimental response,
- \( x_1 \) = temperature,
- \( x_2 \) = phenol loading,
- \( x_3 \) = acid concentration,
- \( x_4 \) = acid volume,
- \( x_5 \) = solvent volume and
- \( x_6 \) = current.

This was fitted to the experimental data by means of linear least squares regression. These calculations are briefly outlined below. A model matrix, \( X \), is first constructed by augmenting the design matrix (Table 6.2, for example) with a column, \( I \), for the constant term (\( \beta_0 \)) and the corresponding columns for the interaction effects. Due to limitations in space, only a part of the model matrix is shown in Table 6.4.

<table>
<thead>
<tr>
<th>Run</th>
<th>Temperature (^\circ)C</th>
<th>Phenol g</th>
<th>Acid Concentration (%)</th>
<th>Acid Volume (\text{cm}^3)</th>
<th>Solvent Volume (\text{cm}^3)</th>
<th>Current mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-0.9876</td>
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<td>1</td>
<td>1</td>
</tr>
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<td>-1</td>
</tr>
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<td>1.0148</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 6. 4: Model matrix without interaction effects
The overall calculation may be summarized by the matrix Equation 6.3 and 6.4 and illustrated in full by Equations 6.5. The calculations are not shown since there is not enough space on a page to display it, so only the matrix equations are displayed.

\[ Y = Xb + e \]  

(6.3)

where  
\( y \) = the column vector of experimental responses,  
\( X \) = the model matrix,  
\( b \) = the column vector of model parameters and  
\( e \) = the column vector of error terms associated with each model parameter.
The procedure used during the least squares fit of the data is summarized by the matrix Equation 6.5.

\[(X'X)^{-1}X'y = b\]  
\[(6.5)\]

The response surface models for the various responses are shown in Equations 6.6 to 6.9 below.

Yield hydroquinone:

\[Y = 52.48 + 0.68 x_1 - 0.72 x_2 + 0.63 x_3 - 4.445E-03 x_4 - 0.99 x_5\]
\[+ 1.77 x_6 - 0.63 x_1x_3 + 0.45 x_1x_4 - 1.85 x_1x_5 + 2.91 x_1x_6 - 1.66 x_2x_4\]
\[- 1.36 x_2x_5 - 0.11 x_2x_6 + 0.22 x_3x_4 + 0.81 x_3x_5\]  
\[(6.6)\]

Ratio hydroquinone/catechol:

\[Y = + 33.32 - 2.08 x_1 + 0.37 x_2 - 0.29 x_3 - 1.91 x_4 + 0.12 x_5\]
\[+ 0.97 x_6 + 0.79 x_1x_3 + 4.14 x_1x_4 + 1.00 x_1x_5 + 2.09 x_1x_6 - 1.74 x_2x_4\]
\[+ 0.57 x_2x_5 - 0.91 x_2x_6 - 5.78 x_3x_4 - 0.025 x_3x_5\]  
\[(6.7)\]
Accountability:

\[
Y = 84.50 + 0.89 x_1 + 1.22 x_2 - 0.099 x_3 + 0.23 x_4 - 1.06 x_5 + 1.91 x_6 \\
- 0.90 x_1 x_3 - 0.73 x_1 x_4 - 1.21 x_1 x_5 + 1.71 x_1 x_6 + 0.13 x_2 x_5 + 0.45 x_2 x_6 \quad (6.8) \\
+ 0.25 x_3 x_4 + 0.79 x_3 x_5 - 0.31 x_3 x_6
\]

Current efficiency:

\[
Y = +34.99 + 0.46 x_1 - 0.48 x_2 + 0.42 x_3 - 2.963E-03 x_4 - 0.66 x_5 \\
+ 1.18 x_6 - 0.42 x_1 x_3 + 0.30 x_1 x_4 - 1.24 x_1 x_5 + 1.94 x_1 x_6 - 1.11 x_2 x_4 \quad (6.9) \\
- 0.91 x_2 x_5 - 0.074 x_2 x_6 + 0.15 x_3 x_4 + 0.54 x_3 x_5
\]

6.5.2 Statistical evaluation of results

Before using the response surface model shown above for comparison and optimisation purposes, it is necessary if possible to simplify the model and to confirm that these models are indeed good descriptions of the actual response surfaces. Several statistical tests, both numerical and graphical, have been described for evaluating experimental determined repose surfaces. Many of these have been applied to the response surface models given in Equations 6.6 to 6.9, and are briefly described below.

Due to the large number of effects both main and interaction, it was decided to use normal probabilities mainly to obtain the significant effects. An ANOVA table would then be generated on the model in order to see if the new model yields a acceptable results.

6.5.1.1 Graphical analysis techniques

Graphical methods were used to determine which factors are significant aswell as determining the validity of the response surface models.

In order to achieve this, normal probability plots of the effects, residuals and a plot of residuals versus predicted responses, will be considered.
**Normal probability plot of effects**

The procedure for constructing a normal probability plot may be summarized as follows:

- Arrange the data in order of increasing value.
- Write down the cumulative frequency of each point.
- Calculate the % cumulative frequency for each point using the formula in Equation 6.10.

\[
\text{% Cumulative Frequency} = \frac{100 \times \text{cumulative frequency}}{\text{n}+1}
\]  

(6.10)

where \(n\) = the total number of data points in the original set.

The plots are shown in Figures 6.1 to 6.4, where the significant effects are highlighted.

**Figure 6.1: Normal probability plot of effects (hydroquinone yield)**
Figure 6.2: Normal probability plot of effects (hydroquinone / catechol ratio)

Figure 6.3: Normal probability plot of effects (accountability)
From these normal probability plots it can be seen that there are some factors which have an effect on the product yield; these factors are shown in Table 6.5.

Table 6.5: Significant effects determined from the normal probability plots.

<table>
<thead>
<tr>
<th>Response</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Hydroquinone %</td>
<td>A, E, F, AE and AF</td>
</tr>
<tr>
<td>Ratio Hydroquinone: Catechol</td>
<td>A, C, D, AD and CD</td>
</tr>
<tr>
<td>Accountability</td>
<td>A, B, E, F, AF and AE</td>
</tr>
<tr>
<td>Current efficiency</td>
<td>A, B, E, F, AE, AF and BE</td>
</tr>
</tbody>
</table>

Since these factors proved to be significant, the other non-significant factors were dropped from the model, resulting in the model described by Equations 6.11 to 6.14.
Yield hydroquinone:

\[ Y = 52.48 + 0.69x_1 - 1.02x_5 + 1.77x_6 - 1.86x_1x_5 + 2.91x_1x_6 \]  \hspace{1cm} (6.11)

Ratio hydroquinone: catechol:

\[ Y = 33.33 - 2.08x_1 - 0.71x_2 - 1.94x_4 + 4.15x_1x_4 - 6.21x_3x_4 \]  \hspace{1cm} (6.12)

Accountability:

\[ Y = 84.49 + 0.89x_1 + 2.06x_2 - 1.06x_5 + 1.91x_6 - 1.22x_1x_5 \]
\[ \quad + 1.71x_1x_6 \]  \hspace{1cm} (6.13)

Current efficiency:

\[ Y = 34.98 + 0.46x_1 + 0.11x_2 - 0.67x_5 + 1.17x_6 - 1.24x_1x_5 \]
\[ \quad + 1.94x_1x_6 - 0.74x_2x_5 \]  \hspace{1cm} (6.14)

- **Normal probability plots of residuals**

If a response surface is adequate, it can be assumed that the residuals will depend only on normal distributed random experimental error. The plot is generated exactly in the same manner as above except that the factors used vary. The residuals are calculated as shown in Equation 6.15 followed by the plots in Figures 6.5 to 6.8.

\[ e = R^{\text{obs}} - R^{\text{pred}} \]  \hspace{1cm} (6.15)

Where: \( e \) = the residual, 
\( R^{\text{obs}} \) = the observed response and 
\( R^{\text{pred}} \) = the predicted response
Figure 6.5: Normal probability residuals (hydroquinone yield)

Figure 6.6: Normal probability residuals (hydroquinone / catechol ratio)
Figure 6.7: Normal probability residuals (accountability)

Figure 6.8: Normal probability residuals (current efficiency)

All figures show good normality since they give straight lines.
• **Plot of residuals versus predicted responses**\(^{85}\)

Another test, which is always recommended, is to plot the residuals in each experiment against the predicted response from the same reaction. An adequate model should give a plot in which the points show a random scatter such that the upper and lower limits of the pattern form two parallel horizontal lines at approximately equal distance from the zero line. Anomalous features that can sometimes indicate problems with fitted response surface models including instances when:

• The upper and lower limits diverge such that the pattern appears funnel-like. This is normally an indication that the experimental error differs in different parts of the experimental domain and, hence, the assumption of constant error variance is violated.

• The upper and lower limits are parallel, but not horizontal. This is normally indicative of the presence of systematic error.

• The upper and lower limits are bent so as to give a pattern that results in an arch. This could indicate that a second-order term has been left out of the response surface model.

A plot of the residuals against the predicted response for response surface models for each response is shown in Figures 6.9 to 6.12.
Figure 6. 9: Normal probability residuals v. predicted response (hydroquinone yield)

![Residuals vs. Predicted Graph]

Figure 6. 10: Normal probability residuals v. predicted response (hydroquinone: catechol ratio)

![Residuals vs. Predicted Graph]
Figure 6.11: Normal probability residuals v. predicted response (accountability)

Figure 6.12: Normal probability residuals v. predicted response (current efficiency)
From these Figures (6.9 to 6.12) it can be seen that the predicted models show that there is a normal distribution and that the model can be accepted.

6.5.1.2 Analysis of variance (ANOVA)

ANOVA is a powerful statistical technique that can be used to separate variances during the deliberate variation of experimental variances for pure experimental variance.

The procedures used will be shown for the responses (yield hydroquinone, ratio hydroquinone / catechol, accountability and current efficiency) in order to determine whether the reduced models are acceptable.

- **Calculation of the total sum of squares, SST**

From the series of n-experiments used to determine a response surface model, the sum of squares, called the total sum of squares, SST, can be computed by simply obtaining the sum of squared responses (Equation 6.16). The total sum of squares is calculated with (n) degrees of freedom, where n is the total number of experiments in the design.

\[
SST = \Sigma y_i^2 = y'y
\]  

(6.16)

- **Calculation of sum of squares due to regression, SSR**

The sum of squares due to regression is calculated by calculating predicted responses for every experimental point in the original design by substitution of the individual model elements into the experimental response surface model (Equation 6.17).

\[
SSR = \Sigma (y_i^{pred})^2 = (XB)^2 = [XB]'[XB] = B'X'XB
\]  

(6.17)

- **Treatment sum of squares**

The contribution of the individual factor to the total sum of squares in the model is determined from the corresponding column vector, \(x_i\), in the design
matrix, $X$, and the estimated model parameter $B_i$, by computing the sum over all experiments (Equation 6.18).

$$TSS = \sum [x_{ij}^2] B_j^2 = x_j' x_j B_j^2$$  \hspace{1cm} (6.18)

- **Residual sum of squares**

  This is obtained by determining the difference between the total sum of squares and the sum of squares due to regression (Equation 6.19).

$$RSS = SST - SSR$$  \hspace{1cm} (6.19)

If this model proves to be acceptable the residual sum of squares should be an indication of experimental error.

- **Mean error square**

  When we calculate the model parameters we use all the observed responses once for each model parameter. This means that for each model parameter estimate, one degree of freedom is consumed. With $n$ experimental observations and $p$ parameters in the model, there are $(n-p)$ degrees of freedom left for the mean error square (Equation 6.20)

$$MSE = SSR/(n-p)$$  \hspace{1cm} (6.20)

These calculations are summarized in the ANOVA tables for the different responses in Tables 6.6 to 6.9.

- **Statistical evaluation – model**

  The efficiency of the fit of the experimentally determined response surface model is determined with the aid of an $F$-test by comparing the SST to the mean SSR. If this calculated $F$-value is higher than that obtained from the $F$-table for the corresponding degrees of freedom, the value in question is significant, or if probability $> F$ is smaller than 0.05 the model is acceptable.
The analysis described above is summarized in Tables 6.6 to 6.9, for the yield of hydroquinone, ratio of hydroquinone: catechol, accountability and current efficiency.

Table 6. 6: ANOVA table for the model describing the yield of hydroquinone.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Probability &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>265.34</td>
<td>5</td>
<td>53.07</td>
<td>8.39</td>
<td>0.0024</td>
</tr>
<tr>
<td>Residual</td>
<td>63.24</td>
<td>10</td>
<td>6.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>328.58</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. 7: ANOVA table for the model describing the ratio of hydroquinone to catechol

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Probability &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1029.22</td>
<td>5</td>
<td>205.84</td>
<td>13.37</td>
<td>0.0004</td>
</tr>
<tr>
<td>Residual</td>
<td>153.99</td>
<td>10</td>
<td>15.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>1183.21</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. 8: ANOVA table for the model describing the accountability

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Probability &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>228.18</td>
<td>6</td>
<td>38.03</td>
<td>13.13</td>
<td>0.0005</td>
</tr>
<tr>
<td>Residual</td>
<td>26.07</td>
<td>9</td>
<td>2.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>254.25</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6. 9: ANOVA table for the model describing the current efficiency

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Probability &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>126.84</td>
<td>7</td>
<td>18.12</td>
<td>7.55</td>
<td>0.0053</td>
</tr>
<tr>
<td>Residual</td>
<td>19.20</td>
<td>8</td>
<td>2.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>146.04</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the ANOVA tables it can be seen that the models selected with the aid of the normal probability plots are significant and acceptable and that these
models are correct, since the probability > F values are much lower than 0.05 in all the cases investigated.

6.5.1.3 Analysis of fitted response

Electrochemical hydroxylation of phenol to hydroquinone was evaluated using a response surface model. Response surface diagrams were used in order to determine the optimum conditions for the reactions; the optimum conditions are shown in Table 6.10 and the diagrams used to determine them are shown in Figures 6.13 to 6.16 and Table 6.10. The values are given in coded format and the cells in which no values are given do not affect the reaction.
Table 6.10: Factors, which proved to be significant for the different responses

<table>
<thead>
<tr>
<th>Variable</th>
<th>Yield Hydroquinone %</th>
<th>Ratio Hydroquinone / Catechol</th>
<th>Accountability</th>
<th>Current efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Phenol loading</td>
<td>*</td>
<td>*</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Acid concentration</td>
<td>*</td>
<td>-1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acid volume</td>
<td>*</td>
<td>1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acetonitrile volume</td>
<td>-1</td>
<td>*</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Current</td>
<td>1</td>
<td>*</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Predicted response</td>
<td>60.73</td>
<td>40.38</td>
<td>93.33</td>
<td>41.23</td>
</tr>
</tbody>
</table>

Figure 6.13: Response surface diagram (yield hydroquinone)
Figure 6.14: Response surface diagram (ratio hydroquinone: catechol)

Figure 6.15: Response surface diagram (accountability)
6.6 Discussion and Conclusion

The significant effects were determined with the aid of normal probability plots of effects and these plots give a straight line. All the effects, which are situated on the straight line, are normally distributed and do not effect the reaction; the effects that are not situated on the line are not normally distributed and thus they are significant. These significant factors were determined and are shown as the highlighted points in Figures 6.1 to 6.4.

The significant effects determined above were then subjected to further tests to verify their importance. These tests include normal probability plots of the residuals, the plots of the residuals versus predicted responses and an ANOVA investigation:

- Normal probability plots of the residuals: If the model determined from the significant effects is an accurate representation of the response, this plot will give a straight line. The plots for the various responses are
shown in Figures 6.5 to 6.8, and it can be seen that they all yield a straight line so it can be said that the model is acceptable.

- Plots of the residuals versus predicted responses: For the model to be accepted these plots should show a normal scatter along the x-axis; this is indicated by the points being evenly distributed on either side of the line. This was shown to be the case in Figures 6.9 to 6.12.

- ANOVA investigation: The efficiency of the fit of the experimentally determined response surface model is determined with the aid of an F-test as shown and explained in Section 6.5.2. For the model to be accepted and proved to be significant the probability > F should be smaller than 0.05. From the Tables 6.6 to 6.9 it could be seen that all the F values were lower than 0.05. This indicates that the models are acceptable.

All these statistical investigations proved that the models were valid.

From the models (Equations 6.11 to 6.14) it can be seen that various factors affect the responses in different ways. Concentrating on the most primary response, the hydroquinone yield, it can be seen that it is only affected by temperature, solvent volume and current density, and of these factors current proved to be the most significant of the single factor interactions.

- Current density: It can be seen that increasing the current from 1600 A. m\(^{-2}\) to 2400 A. m\(^{-2}\) has the effect of increasing the yield by 3.54 %. This is not surprising since a higher current density will allow for more oxidation and reduction to take place and therefore increase the production of hydroquinone.

- Phenol loading: increasing the phenol loading from 0.5 g to 1.0 g has the effect of increasing the yield by 1.38 %. The low percentage increase in the yield upon doubling the phenol concentration is due to the re-oxidation of the target compound, the hydroquinone, to the benzoquinone at the anode. As seen from the oxidation potentials in Table 5.1, hydroquinone is readily oxidised. A higher concentration of
phenol will produce a higher concentration of hydroquinone, which will be re-oxidised to a greater extent at the anode, causing a drop in current efficiency. A divided cell, where cathode and anode are separated, will prevent the re-oxidation of the hydroquinone.

- Solvent volume: A decrease in the solvent volume from 24 cm$^3$ to 18 cm$^3$ has the effect of increasing the yield by 2.04 %. This is due to an increase in the substrate concentration.

Considering the above, the optimum conditions were determined with the aid of three-dimensional surface plots. These indicated that the optimum conditions were as shown in Table 6.10.

In summary the maximum yield of hydroquinone (most important response) attainable within the experimental domain will be 60.73 %, using 1 g of phenol, 18 cm$^3$ of acetonitrile and 1200 mA of current. This was confirmed by experiments.

### 6.7 Conclusive remarks

The results obtained from the statistical analysis were shown to be acceptable using a variety of techniques, ranging from normal probability plots to ANOVA tables. The models calculated for the various responses, indicated that all the factors investigated had some or other effect on at least one of the responses. So it was concluded from the “scanning” design that a variety of factors can be eliminated if the order of importance of the response can be determined.
CHAPTER 7

SUMMARY AND CONCLUDING REMARKS

7.1 General observations

The electrochemical hydroxylation of aromatic substrates was investigated in some detail during the course of this investigation. The main objective of the study was to produce 1,4-dihydroxybenzene, with respect to the following issues:

- Increase the selectivity and yield of the hydroxylation to the dihydroxybenzenes, preferably the 1,4-dihydroxybenzene isomer.
- Increasing the rate of hydroxylation without affecting the reaction selectivity.

The main findings of the work are summarized in the following sections.

7.2 Screening of hydroxylation systems

Two main hydroxylation systems were investigated, acetoxylation and direct electrochemical hydroxylation. These systems showed the most promise for the hydroxylation of aromatic substrates.

- Acyloxylation: In this system the use of two different nucleophiles were investigated: acetoxylation where the nucleophile was an acetate anion and trifluoro-acetoxylation where the nucleophile was the trifluoroacetate anion. The aromatic acetates so formed would then be hydrolysed to the corresponding dihydroxybenzenes. The substrates investigated were phenol and phenyl acetate.
  - Acetoxylation: The results indicated that the acetoxylation of phenol did not yield any acetoxylated products, but instead undergoes dimerization reactions. Phenyl acetate showed some acetoxylation, but it did not occur to a large extent, since the investigation yielded
low values for current efficiencies, product yields and accountabilities.

- Trifluoro-acetoxylation: The results indicated that phenol and phenyl acetate underwent trifluoro-acetoxylation, with better current efficiencies, product yields and accountabilities than above but still not in large enough yields.
- Direct electrochemical hydroxylation: The substrates investigated were phenol, 2-tert-butylphenol and 2,6-di-tert-butylphenol. The results showed that the process yielded superior results to those observed for acyloxylation.

Considering the current efficiencies, yields, accountabilities and costs of reagents for these reactions, a decision was then made to continue the investigation on direct electrochemical hydroxylation.

### 7.3 Direct electrochemical hydroxylation

During this investigation phenol, 2-tert-butylphenol and 2,6-di-tert-butylphenol were investigated. The results indicated that lead dioxide was the best anodic material and nickel was the best cathodic material.

Product distribution diagrams were performed on these substrates and it was found that the degree of activation of the ring increased with the addition of the tertiary butylated groups. Important information came to light, when considering the results as a function of increasing substitution of the phenol.

- The rate of reaction increased: this was seen from the disappearance of the phenolic substrates.
- The yield of the corresponding hydroquinones and benzoquinones increased.
- The accountabilities increased.
- The amount of other isomers, mainly the 1,2-dihydroxybenzene decreased significantly.
From these results it was seen that the direct electrochemical hydroxylation of 2,6-di-\textit{tert}-butylphenol yielded the best overall results.

### 7.4 Multi-factorial evaluation of the direct electrochemical phenol hydroxylation of phenol

From the fractional factorial design it was found that of the factors investigated temperature, acetonitrile volume and current density proved to be the significant effects, for the most important response selected, which was the hydroquinone yield.

### 7.5 Conclusive remarks and further work

The results of the present study have clearly shown that it is possible to hydroxylate aromatic compounds electrochemically. Of the technologies investigated it was found that the direct electrochemical hydroxylation proved to be the most efficient of the technologies investigated. There are, however, a number of issues, which need to be addressed before the commercial viability of the present oxidation system can be fully evaluated. These include:

- Broader investigation of the electrode materials, especially the structure of the lead dioxide electrode surface.
- Investigation of the final reactor setup (batch or continuous and divided or undivided), which could yield better results.
- Performing a mass balance on the hydroxylation reaction mixtures, including identification and quantification of all by-products.
- Broader investigation into possible co-solvents and their effects.

Having determined that hydroxylation occurs with better yields and efficiency with increasing substitution of tertiary butyl groups, the question arises, whether to use phenol and hydroxylate it to hydroquinone or to butylate phenol to either the mono- or di-substituted phenol followed by hydroxylation and de-butylation.
From this investigation it cannot be decided which route to follow. It is thus recommended that the hydroxylation of all three substrates be thoroughly investigated and optimised using full second order models, in order to determine which of the processes are the most promising.

As can be seen from the investigation, a variety of phenolic compounds can be hydroxylated. It could then be interesting to investigate the possibility of hydroxylating other phenolic compounds, which would be important for the chemical industry in South Africa.
References


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ADDENUM