DESIGN OF A PLANT TO PRODUCE 1000 TONNES PER DAY OF CAUSTIC SODA USING ELECTROLYTIC DIAPHRAGM CELL.

BY

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A Project Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of Bachelor of Engineering (B. Eng) in Chemical Engineering Department.

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OCTOBER, 2006.

DECLARATION

I hereby declare that this work was done by me under the supervision of Prof. K.R. Onifade of the department of chemical engineering, Federal University of Technology, Minna, Niger state.

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CERTIFCATION

This is to certify that I have thoroughly read and approved this project work, which I found adequate, both in scope and quality for the partial fulfillment of the requirement for the award of Bachelor of Engineering (B.Eng.) in Chemical Engineering.

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DR. M.O EDOGA **DATE**

Head of Department

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EXTERNAL EXAMINER **DATE**

DEDICATION

This work is dedicated to my beloved parents, **ARC. A.Y. ALFA** and **HAJIYA RAKIYA BA'ABA ALFA** for their parental support.

AKNOWLEDGEMENT

Glory is due to Allah, the Mighty Lord of Heaven and Earth who has guided and protected me in completing this work successfully.

Profound appreciation is expressed to my humble supervisor **Prof. K.R. Onifade** who despite the work loads on him showed enough understanding and made valuable contributions to the success of this work.

Enormous appreciation is shown to my departmental lecturers especially the Dean of Engineering **Prof. Odigure**, my **H.O.D, Dr. Edoga, Engr.Abdulwahab Giwa** and all other staff of Chemical Engineering Department.

My sincere gratitude goes to my parents, **Arc. A.Y. Alfa and Hajiya Rakiya Alfa** who were never tired of imparting in invigorating word to me at any instance. My siblings **Ndatsu, Bala, Nana, Nna, Habiba** and **Fatima**; I care for you all.

I also appreciate the concern shown by my fiancé **Ahmed Alfa** and his entire family. This appreciation is extended to **Engr. Hassan Akande** of Innovative Technology, Kaduna for all his effort.

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Many people have directly or indirectly played an important role in this undertaken. They are mentioned here so that blames can be laid in the right quarter. They are **Mrs. Amina Asabe Alfa, Mrs. Habib, Uncle Mohammed Alfa, YamaKanta, Isah Danladi, Jumai Adams, Rukkayah, Josephine** and all my colleagues in general. I thank you all.

EXECUTIVE SUMMARY

The aim of this project was to design a plant to produce 1000tons/day of caustic soda using locally available raw material. The local raw material used for the production of the caustic soda was brine which is available in Lagos in abundant quantity. The brine was subjected to electrolysis using electrolytic cell. Other units of equipment involved in the plant include: saturator, precipitator, filter and cooler. The diameter and height of the electrolytic cell used of this plant were found to be 4.78 and 5.975m respectively. For the production of 1000 tons per day of caustic soda, 101606.00kg/day of sodium chloride (NaCl) is required to be passed to the saturator as the fresh input. The economic analysis of the plant showed that the fixed capital investment of the plant is ₦581514365.70. The pay back period of the plant which was calculated to be 3.177 years showed that the plant is economically viable.

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Nomenclature

Symbol Meaning

M_S = Marshall and Smith Index

Fm = Factor associated with material

Fp = Factor associated with pressure

PC = Purchased equipment cost

er = Exchange Rate

Fc = Factor of cost

CHAPTER ONE

1.0 INTRODUCTION

1.1 General Introduction

Caustic soda is most commonly manufactured by the electrolysis of sodium chloride brine in either a mercury amalgam, membrane or diaphragm electrolytic cell. The coproducts are chlorine and hydrogen. The largest users of caustic soda are the pulp and paper, detergent and chemical industries. Caustic soda is also used in the alumina, oil and gas and textile industries, mostly for its alkalinity value (OxyChem, 2000).

OxyChem plants are strategically located to conveniently and economically serve industry. Warehouse stocks of our caustic soda and other products are maintained in many principal cities. Distributor stocks are also available in these and many other cities and form a network of supply for the end user's convenience (OxyChem, 2000).

Sodium hydroxide is a white crystalline substance that readily absorbs carbon dioxide and moisture from the air. It is very soluble in water, alcohol and glycerine, and is caustic. Commonly known as caustic soda, lye, or sodium hydrate, it is available commercially in various solid forms, e.g., pellets, sticks, or chips, and in water solutions of various concentrations; both solid and liquid forms vary in purity (www.oxy.com/oxychem/Products/caustic_soda/caustic_soda.htm).

1.2 Aim and objectives of the study

The aim of this project is to design a plant for the production of caustic soda using local available raw material using electrolytic diaphragm cell. This aim will be achieved via the realization of the following objectives:

(1) Preparation of a flow diagram of the plant.

(2) Calculation of the material balances of the components across the individual units.

(3) Calculation of the energy balances of the components across the individual units.

(4) Carry out the detail design of all the units of the plant.

(5) Preparation of the cost estimation of the plant using Marshall and Smith Method.

(6) Others

1.3 Problem Statement

The problem statement of this design project is: "Design of a Plant for the Production of 1000 ton/day of Caustic Soda From Local Raw Material Using Electrolytic Diaphragm Cell".

1.3.1 Service available

Cooling water at 100 lb/in^2 at a maximum temperature of 35°C.

1.3.2 Product specification

The purity of caustic soda should not be less than 99%.

1.3.3 Other requirements

All the equipment must be designed.

1.3.4 Bonus marks

Extra marks will be given for use of a computer aided design (CAD) module in

(a) Preparing flow diagram/flow sheet;

(b) The design of the equipment.

1.3.5 Note on submission of reports

In addition to the hard copies, electronic copy of the report must be submitted in a diskette. Non-compliance with this requirement will attract zero mark assessment for the report.

1.4 Scope of Work

This work is limited to the chemical engineering design of the plant for the production of caustic soda.

1.5 Design Data

The process data required in this design project were sourced from literatures (past projects and textbooks) and internet. In a situation where particular pieces of information are not available, reasonable assumptions will be made.

1.6 Methodology of the Design

Following the problem statement outlined above, this work will be made computer-aided by drawing the flow diagram with the aid of Microsoft Visio, the material balances using spreadsheet (Microsoft Excel). Further, the energy balances, equipment design, equipment optimization and economic analysis will be carried using MathCAD 2000 Professional. Finally, the quantitative flow sheet will be carried out using the combination of Microsoft Excel and Microsoft Visio.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Caustic soda

Caustic soda is a white crystalline substance that readily absorbs carbon dioxide and moisture from the air. It is very soluble in water, alcohol, and glycerine. It is a caustic and a strong base (see acids and bases). Commonly known as caustic soda, lye, or sodium hydrate, it is available commercially in various solid forms, e.g., pellets, sticks, or chips, and in water solutions of various concentrations; both solid and liquid forms vary in purity. The major use of sodium hydroxide is as a chemical and in the manufacture of other chemicals; because it is inexpensive, it is widely used wherever a strong base is needed. It is also used in producing rayon and other textiles, in making paper, in etching aluminium, in making soaps and detergents, and in a wide variety of other uses. The principal method for its manufacture is electrolytic dissociation of sodium chloride; chlorine gas is a coproduct. Small amounts of sodium hydroxide are produced by the soda-lime process in which a concentrated solution of sodium carbonate (soda) is reacted with calcium hydroxide (slaked lime); calcium carbonate precipitates, leaving a sodium hydroxide solution (www.bartleby.com/65/so/sodmhydx.html).

2.1.1 Properties of caustic soda

2.1.1.1 General properties

Pure sodium hydroxide is a white solid, available in pellets, flakes, granules, and also 50% saturated solution. It is very deliquescent and also readily absorbs carbon dioxide from the air, so it should be stored in an airtight container. It is very soluble in water with liberation of heat. It also dissolves in ethanol and methanol, though it exhibits lower solubility in these solvents than does potassium hydroxide. It is insoluble in ether and other non-polar solvents. A sodium hydroxide solution will leave a yellow stain on fabric and paper.

2.1.1.2 Physical properties

General	
Systematic name	Sodium hydroxide
Other names	Lye, Caustic Soda
Molecular formula	$NaOH$
Molar mass	40.0 g/mol
Appearance	White flakes
CAS number	[1310-73-2]
Properties	
Density and phase	2.1 g/cm^3, solid
Solubility in water	111 g/100 ml (20°C)
Melting point	323°C (596 K)
Boiling point	1390°C (1663 K)
Basicity (pKb)	0.2
Hazards	
MSDS	External MSDS
EU classification	Corrosive (C)
R-phrases	R35
S-phrases	S1/2, S26, S37/39, S45
Flash point	Non-flammable.
Other anions	Sodium chloride Sodium sulfate.
Other cations	Potassium hydroxide Calcium hydroxide
Related bases	Ammonia, lime.
Related compounds	Chlorine

Source: (en.wikipedia.org/wiki/Sodium_hydroxide)

2.1.1.3 Chemical properties

Sodium hydroxide is completely ionic, containing sodium ions and hydroxide ions. The hydroxide ion makes sodium hydroxide a strong base which reacts with acids to form water and the corresponding salts, e.g., with hydrochloric acid, sodium chloride is formed:

$$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(l)$$

In general such neutralization reactions are represented by one simple net ionic equation:

$$OH^-(aq) + H^+(aq) \rightarrow H_2O$$

This type of reaction releases heat when a strong acid is used. Such acid-base reactions can also be used for titrations, and indeed this is a common way for measuring the concentration of acids. Related to this is the reaction of sodium hydroxide with acidic oxides. The reaction of carbon dioxide has already been mentioned, but other acidic oxides such as sulfur dioxide (SO_2) also react completely. Such reactions are often used to "scrub" harmful acidic gases (like SO_2 and H_2S) and prevent their release into the atmosphere.

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

Sodium hydroxide slowly reacts with glass to form sodium silicate, so glass joints and stopcocks exposed to NaOH have a tendency to "freeze". Flasks and glass-lined chemical reactors are damaged by long exposure to hot sodium hydroxide, and the glass becomes frosted. Sodium hydroxide does not attack iron or copper, but many other metals such as aluminium, zinc and titanium are attacked rapidly. In 1986 an aluminium road tanker in the UK was mistakenly used to transport 25% sodium hydroxide solution, causing pressurisation of the contents and damage to the tanker. For this same reason aluminium pans should never be cleaned with lye.

$$2Al(s) + 6NaOH(aq) \rightarrow 3H_2(g) + 2Na_3AlO_3(aq)$$

Many non-metals also react with sodium hydroxide, giving salts. For example phosphorus forms sodium hypophosphite, while silicon gives sodium silicate.

Unlike NaOH, the hydroxides of most metals are insoluble, and therefore sodium hydroxide can be used to precipitate metal hydroxides. One such hydroxide is aluminium hydroxide, used as a gelatinous floc to filter out particulate matter in water treatment. Aluminium hydroxide is prepared at the treatment plant from aluminium sulfate by reaction with NaOH:

$$6NaOH(aq) + Al_2(SO_4)_3(aq) \rightarrow 2Al(OH)_3(s) + 3Na_2SO_4(aq)$$

Sodium hydroxide reacts readily with carboxylic acids to form their salts, and it is even a strong enough base to form salts with phenols. NaOH can also be used for the base-driven hydrolysis of esters (as is saponification), amides and alkyl halides. However, the limited solubility of NaOH in organic solvents means that the more soluble KOH is often preferred (en.wikipedia.org/wiki/Sodium_hydroxide).

2.1.2 Uses of Caustic Soda

Caustic soda is used in a wide variety of industrial applications. It is used as a reactant in the manufacture of other sodium compounds which themselves may be intermediate or end-use products, such as sodium hypochlorite which is used as household bleach and disinfectant and sodium phenolate which is used in antiseptics and for the manufacture of Aspirin. It is used in the manufacturing process of soaps and surfactants for used in soap powders and also in the textile industry to remove contaminants, as bleach in the treatment of scoured cloth and to improve luster and dye absorption (www.chemistrystore.com/Caustic_Soda.htm).

Soap is a mixture of chemical compounds formed by the hydrolysis of animal and vegetable oils and fats by the action of caustic soda. Soap powders consist of a mixture of soap and other ingredients which themselves may be sodium chemicals.

The use of caustic soda is mainly confined to finishing operations in the textile industry, i.e.

Scouring: Removes contaminants such as pectins, waxes etc.

Bleaching: Treatment of scoured cloth with an oxidizing agent.

Mercerizing: Improves luster and dye absorption.

Oil Drilling: Caustic soda is used in the oil drilling industry primarily to control the pH of drilling muds and secondary as a bactericide and calcium remover.

Petroleum Oil Refining: Products from the refining operation contain impurities which are removed by treatment with various chemicals including caustic soda, which removes sulphur, sulphur compounds and acidic compounds.

Caustic soda is used in the process of producing Rayon from bleached wood pulp where its role is to dissolve the lignin which binds the cellulose together.

The principal constituent of paper is cellulose fiber and the major source is wood. Caustic soda is involved in chemical treatment of wood to produce cellulose by the sulphate and soda processes.

Caustic soda has a variety of uses in the Food Industry, some examples are:

Refining of animal and vegetable oils to remove fatty acids prior to use in foodstuff production

Dry formulations for bottle washing etc.

General cleansing operations

Cleaning of brewery equipment

Lye peeling of potatoes, fruit and vegetables

Caustic soda is used extensively in the water industry for pH control and ion exchange resin regeneration. Other uses include effluent neutralization and descaling of pipe work systems.

In summary, caustic soda is one of the very few chemicals finding a very broad range of applications. Some principal products or processes in which caustic soda is used are:

- Acid Neutralization
- Agricultural Chemicals
- Aluminium Industry
- Boiler Compounds
- Cellulose Film
- Chemicals:
- Ammonia
- Amyl Amines
- Cresol
- Ethylene Amines
- Formic Acid
- Glycerine

- Maleic Anhydride
- Pentaerythritol
- Phenol
- Propylene Oxide
- Polycarbonates
- Salicylic Acid
- Sodium Aluminate
- Sodium Hydrosulfide
- Sodium Hypochlorite
- Sodium Phosphates
- Styrene
- Vinyl Chloride Monomer
- Detergents
- Drain Cleaners
- Drilling Muds
- Dyestuffs
- Food Processing
- Fruit & Vegetable Peeling
- Glass-Batch Wetting
- Ion-Exchange Resin
- Regeneration
- Ore Flotation and Processing
- Paint Removers
- Petroleum Refining
- pH Adjustment
- Pharmaceuticals

- Pigments
- Pulp & Paper
- Rayon
- Soap
- Surfactants
- Textile Bleaching, Dyeing, and
- Mercerizing
- Vegetable Oil Processing
- Water Treatment

2.1.3 Forms of caustic soda

Liquid caustic soda is available as a 50% solution in four grades; diaphragm, rayon, membrane and purified diaphragm. To be technically correct, only molten caustic soda should be called liquid, but since the term liquid caustic soda has historically been used to describe solutions of caustic soda, it is used in this document interchangeably with the term solution. Anhydrous caustic soda is marketed in four forms; beads, flakes, compound and solid castings. These forms have the same chemical composition and differ only in particle size and shape.

2.2 Salt

In chemistry, a salt is any ionic compound composed of cations (positively charged ions) and anions (negative ions) so that the product is neutral (without a net charge). These component ions can be inorganic (Cl^-) as well as organic (CH_3COO^-) and monoatomic (F^-) as well as polyatomic ions (SO_4^{2-}); they are formed when acids and bases react.

There are several varieties of salts: Normal salts are those that do not contain a hydroxide ion (OH^-) or a hydrogen ion (H^+). Salts that contain a hydroxide ion are basic salts and salts that contain a hydrogen ion are acid salts. An impure salt is a name for salts which have lost their saltiness, and can also refer to natrons. Zwitterions are salts that contain an anionic center and a cationic center in the same molecule; examples include amino acids, many metabolites, peptides and proteins.

When salts are dissolved in water, they are called electrolytes, and are able to conduct electricity, a property that is shared with molten salts. Mixtures of many different ions in solution—like in the cytoplasm of cells, in blood, urine, plant saps and mineral waters—usually do not form defined salts after evaporation of the water. Therefore, their salt content is given for the respective ions.

Salts can be dehydrating to the human body if consumed in excess.

2.2.1 History

The first registers of salt use were produced around 4000 B.C. (roughly) in Egypt, Greece and Rome. Salt was very valuable and used to preserve foods. In Ancient Rome, salt started to be used as money originating the current Latin-derivative term salary. Payments to Roman workers were made in salt. Salt was also given to the parents of the groom in marriage until the 8th century.

The Phoenicians were the first people to harvest salt from the sea. They sold it to other civilizations and most of the time it cost more than gold [citation needed]. The Phoenicians were victims of their success and as a result of harvesting the salt from the sea, the value of salt depreciated. The Phoenicians harvested the salt by flooding plains of land with seawater, then leaving the plains to dry. After the water dried, the salt which was left was collected and sold.

2.2.2 Appearance

Consistency

Salts are usually solid crystals with a relatively high melting point. However, there exist salts that are liquid at room temperature, so-called ionic liquids. Inorganic salts usually have a low hardness and a low compressibility, similar to edible salt.

Color

Salts can be clear and transparent (sodium chloride), opaque (titanium dioxide), and even metallic and lustrous (iron disulfide).

Salts exist in all different colors, e.g. yellow (sodium chromate), orange (potassium dichromate), red (mercury sulfide), mauve (cobalt chloride hexahydrate), blue (copper sulfate pentahydrate, ferric hexacyanoferrate), green (nickel oxide), colorless (magnesium sulfate), white (titanium dioxide), and black (manganese dioxide). Most minerals and inorganic pigments as well as many synthetic organic dyes are salts.

Taste

Different salts can elicit all five basic tastes, e.g. salty (sodium chloride), sweet (lead diacetate), sour (potassium bitartrate), bitter (magnesium sulfate), and umami or savory (monosodium glutamate) (http://en.wikipedia.org/wiki/Salt).

Odor

Pure salts are non-volatile and odorless, while impure salts may smell after the conjugate acid (e.g. acetates like acetic acid (vinegar) and cyanides like hydrogen cyanide (almonds)) or the conjugate base (e.g. ammonium salts like ammonia) of the component ions (http://en.wikipedia.org/wiki/Salt).

2.2.3 Physical properties of salt

Property	Value
Molecular weight - NaCl	58.4428
Atomic weight - Na	22.989768 (39.337%)
Atomic weight - Cl	35.4527 (60.663%)
Eutectic composition	23.31% NaCl
Freezing point of eutectic mixture	-21.12° C (-6.016°F)
Crystal form	isometric, cubic
Color	clear to white
Index of refraction	1.5442
Density or specific gravity	2.165 kg/m3 (135 lb/ft3)
Bulk density, approximate (dry, ASTM D 632 gradation)	1.154 kg/m3 (72 lb/ft3)
Angle of repose (dry, ASTM D 632 gradation)	32°
Melting point	800.8° C (1,473.4° F)
Boiling point	1,465°C (2,669° F)
Hardness (Moh's Scale)	2.5
Critical humidity at 20 °C, (68° F)	0.753
pH of aqueous solution	neutral

Source: www.saltinstitute.org/15.html

2.3 Chlor-Alkali Industry

The chlor-alkali industry is the industry that produces chlorine (Cl_2) and alkali, sodium hydroxide (NaOH) or potassium hydroxide (KOH), by electrolysis of a salt solution. The main technologies applied for chlor-alkali production are mercury, diaphragm and membrane cell electrolysis, mainly using sodium chloride (NaCl) as feed or to a lesser extent using potassium chloride (KCl) for the production of potassium hydroxide (IPPC, 2001).

The diaphragm cell process (Griesheim cell, 1885) and the mercury cell process (Castner-Kellner cell, 1892) were both introduced in the late 1800s. The membrane cell process was developed much more recently (1970). Each of these processes represents a different method of keeping the chlorine produced at the anode separate from the caustic soda and hydrogen produced, directly or indirectly, at the cathode. Currently, 95% of world chlorine production is
obtained by the chlor-alkali process.

2.3.1 Industrial and economical development of the chlor-alkali sector

In 1800, Cruickshank was the first to prepare chlorine electrochemically. The process was, however, of little significance until the development of a suitable generator and of synthetic graphite for anodes in 1892. These two developments made possible the electrolytic production of chlorine, the chlor-alkali process, on an industrial scale. About the same time, both the diaphragm cell process (Griesheim cell, 1885) and the mercury cell process (Castner-Kellner cell, 1892) were introduced. The membrane cell process was developed much more recently
(1970). Currently, 95% of world chlorine production is obtained by the chlor-alkali process (Ullmann's 1996).

Since 1970 graphite anodes have been largely superseded by activated titanium anodes in the diaphragm and mercury cell processes. The newer membrane cell process uses only activated titanium anodes. [Ullmann's, 1996]
Production of chlorine was very low in the 1800s and chlorine was only used for bleaching. In 1887, annual world production was 115 tonnes [Le Chlore, 1996]. Chlorine production since the 1940s has risen enormously, on the back of the burgeoning demand for plastics, notably PVC [J. Ind. Ecology, 1997] and polyurethanes. The production of chloroaromatics (e.g. chlorobenzene for phenol synthesis), propylene oxide (chlorohydrin process), solvents containing chlorinated hydrocarbons, and inorganic chlorine compounds are also important factors behind the increased use of chlorine after 1940.

After a fall at the beginning of the 1990s, production in western Europe now seems to be stabilised at around 9 millions tonnes per year (9.2 million tonnes in 1999). This placed it behind the United States, with production of 11.2 million tonnes in 1994, but ahead of Japan, with 4.2 million tonnes production capacity in 1995. The world-wide chlorine production was 38 million tonnes in 1994. The global demand for both chlorine and caustic has been forecast to increase, although mainly in Latin America and Asia.

2.4 Technologies for the production of caustic soda

The main technologies applied for chlor-alkali production are mercury, diaphragm and membrane cell electrolysis, mainly using sodium chloride as feed or to a lesser extent using potassium chloride for the production of potassium hydroxide. Other electrochemical processes in which chlorine is produces include the electrolysis of hydrochloric acid and the electrolysis of molten alkali-metal and alkaline-earth-metal chlorides, in which the chlorine is a by-product, but these account for less than 3% of the total chlorine production capacity.

Where caustic soda production is concerned, an alternative route to the electrolysis of sodium chloride is the lime-soda process. Today, this process is not considered as a profitable operation in some places compared with the electrolysis of sodium chloride except in the area where mineral deposits of natural carbonate exist.

2.4.1 Description of the various processing technologies

The chlor-alkali industry produces chlorine and caustic solution (sodium or potassium hydroxide) simultaneously by means of decomposition of a solution of salt in water. Along with the chlorine and the caustic solution, hydrogen is produced. An industrial chlor-alkali production unit comprises a series of operations, structured as shown in Figure 2.1.

In the chlor-alkali electrolysis process, a chloride-salt solution is decomposed electrolytically by direct current. Most of the time sodium chloride is used in the process and less frequently potassium chloride (about 3-4% of the chlorine production capacity). Other processes such as the electrolysis of hydrochloric acid or the electrolysis of molten sodium chloride are applied, but these only account for about 3% of total chlorine production capacity in Europe.

There are three basic processes for the electrolytic production of chlorine, the nature of the cathode reaction depending on the specific process. These three processes are the diaphragm cell process (Griesheim cell, 1885), the mercury cell process (Castner–Kellner cell, 1892), and the membrane cell process (1970). Each process represents a different method of keeping the chlorine produced at the anode separate from the caustic soda and hydrogen produced, directly or indirectly, at the cathode [Ullmann's, 1996].

Caustic soda is produced commercially by an electrolytic process as shown in the flow diagram below. Brine, prepared from sodium chloride, is electrolyzed in either a mercury cell, diaphragm cell or membrane cell. The coproducts are chlorine and hydrogen (OxyChem, 2000).

In the mercury cell process, a sodium-mercury amalgam is formed in the cell. The amalgam is sent to a decomposer where it is reacted with water to form liquid NaOH, hydrogen and free mercury. The free mercury is returned to the electrolytic cell. The resulting caustic soda solution is then inventoried in storage tanks at a 50% solution. The solution is shipped in tank trucks, tank cars or barges (OxyChem, 2000).

In the membrane process, a solution of approximately 30% in strength is formed. The solution is then sent to evaporators, which concentrate it to a strength of 50% by removing the appropriate amount of water. The resulting caustic soda solution is inventoried in storage tanks prior to shipment (OxyChem, 2000).

The diaphragm process is very similar to the membrane process except that a solution of only 10-12% is formed in the cell. Therefore, additional evaporation is required to reach the saleable concentration of 50% (OxyChem, 2000).

The anhydrous forms of caustic soda are obtained through further concentration of 50% caustic soda. Solid caustic soda results when molten caustic soda, from which all the water has been evaporated, is allowed to cool and solidify. Flake caustic soda is made by passing molten caustic soda over cooled flaking rolls to form flakes of uniform thickness. The flakes can be milled and screened into several crystalline products with controlled particle size. The manufacture of caustic soda beads involves feeding molten liquor into a prilling tower under carefully controlled operating conditions, producing a spherical bead (IPPC, 2001).

The basic principle in the electrolysis of a sodium chloride solution is the following:

- At the anode, chloride ions are oxidised and chlorine (Cl_2) is formed.
- At the cathode: In the mercury process a sodium/mercury amalgam is formed and hydrogen (H_2) and hydroxide ions (OH^-) are formed by the reaction of the sodium in the amalgam with water in the denuder. In membrane and diaphragm cells, water

decomposes to form hydrogen (H_2) and hydroxide ions (OH^-) at the cathode (IPPC, 2001).

For all processes the dissolving of salt, sodium chloride, is:

$NaCl \rightarrow Na^+ + Cl^-$

The **anode** reaction for all processes is:

$2Cl^-_{(aq)} \rightarrow Cl_{2(g)} + 2\ e^-$

The **cathode** reaction is:

$2\ Na^+(aq) + 2H_2O + 2e^- \rightarrow H_{2(g)} + 2Na^+_{(aq)} + 2OH^-_{(aq)}$

The **overall** reaction is:

$2Na^+_{(aq)} + 2Cl^-_{(aq)} + 2H_2O \rightarrow 2Na^+_{(aq)} + 2OH^-_{(aq)} + Cl_{2(g)} + H_{2(g)}$

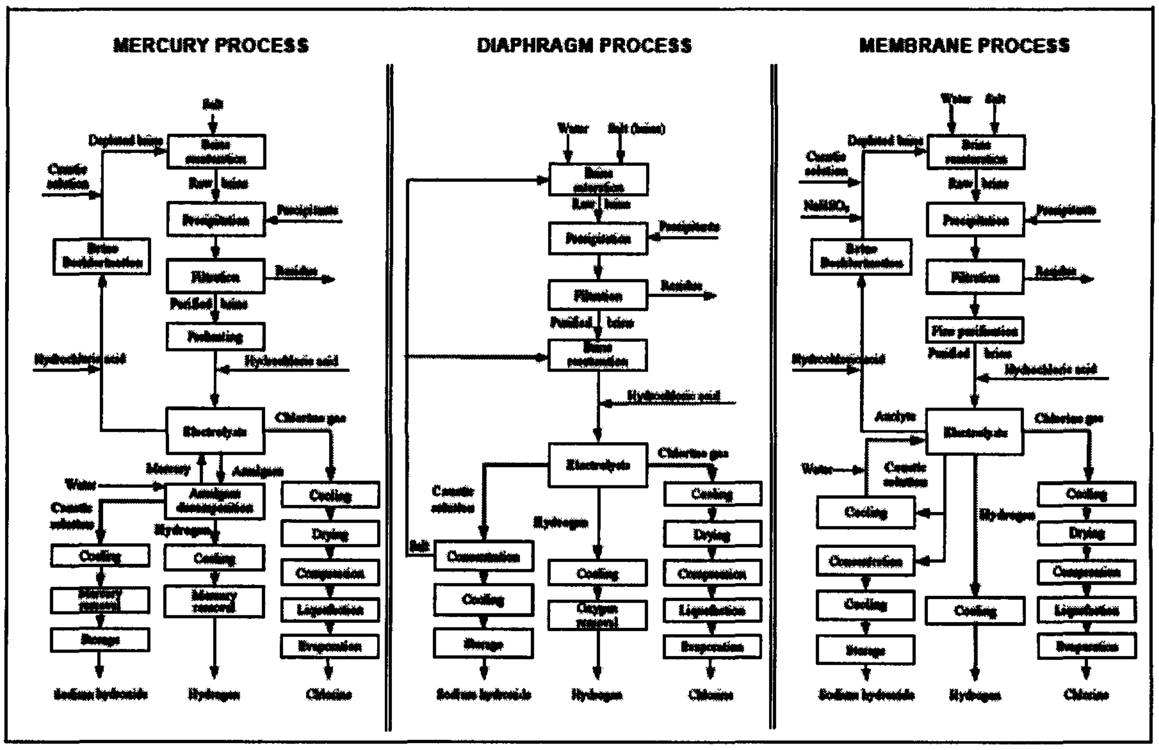


Figure 2.1: Flow diagram of the three main chlor-alkali processes based on [Kirk-Othmer, 1991], [Ullmann's, 1996]

2.4.2 Detailed description of the diaphragm cell process

The diaphragm process was developed in the 1880s in the USA and was the first commercial process used to produce chlorine and caustic soda from brine. In North America, diaphragm cells are still the primary technology, accounting for roughly 70% of all USA production. The process differs from the mercury cell process in that all reactions take place within one cell and the cell effluent contains both salt and caustic soda. A diaphragm is employed to separate the chlorine liberated at the anode, and the hydrogen and caustic soda produced directly at the cathode. Without the diaphragm to isolate them, the hydrogen and chlorine would spontaneously ignite and the caustic soda and chlorine would react to form sodium hypochlorite ($NaClO$), with further reaction to produce sodium chlorate ($NaClO_3$) [Kirk-Othmer, 1991].

The diaphragm is usually made of asbestos and separates the feed brine (anolyte) from the caustic-containing catholyte. Purified brine enters the anode compartment and percolates through the diaphragm into the cathode chamber. The percolation rate is controlled by maintaining a higher liquid level in the anode compartment to establish a positive and carefully controlled hydrostatic head. The percolation rate is determined as a compromise between a low rate that would produce a desirably high concentration of caustic soda in the catholyte (which provides the cell effluent) and a high rate to limit back-migration of hydroxyl ions from catholyte to anolyte, which decreases cathode current efficiency [Kirk Othmer, 1991].

In the diaphragm cell, saturated brine (about 25% NaCl) is decomposed to approximately 50% of its original concentration in a pass through the electrolyser as compared to a 16% decomposition of salt per pass in mercury cells. Heating caused by passage of current through the diaphragm cell raises the operating temperature of the electrolyte to 80-99 °C.

When graphite anodes were used, the diaphragm became inoperable after 90-100 days due to plugging of the diaphragm by particles of graphite. Nowadays, all plants in the European Union use metal anodes and the lifetime of the diaphragm is over one year. Their service life has also increased because their compositions have changed. At the beginning the diaphragms were made of asbestos only and were rapidly clogged by calcium and magnesium ions coming from the brine. Asbestos was chosen because of its good chemical stability and because it is a relatively inexpensive and abundant material. Beginning in the early1970s, asbestos diaphragms began to be replaced by diaphragms containing 75% asbestos and 25% of fibrous fluorocarbon polymer of high chemical resistance. These diaphragms, trade named Modified Diaphragms, are more stable. The polymer stabilises the asbestos, which in itself lowers cell voltage and also allows for the use of the expandable anode [Le Chlore, 1995][Ullmann's, 1996]. Chrysotile asbestos ("white asbestos") is the only form of asbestos used in diaphragm cells.

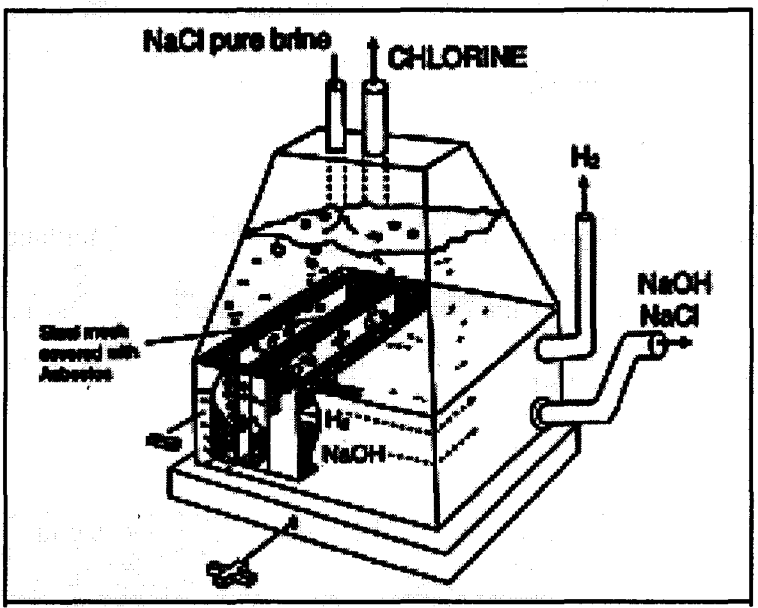


Figure 2.6: Typical diaphragm electrolysis cell (Source: USEPA, 1995)

Both diaphragm and membrane cells for the production of chlorine and sodium hydroxide are classified as either monopolar or bipolar. The designation does not refer to the electrochemical reactions that take place, which of course require two poles or electrodes for all cells, but to the electrolyser construction or assembly. There are many more chlor-alkali production facilities with monopolar cells than with bipolar cells. The monopolar electrolyser is assembled so that the anodes and cathodes are arranged in parallel. As a result of this configuration, all cells have the same voltage of about three to four volts; up to 200 cells can be constructed in one circuit (IPPC, 2001).

Bipolar electrolysers have unit assemblies of the anode of one cell unit directly connected to the cathode of the next cell unit, thus minimising intercell voltage loss. These units are assembled in series (IPPC, 2001).

All diaphragm cells produce cell liquor that contains ca. 11% caustic soda and 18% sodium chloride. This solution is evaporated to 50% NaOH by weight at which point all of the salt, except a residual 1.0-1.5% by weight, precipitates out. The salt generated is very pure and is typically used to make more brine. This high quality sodium chloride is sometimes used as a raw material for an amalgam or membrane process.

Low concentrations of oxygen in chlorine are formed by electrolytic decomposition of water and hypochlorous acid (from the reaction of chlorine with water) (IPPC, 2001).

Precipitation of magnesium and calcium hydroxides on the catholyte side of the diaphragm may also create blocking problems. Hydrochloric acid is often added to the brine to remove CO_2; it may also be added to the brine entering the anode compartment to reduce back-migration of hydroxyl ions and to suppress formation of hypochlorous acid.

2.4.2 Auxiliary processes

Apart from the cells, which remain the heart of the chlorine production line, there are other processing steps or equipment, common to amalgam, diaphragm and membrane technologies.

These are:

- salt unloading and storage
- caustic processing
- hydrogen processing.

2.4.2.1 Salt unloading and storage

The brine used in the mercury cell and membrane processes is normally saturated with solid salt, although some installations use solution-mined brine on a once-through basis (i.e. no brine recirculation).

Brine is generally produced by the dissolving of fresh salt in water or depleted brine from mercury and membrane processes. The basic raw material is usually solid salt: rock salt, solar salt, or vacuum-evaporated salt from purifying and evaporating solution-mined brine. Generally the salt is stored in a sealed area equipped with a roof. Because of its high purity the vacuum salt in particular needs to be protected.

2.4.2.2 Brine purification and Resaturation

2.4.2.2.1 Brine purification

As can be seen in Figure 2.1, the brine purification process consists of a primary system for mercury and diaphragm technologies and an additional secondary system for membrane technology. This operation is needed to avoid any undesirable components (sulphate anions, cations of Ca, Mg, Ba and metals) that can affect the electrolytic process. The quality of the raw material and the brine quality requirements for each of the three technologies determine the complexity of the brine treatment unit.

Primary purification

Precipitation

The initial stage of purification uses sodium carbonate and sodium hydroxide to precipitate calcium and magnesium ions as calcium carbonate ($CaCO_3$) and magnesium hydroxide ($Mg(OH)_2$). Metals (iron, titanium, molybdenum, nickel, chromium, vanadium, tungsten) may also precipitate as hydroxide during this operation. The usual way to avoid metals is to specify their exclusion in the purchase and transport specification for the salt. Sodium sulphate is controlled by adding calcium chloride ($CaCl_2$) or barium salts to remove sulphate anions by precipitation of calcium sulphate ($CaSO_4$) or barium sulphate ($BaSO_4$). Precipitation of barium sulphate can take place simultaneously with the precipitation of calcium carbonate and magnesium hydroxide, whereas the precipitation of calcium sulphate requires a separate vessel.

Filtration

The precipitated impurities are removed by sedimentation, filtration or a combination of both. The separated filter cake is generally concentrated to 50-60% (although a figure of 60-80% is reported in the literature) solids content in rotary drum vacuum filters or centrifuges before disposal. [Ullmann's, 1996]. The purified brine should contain ideally [Ullmann's, 1996]:

Ca: <2 mg/l

Mg: <1 mg/l

SO4: <5 g/l

2.4.2.2.2 Brine resaturation and dechlorination

Mercury and membrane systems usually operate with brine recirculation and resaturation. There are, however, 3 waste brine mercury plants and 1 waste brine membrane plant operating in western Europe. Some diaphragm cell lines have a once-through brine circuit, whilst others employ brine saturation using the salt recovered from the caustic evaporators.

In the case of diaphragm cells, the catholyte liquor (10-12% NaOH, 15% NaCl) goes directly to the caustic evaporators where solid salt and 50% caustic are recovered together. Fresh brine can be saturated with recycled solid salt from the caustic evaporators before entering the diaphragm electrolysers. Resaturators can be either open or closed vessels. The pH of the brine sent to the electrolysers may be adjusted to an acidic value (pH 4) with hydrochloric acid in order to protect the anode coating, to keep the formation of chlorate at a low level and to decrease the oxygen content in the chlorine gas. Hydrochloric acid can also be added in the anodic compartments of membrane cells to further reduce the content of oxygen in the chlorine, especially for electrolysers with older membranes (poorer performances) The (bi)carbonates introduced with the salt are decomposed by these acid additions, producing gaseous carbon dioxide.

2.4.2.4 Caustic production, storage and handling

Sodium hydroxide (caustic soda) is produced in a fixed ratio of 1.128 tonnes (as 100% NaOH) per tonne chlorine produced.

The caustic soda solution from the three technologies is treated in slightly different ways due to the difference in composition and concentration.

In the case of diaphragm and membrane technologies the caustic soda is concentrated by evaporation before final storage.

Steam is used as the source of evaporative energy. The presence of salt in the diaphragm cell liquor requires that the evaporator is equipped with scraper blades or other devices to draw off the precipitated salt. This high quality sodium chloride can then be used to enrich depleted brine, sometimes it is used as a raw material for an amalgam or membrane process. The residual level of sodium chloride in sodium hydroxide from diaphragm cell is about 1% and sodium chlorate 0.1%. For this reason, it is unsuitable for certain end applications such as the manufacture of rayon.

Salt and sodium chlorate in the caustic soda from diaphragm cells can be reduced by ammonia extraction to increase marketability, but at increased cost.

The caustic soda from membrane cells is of high quality, although the caustic soda produced (usually around 33% NaOH) needs concentration to 50% NaOH for some applications. The salt content of the membrane-cell caustic soda lies between 20-100 ppm (in 100% NaOH), but is on average slightly higher than mercury cell caustic.

In some plants the caustic soda is further concentrated to a 73% solution and to 100% as solid caustic prills or flakes.

Some chlor-alkali production facilities can combine the caustic production process from mercury and membrane cells in order to minimise energy costs. It is possible to feed 33% caustic from the membrane cells to the decomposer to produce 50% caustic without the need for evaporation.

Because of its highly reactive and corrosive properties, caustic soda may corrode containers and handling equipment. Construction materials must be suited to the caustic soda handled and stored.

Sodium hydroxide solutions require steam or electrical heating where temperatures can fall below the upper freezing point. Frozen pipelines present both safety and environmental risks when attempts are made to unblock them.

Storage tanks may be lined in order to minimise iron contamination of the product or to avoid stress corrosion cracking the tank. Tanks are usually included in procedures to prevent overflow or spillage of caustic soda. Such procedures include containment and mitigation. It should be noted that dissolved hydrogen gas can be released into the vapour space above the liquid in storage tanks. Tanks are normally vented from the highest point. Testing for an explosive mixture of hydrogen in air normally precedes any maintenance activity in the area (IPPC, 2001).

2.4.3 Justification of the selected technology

Diaphragm cells have the advantage of:

- operating at a lower voltage than mercury cells
- operating with less pure brine than required by membrane cells

When using asbestos diaphragms, the diaphragm process inherently gives rise to environmental releases of asbestos.

CHAPTER THREE

3.0 MATERIAL BALANCES

3.1 MATERIAL BALANCES FOR THE PRODUCTION OF 1000 TONS PER DAY OF CAUSTIC SODA

Basis = 100.00 kmol/day of brine

Fresh Feed (Brine)

Comp	Mol%
NaCl	15.00
Water	81.50
Ca+	2.00
Mg+	1.50
Total	100.00

Source:

Components

Comp	Mol Wt
NaCl	58.50
H2O	18.00
Ca+	40.00
Mg+	24.00
Na2CO3	106.00
NaOH	40.00
CaCO3	100.00
Mg(OH)2	58.00
Cl2	71.00
H2	2.00
Na+	23.00

Material balances across the saturator

Operation: Increasing the concentration of the salt in the solution

Assumptio Salt added i 10.00 % of the fresh solution

	IN							OUT					
	Input			Addition				Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%		kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	15.00	877.50	15.00	10.00	585.00	100.00		0.00	0.00	#DIV/0!	25.00	1462.50	22.73
H2O	81.50	1467.00	81.50	0.00	0.00	0.00		0.00	0.00	#DIV/0!	81.50	1467.00	74.09
Ca+	2.00	80.00	2.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	2.00	80.00	1.82
Mg+	1.50	36.00	1.50	0.00	0.00	0.00		0.00	0.00	#DIV/0!	1.50	36.00	1.36
Na2CO3	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
CaCO3	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	100.00	2460.50	100.00	10.00	585.00	100.00		0.00	0.00	#DIV/0!	110.00	3045.50	100.00

Material balances across the preciptator

Operation: Precipitation of the impurities and the dissolved salts

Reactions: Ca+ + Na2CO3 => CaCO3 + 2Na+

Mg+ + 2NaOH => Mg(OH)2 + 2Na+

	IN							OUT					
	Input			Addition				Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%		kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25.00	1462.50	22.73	0.00	0.00	0.00		0.00	0.00	#DIV/0!	25.00	1462.50	21.37
H2O	81.50	1467.00	74.09	0.00	0.00	0.00		0.00	0.00	#DIV/0!	81.50	1467.00	69.66
Ca+	2.00	80.00	1.82	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	1.50	36.00	1.36	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	2.00	212.00	40.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	3.00	120.00	60.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
CaCO3	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	2.00	200.00	1.71
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	1.50	87.00	1.28
Cl2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	#DIV/0!	7.00	161.00	5.98
Total	110.00	3045.50	100.00	5.00	332.00	100.00		0.00	0.00	#DIV/0!	117.00	3377.50	100.00

Material balances across the filter

Operation: Separation of the residue

Assumptio 100.00 % of the precipitates and the ions are removed

	IN							OUT					
	Input			Addition				Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%		kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25.00	1462.50	21.37	0.00	0.00	#DIV/0!		0.00	0.00	0.00	25.00	1462.50	23.47
H2O	81.50	1467.00	69.66	0.00	0.00	#DIV/0!		0.00	0.00	0.00	81.50	1467.00	76.53
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
CaCO3	2.00	200.00	1.71	0.00	0.00	#DIV/0!		2.00	200.00	19.05	0.00	0.00	0.00
Mg(OH)2	1.50	87.00	1.28	0.00	0.00	#DIV/0!		1.50	87.00	14.29	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!		0.00	0.00	0.00	0.00	0.00	0.00
Na+	7.00	161.00	5.98	0.00	0.00	#DIV/0!		7.00	161.00	66.67	0.00	0.00	0.00
Total	117.00	3377.50	100.00	0.00	0.00	#DIV/0!		10.50	448.00	100.00	106.50	2929.50	100.00

Material balances across the electrolytic cell

Operation: Production of caustic soda

Assumption:100% conversion

Reactions: For all the dissolving salt, sodium chloride is,

NaCl => Na+ + Cl-

The anode reaction for all processesis:

2Cl-(aq(=> Cl2(g) + 2e-

The cathode reaction is:

2Na+(aq) + 2H2O + 2e- => H2(g) + 2Na+(aq) + 2OH-(aq)

The overall reaction is:

2Na+(aq) + 2Cl-(aq) + 2H2O => 2Na+(aq) + 2OH-(aq) + Cl2(g) + H2(g)

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25.00	1462.50	23.47	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2O	81.50	1467.00	76.53	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25.00	1000.00	50.00
CaCO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	12.50	887.50	25.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	12.50	25.00	25.00
Na+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	106.50	2929.50	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	50.00	1912.50	100.00

Material balances across the cooler

Operation: Reduction of the temperature of the product

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2O	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	25.00	1000.00	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25.00	1000.00	100.00
CaCO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	25.00	1000.00	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25.00	1000.00	100.00

Calculation of scale up factor:

Conversion factor:	1.00	ton/day =	1016.06	kg/day
Production Rate =	1000.00	ton/day =	1016060.00	kg/day
Caustic soda obtained from the basis =			1000.00	kg/day
The scale up factor is =	1016.06			

SCALED UP MATERIAL BALANCES

Material balances across the saturator

Operation: Increasing the concentration of the salt in the solution

Assumptio Salt added i 10.00 % of the fresh solution

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	15240.90	891592.65	15.00	10160.60	594395.10	100.00	0.00	0.00	#DIV/0!	25401.50	1485987.75	22.73
H2O	82808.89	1490560.02	81.50	0.00	0.00	0.00	0.00	0.00	#DIV/0!	82808.89	1490560.02	74.09
Ca+	2032.12	81284.80	2.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	2032.12	81284.80	1.82
Mg+	1524.09	36578.16	1.50	0.00	0.00	0.00	0.00	0.00	#DIV/0!	1524.09	36578.16	1.36
Na2CO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
CaCO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	101606.00	2500015.63	100.00	10160.60	594395.10	100.00	0.00	0.00	#DIV/0!	111766.60	3094410.73	100.00

Material balances across the preciptator

Operation: Precipitation of the impurities and the dissolved salts

Reactions: Ca+ + Na2CO3 => CaCO3 + 2Na+

Mg+ + 2NaOH => Mg(OH)2 + 2Na+

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25401.50	1485987.75	22.73	0.00	0.00	0.00	0.00	0.00	#DIV/0!	25401.50	1485987.75	21.37
H2O	82808.89	1490560.02	74.09	0.00	0.00	0.00	0.00	0.00	#DIV/0!	82808.89	1490560.02	69.66
Ca+	2032.12	81284.80	1.82	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	1524.09	36578.16	1.36	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	2032.12	215404.72	40.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	3048.18	121927.20	60.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
CaCO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	2032.12	203212.00	1.71
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	1524.09	88397.22	1.28
Cl2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!	7112.42	163585.66	5.98
Total	111766.60	3094410.73	100.00	5080.30	337331.92	100.00	0.00	0.00	#DIV/0!	118879.02	3431742.65	100.00

Material balances across the filter

Operation: Separation of the residue

Assumptio 100.00 % of the precipitates and the ions are removed

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25401.50	1485987.75	21.37	0.00	0.00	#DIV/0!	0.00	0.00	0.00	25401.50	1485987.75	23.47
H2O	82808.89	1490560.02	69.66	0.00	0.00	#DIV/0!	0.00	0.00	0.00	82808.89	1490560.02	76.53
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
CaCO3	2032.12	203212.00	1.71	0.00	0.00	#DIV/0!	2032.12	203212.00	19.05	0.00	0.00	0.00
Mg(OH)2	1524.09	88397.22	1.28	0.00	0.00	#DIV/0!	1524.09	88397.22	14.29	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00
Na+	7112.42	163585.66	5.98	0.00	0.00	#DIV/0!	7112.42	163585.66	66.67	0.00	0.00	0.00
Total	118879.02	3431742.65	100.00	0.00	0.00	#DIV/0!	10668.63	455194.88	100.00	108210.39	2976547.77	100.00

Material balances across the electrolytic cell

Operation: Production of caustic soda

Assumption:100% conversion

Reactions: For all the dissolving salt, sodium chloride is,

NaCl => Na+ + Cl-

The anode reaction for all processesis:

2Cl-(aq(=> Cl2(g) + 2e-

The cathode reaction is:

2Na+(aq) + 2H2O + 2e- => H2(g) + 2Na+(aq) + 2OH-(aq)

The overall reaction is:

2Na+(aq) + 2Cl-(aq) + 2H2O => 2Na+(aq) + 2OH-(aq) + Cl2(g) + H2(g)

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	25401.50	1485987.75	23.47	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2O	82808.89	1490560.02	76.53	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25401.50	1016060.00	50.00
CaCO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	12700.75	901753.25	25.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	12700.75	25401.50	25.00
Na+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	108210.39	2976547.77	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	50803.00	1943214.75	100.00

Material balances across the cooler

Operation: Reduction of the temperature of the product

	IN						OUT					
	Input			Addition			Loss			Output		
Comp.	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%	kmol/day	kg/day	mol%
NaCl	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2O	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Ca+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
NaOH	25401.50	1016060.00	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25401.50	1016060.00	100.00
CaCO3	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
H2	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Na+	0.00	0.00	0.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	0.00	0.00	0.00
Total	25401.50	1016060.00	100.00	0.00	0.00	#DIV/0!	0.00	0.00	#DIV/0!	25401.50	1016060.00	100.00

4.0 ENERGY BALANCES

Components and their molecular weights:

$$\begin{pmatrix} \text{NaCl} \\ H_2O \\ \text{Ca} \\ \text{Mg} \\ Na_2CO_3 \\ \text{NaOH} \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \\ \text{Na} \end{pmatrix} \qquad mw := \begin{pmatrix} 58.5 \\ 18 \\ 40 \\ 24 \\ 106 \\ 40 \\ 100 \\ 58 \\ 71 \\ 2 \\ 23 \end{pmatrix} \cdot \frac{kg}{kmol}$$

Themodynamic Properties:

$$coeff := \begin{bmatrix} 37.3596 & 9.87\cdot10^{-4} & -\left(2.90\cdot10^{-7}\right) & 2.90\cdot10^{-11} & -\left(4.11\cdot10^{5}\right) & 1.71\cdot10^{5} \\ 18.2964 & 4.72\cdot10^{-1} & -\left(1.34\cdot10^{-3}\right) & 1.31\cdot10^{-6} & -\left(2.86\cdot10^{5}\right) & 4.07\cdot10^{4} \\ 5.31 & 0.000333 & 0 & 0 & 0 & 0 \\ 6.2 & 0.00133 & -67800 & 0 & 0 & 0 \\ 121 & 0 & 0 & 0 & 0 & 0 \\ 43.5656 & 1.76\cdot10^{-2} & -\left(7.56\cdot10^{-6}\right) & 1.09\cdot10^{-7} & -\left(4.26\cdot10^{5}\right) & 0.00 \\ 82.34 & 0.05 & -\left(1.29\cdot10^{-6}\right) & 0 & -\left(1.21\cdot10^{3}\right) & 0 \\ 45.44 & 5.01\cdot10^{-3} & -873200 & 0 & -924660 & 0 \\ 24.9616 & 4.57\cdot10^{-2} & -\left(6.17\cdot10^{-5}\right) & 2.95\cdot10^{-8} & 0 & 20410 \\ 27.14 & 9.27\cdot10^{-3} & -\left(1.38\cdot10^{-5}\right) & 7.65\cdot10^{-9} & 0 & 904 \\ 5.01 & 5.36\cdot10^{-3} & 0.00 & 0.00 & 0 & 0 \end{bmatrix} \qquad \begin{pmatrix} \text{NaCl} \\ H_2O \\ \text{Ca} \\ \text{Mg} \\ Na_2CO_3 \\ \text{NaOH} \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \\ \text{Na} \end{pmatrix}$$

$$a := \overrightarrow{coeff^{\langle 1\rangle}} \cdot \frac{kJ}{kmol\cdot K} \qquad b := \overrightarrow{coeff^{\langle 2\rangle}} \cdot \frac{kJ}{kmol\cdot K^2}$$

$$c := \overrightarrow{coeff^{\langle 3\rangle}} \cdot \frac{kJ}{kmol\cdot K^3} \qquad d := \overrightarrow{coeff^{\langle 4\rangle}} \cdot \frac{kJ}{kmol\cdot K^4}$$

$$H_r := \overrightarrow{coeff^{\langle 5\rangle}} \cdot \frac{kJ}{kmol} \qquad H_v := \overrightarrow{coeff^{\langle 6\rangle}} \cdot \frac{kJ}{kmol}$$

Reference temperature: $T_r := 298\ K$

4.1 Energy Balances on Saturator

Material flows of the saturator **Temperature**

$$n := \begin{pmatrix} 15240.90 & 10160.60 & 0.00 & 25401.50 \\ 82808.89 & 0.00 & 0.00 & 82808.89 \\ 2032.12 & 0.00 & 0.00 & 2032.12 \\ 1524.09 & 0.00 & 0.00 & 1524.09 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \end{pmatrix} \cdot \frac{\text{kmol}}{\text{day}} \qquad \begin{pmatrix} T_i \\ T_a \\ T_l \\ T_o \end{pmatrix} := \begin{pmatrix} 303 \\ 303 \\ 0 \\ 330 \end{pmatrix} \cdot K$$

$n_i := n^{\langle 1 \rangle}$ $n_a := n^{\langle 2 \rangle}$ $n_l := n^{\langle 3 \rangle}$ $n_o := n^{\langle 4 \rangle}$

$T_i = 303\,K$ $T_a = 303\,K$ $T_l = 0\,K$ $T_o = 330\,K$

Energy In

Energy of input

$$\begin{aligned} \Delta H_i := {} & n_{i_1} \cdot \left[\int_{T_r}^{T_i} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{i_2} \cdot \left[\int_{T_r}^{T_i} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_3} \cdot \left[\int_{T_r}^{T_i} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{i_4} \cdot \left[\int_{T_r}^{T_i} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_5} \cdot \left[\int_{T_r}^{T_i} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{i_6} \cdot \left[\int_{T_r}^{T_i} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_7} \cdot \int_{T_r}^{T_i} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{i_8} \cdot \int_{T_r}^{T_i} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\ & + n_{i_9} \cdot \int_{T_r}^{T_i} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{i_{10}} \cdot \int_{T_r}^{T_i} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\ & + n_{i_{11}} \cdot \int_{T_r}^{T_i} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT \end{aligned}$$

$$\Delta H_i = -4.666 \times 10^{13} \, \frac{\text{kJ}}{\text{day}}$$

Energy of addition

$T_a = 303\ \text{K}$

$$
\begin{aligned}
\Delta H_a := {} & n_{a_1} \cdot \left[\int_{T_r}^{T_a} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{a_2} \cdot \left[\int_{T_r}^{T_a} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_3} \cdot \left[\int_{T_r}^{T_a} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{a_4} \cdot \left[\int_{T_r}^{T_a} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_5} \cdot \left[\int_{T_r}^{T_a} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{a_6} \cdot \left[\int_{T_r}^{T_a} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_7} \cdot \int_{T_r}^{T_a} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{a_8} \cdot \int_{T_r}^{T_a} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{a_9} \cdot \int_{T_r}^{T_a} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{a_{10}} \cdot \int_{T_r}^{T_a} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{a_{11}} \cdot \int_{T_r}^{T_a} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}
$$

$$\Delta H_a = 1.912 \times 10^{6}\ \frac{\text{kJ}}{\text{day}}$$

Total energy in: $\Delta H_{in} := \Delta H_i + \Delta H_a$

$$\Delta H_{in} = -4.666 \times 10^{13}\ \frac{\text{kJ}}{\text{day}}$$

Energy Out

Energy of Output

$T_o = 330\ \text{K}$

$$
\begin{aligned}
\Delta H_o := {} & n_{o_1} \cdot \left[\int_{T_r}^{T_o} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{o_2} \cdot \left[\int_{T_r}^{T_o} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_3} \cdot \left[\int_{T_r}^{T_o} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{o_4} \cdot \left[\int_{T_r}^{T_o} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_5} \cdot \left[\int_{T_r}^{T_o} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{o_6} \cdot \left[\int_{T_r}^{T_o} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_7} \cdot \int_{T_r}^{T_o} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{o_8} \cdot \int_{T_r}^{T_o} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{o_9} \cdot \int_{T_r}^{T_o} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{o_{10}} \cdot \int_{T_r}^{T_o} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{o_{11}} \cdot \int_{T_r}^{T_o} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}
$$

$$\Delta H_o = -3.263 \times 10^{14}\ \frac{\text{kJ}}{\text{day}}$$

Total energy out: $\Delta H_{out} := \Delta H_o$ $\qquad \Delta H_{out} = -3.263 \times 10^{14} \frac{kJ}{day}$

Heat load: $\Delta H_l := \Delta H_{out} - \Delta H_{in}$ $\qquad \Delta H_l = -2.7$[illegible] $\times 10^{14} \frac{kJ}{day}$

4.2 Energy Balances on Precipitator

Material flows of the precipitator **Temperature**

$$n := \begin{pmatrix} 25401.50 & 0.00 & 0.00 & 25401.50 \\ 82808.89 & 0.00 & 0.00 & 82808.89 \\ 2032.12 & 0.00 & 0.00 & 0.00 \\ 1524.09 & 0.00 & 0.00 & 0.00 \\ 0.00 & 2032.12 & 0.00 & 0.00 \\ 0.00 & 3048.18 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 2032.12 \\ 0.00 & 0.00 & 0.00 & 1524.09 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 7112.42 \end{pmatrix} \cdot \frac{kmol}{day} \qquad \begin{pmatrix} T_i \\ T_a \\ T_l \\ T_o \end{pmatrix} := \begin{pmatrix} 330 \\ 303 \\ 317 \\ 317 \end{pmatrix} \cdot K$$

$n_i := n^{\langle 1 \rangle}$ $\qquad n_a := n^{\langle 2 \rangle}$ $\qquad n_l := n^{\langle 3 \rangle}$ $\qquad n_o := n^{\langle 4 \rangle}$

$T_i = 330\,K$ $\qquad T_a = 303\,K$ $\qquad T_l = 317\,K$ $\qquad T_o = 317\,K$

Energy In

Energy of input

$$\begin{aligned}\Delta H_i := {} & n_{i_1} \cdot \left[\int_{T_r}^{T_i} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{i_2} \cdot \left[\int_{T_r}^{T_i} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_3} \cdot \left[\int_{T_r}^{T_i} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{i_4} \cdot \left[\int_{T_r}^{T_i} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_5} \cdot \left[\int_{T_r}^{T_i} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{i_6} \cdot \left[\int_{T_r}^{T_i} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_7} \cdot \int_{T_r}^{T_i} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{i_8} \cdot \int_{T_r}^{T_i} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\ & + n_{i_9} \cdot \int_{T_r}^{T_i} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{i_{10}} \cdot \int_{T_r}^{T_i} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\ & + n_{i_{11}} \cdot \int_{T_r}^{T_i} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT\end{aligned}$$

day

Energy of addition

$T_a = 303\,\mathrm{K}$

$$
\begin{aligned}
\Delta H_a := {} & n_{a_1}\cdot\left[\int_{T_r}^{T_a}\left(a_1+b_1\cdot T+c_1\cdot T^2+d_1\cdot T^3\right)dT\right]+n_{a_2}\cdot\left[\int_{T_r}^{T_a}\left(a_2+b_2\cdot T+c_2\cdot T^2+d_2\cdot T^3\right)dT\right]\ldots\\
&+n_{a_3}\cdot\left[\int_{T_r}^{T_a}\left(a_3+b_3\cdot T+c_3\cdot T^2+d_3\cdot T^3\right)dT\right]+n_{a_4}\cdot\left[\int_{T_r}^{T_a}\left(a_4+b_4\cdot T+c_4\cdot T^2+d_4\cdot T^3\right)dT\right]\ldots\\
&+n_{a_5}\cdot\left[\int_{T_r}^{T_a}\left(a_5+b_5\cdot T+c_5\cdot T^2+d_5\cdot T^3\right)dT\right]+n_{a_6}\cdot\left[\int_{T_r}^{T_a}\left(a_6+b_6\cdot T+c_6\cdot T^2+d_6\cdot T^3\right)dT\right]\ldots\\
&+n_{a_7}\cdot\int_{T_r}^{T_a}\left(a_7+b_7\cdot T+c_7\cdot T^2+d_7\cdot T^3\right)dT+n_{a_8}\cdot\int_{T_r}^{T_a}\left(a_8+b_8\cdot T+c_8\cdot T^2+d_8\cdot T^3\right)dT\ldots\\
&+n_{a_9}\cdot\int_{T_r}^{T_a}\left(a_9+b_9\cdot T+c_9\cdot T^2+d_9\cdot T^3\right)dT+n_{a_{10}}\cdot\int_{T_r}^{T_a}\left(a_{10}+b_{10}\cdot T+c_{10}\cdot T^2+d_{10}\cdot T^3\right)dT\ldots\\
&+n_{a_{11}}\cdot\int_{T_r}^{T_a}\left(a_{11}+b_{11}\cdot T+c_{11}\cdot T^2+d_{11}\cdot T^3\right)dT
\end{aligned}
$$

$$\Delta H_a = 2.009\times 10^{6}\,\frac{\mathrm{kJ}}{\mathrm{day}}$$

Total energy in: $\Delta H_{in} := \Delta H_i + \Delta H_a$

$$\Delta H_{in} = -3.263\times 10^{14}\,\frac{\mathrm{kJ}}{\mathrm{day}}$$

Energy Out

Energy of Output

$T_o = 317\,\mathrm{K}$

$$
\begin{aligned}
\Delta H_o := {} & n_{o_1}\cdot\left[\int_{T_r}^{T_o}\left(a_1+b_1\cdot T+c_1\cdot T^2+d_1\cdot T^3\right)dT\right]+n_{o_2}\cdot\left[\int_{T_r}^{T_o}\left(a_2+b_2\cdot T+c_2\cdot T^2+d_2\cdot T^3\right)dT\right]\ldots\\
&+n_{o_3}\cdot\left[\int_{T_r}^{T_o}\left(a_3+b_3\cdot T+c_3\cdot T^2+d_3\cdot T^3\right)dT\right]+n_{o_4}\cdot\left[\int_{T_r}^{T_o}\left(a_4+b_4\cdot T+c_4\cdot T^2+d_4\cdot T^3\right)dT\right]\ldots\\
&+n_{o_5}\cdot\left[\int_{T_r}^{T_o}\left(a_5+b_5\cdot T+c_5\cdot T^2+d_5\cdot T^3\right)dT\right]+n_{o_6}\cdot\left[\int_{T_r}^{T_o}\left(a_6+b_6\cdot T+c_6\cdot T^2+d_6\cdot T^3\right)dT\right]\ldots\\
&+n_{o_7}\cdot\int_{T_r}^{T_o}\left(a_7+b_7\cdot T+c_7\cdot T^2+d_7\cdot T^3\right)dT+n_{o_8}\cdot\int_{T_r}^{T_o}\left(a_8+b_8\cdot T+c_8\cdot T^2+d_8\cdot T^3\right)dT\ldots\\
&+n_{o_9}\cdot\int_{T_r}^{T_o}\left(a_9+b_9\cdot T+c_9\cdot T^2+d_9\cdot T^3\right)dT+n_{o_{10}}\cdot\int_{T_r}^{T_o}\left(a_{10}+b_{10}\cdot T+c_{10}\cdot T^2+d_{10}\cdot T^3\right)dT\ldots\\
&+n_{o_{11}}\cdot\int_{T_r}^{T_o}\left(a_{11}+b_{11}\cdot T+c_{11}\cdot T^2+d_{11}\cdot T^3\right)dT
\end{aligned}
$$

$$\Delta H_o = -2.392\times 10^{15}\,\frac{\mathrm{kJ}}{\mathrm{day}}$$

Total energy out: $\Delta H_{out} := \Delta H_o$

$$\Delta H_{out} = -2.392 \times 10^{15} \frac{kJ}{day}$$

Heat load: $\Delta H_2 := \Delta H_{out} - \Delta H_{in}$

$$\Delta H_2 = -2.065 \times 10^{15} \frac{kJ}{day}$$

4.3 Energy Balances on Filter

Material flows of the filter

$$n := \begin{pmatrix} 25401.50 & 0.00 & 0.00 & 25401.50 \\ 82808.89 & 0.00 & 0.00 & 82808.89 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 2032.12 & 0.00 & 2032.12 & 0.00 \\ 1524.09 & 0.00 & 1524.09 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 7112.42 & 0.00 & 7112.42 & 0.00 \end{pmatrix} \cdot \frac{kmol}{day}$$

Temperature

$$\begin{pmatrix} T_i \\ T_a \\ T_l \\ T_o \end{pmatrix} := \begin{pmatrix} 317 \\ 0 \\ 317 \\ 317 \end{pmatrix} \cdot K$$

$n_i := n^{\langle 1 \rangle}$ $n_a := n^{\langle 2 \rangle}$ $n_l := n^{\langle 3 \rangle}$ $n_o := n^{\langle 4 \rangle}$

$T_i = 317\,K$ $T_a = 0\,K$ $T_l = 317\,K$ $T_o = 317\,K$

Energy In

Energy of input

$$\begin{aligned} \Delta H_i := {} & n_{i_1} \cdot \left[\int_{T_r}^{T_i} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{i_2} \cdot \left[\int_{T_r}^{T_i} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_3} \cdot \left[\int_{T_r}^{T_i} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{i_4} \cdot \left[\int_{T_r}^{T_i} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_5} \cdot \left[\int_{T_r}^{T_i} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{i_6} \cdot \left[\int_{T_r}^{T_i} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\ & + n_{i_7} \cdot \int_{T_r}^{T_i} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{i_8} \cdot \int_{T_r}^{T_i} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\ & + n_{i_9} \cdot \int_{T_r}^{T_i} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{i_{10}} \cdot \int_{T_r}^{T_i} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\ & + n_{i_{11}} \cdot \int_{T_r}^{T_i} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT \end{aligned}$$

$$\frac{kJ}{day}$$

Total energy in: $\Delta H_{in} := \Delta H_i$

$$\Delta H_{in} = -2.392 \times 10^{15} \frac{kJ}{day}$$

Energy Out

Energy of Loss

$T_l = 317\,K$

$$\begin{aligned}
\Delta H_l := {} & n_{l_1} \cdot \left[\int_{T_r}^{T_l} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{l_2} \cdot \left[\int_{T_r}^{T_l} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{l_3} \cdot \left[\int_{T_r}^{T_l} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{l_4} \cdot \left[\int_{T_r}^{T_l} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{l_5} \cdot \left[\int_{T_r}^{T_l} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{l_6} \cdot \left[\int_{T_r}^{T_l} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{l_7} \cdot \int_{T_r}^{T_l} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{l_8} \cdot \int_{T_r}^{T_l} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{l_9} \cdot \int_{T_r}^{T_l} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{l_{10}} \cdot \int_{T_r}^{T_l} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{l_{11}} \cdot \int_{T_r}^{T_l} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}$$

$$\Delta H_l = -2.392 \times 10^{15} \frac{kJ}{day}$$

Energy of Output

$T_o = 317\,K$

$$\begin{aligned}
\Delta H_o := {} & n_{o_1} \cdot \left[\int_{T_r}^{T_o} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{o_2} \cdot \left[\int_{T_r}^{T_o} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_3} \cdot \left[\int_{T_r}^{T_o} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{o_4} \cdot \left[\int_{T_r}^{T_o} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_5} \cdot \left[\int_{T_r}^{T_o} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{o_6} \cdot \left[\int_{T_r}^{T_o} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{o_7} \cdot \int_{T_r}^{T_o} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{o_8} \cdot \int_{T_r}^{T_o} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{o_9} \cdot \int_{T_r}^{T_o} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{o_{10}} \cdot \int_{T_r}^{T_o} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{o_{11}} \cdot \int_{T_r}^{T_o} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}$$

$$\Delta H_o = 1.359 \times 10^{8} \frac{kJ}{day}$$

Total energy out: $\Delta H_{out} := \Delta H_l + \Delta H_o$

$$\Delta H_{out} = -2.392 \times 10^{15} \frac{kJ}{day}$$

Heat load: $\Delta H_3 := \Delta H_{out} - \Delta H_{in}$

$$\Delta H_3 = 0\,\frac{kJ}{day}$$

4.4 Energy Balances on Electrolytic Cell

Material flows of the electrolytic cell **Temperature**

$$n := \begin{pmatrix} 25401.50 & 0.00 & 0.00 & 0.00 \\ 82808.89 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 25401.50 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 12700.75 \\ 0.00 & 0.00 & 0.00 & 12700.75 \\ 0.00 & 0.00 & 0.00 & 0.00 \end{pmatrix} \cdot \frac{kmol}{day}$$

$$\begin{pmatrix} T_i \\ T_a \\ T_l \\ T_o \end{pmatrix} := \begin{pmatrix} 317 \\ 0 \\ 0 \\ 379 \end{pmatrix} \cdot K$$

$n_i := n^{\langle 1 \rangle}$ $n_a := n^{\langle 2 \rangle}$ $n_l := n^{\langle 3 \rangle}$ $n_o := n^{\langle 4 \rangle}$

$T_i = 317\,K$ $T_a = 0\,K$ $T_l = 0\,K$ $T_o = 379\,K$

Energy In

Energy of input

$$\begin{aligned}\Delta H_i := {} & n_{i_1} \cdot \left[\int_{T_r}^{T_i} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT + H_{r_1}\right] + n_{i_2} \cdot \left[\int_{T_r}^{T_i} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT + H_{r_2}\right] \dots \\ & + n_{i_3} \cdot \left[\int_{T_r}^{T_i} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT + H_{r_3}\right] + n_{i_4} \cdot \left[\int_{T_r}^{T_i} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT + H_{r_4}\right] \dots \\ & + n_{i_5} \cdot \left[\int_{T_r}^{T_i} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT + H_{r_5}\right] + n_{i_6} \cdot \left[\int_{T_r}^{T_i} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT + H_{r_6}\right] \dots \\ & + n_{i_7} \cdot \left[\int_{T_r}^{T_i} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + H_{r_7}\right] + n_{i_8} \cdot \left[\int_{T_r}^{T_i} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT + H_{r_8}\right] \dots \\ & + n_{i_9} \cdot \left[\int_{T_r}^{T_i} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + H_{r_9}\right] + n_{i_{10}} \cdot \left[\int_{T_r}^{T_i} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT + H_{r_{10}}\right] \\ & + n_{i_{11}} \cdot \left[\int_{T_r}^{T_i} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT + H_{r_{10}}\right]\end{aligned}$$

$$\Delta H_i = -3.399 \times 10^{10}\,\frac{kJ}{day}$$

Total energy in: $\Delta H_{in} := \Delta H_i$

$$\Delta H_{in} = -3.399 \times 10^{10}\,\frac{kJ}{day}$$

Energy Out

Energy of Output

$T_o = 379\,K$

$$\Delta H_o := n_{o_1}\cdot\left[\int_{T_r}^{T_o}\left(a_1 + b_1\cdot T + c_1\cdot T^2 + d_1\cdot T^3\right)dT + H_{r_1}\right] + n_{o_2}\cdot\left[\int_{T_r}^{T_o}\left(a_2 + b_2\cdot T + c_2\cdot T^2 + d_2\cdot T^3\right)dT + H_{r_2}\right]\ldots$$

$$+ n_{o_3}\cdot\left[\int_{T_r}^{T_o}\left(a_3 + b_3\cdot T + c_3\cdot T^2 + d_3\cdot T^3\right)dT + H_{r_3}\right] + n_{o_4}\cdot\left[\int_{T_r}^{T_o}\left(a_4 + b_4\cdot T + c_4\cdot T^2 + d_4\cdot T^3\right)dT + H_{r_4}\right]\ldots$$

$$+ n_{o_5}\cdot\left[\int_{T_r}^{T_o}\left(a_5 + b_5\cdot T + c_5\cdot T^2 + d_5\cdot T^3\right)dT + H_{r_5}\right] + n_{o_6}\cdot\left[\int_{T_r}^{T_o}\left(a_6 + b_6\cdot T + c_6\cdot T^2 + d_6\cdot T^3\right)dT + H_{r_6}\right]\ldots$$

$$+ n_{o_7}\cdot\left[\int_{T_r}^{T_o}\left(a_7 + b_7\cdot T + c_7\cdot T^2 + d_7\cdot T^3\right)dT + H_{r_7}\right] + n_{o_8}\cdot\left[\int_{T_r}^{T_o}\left(a_8 + b_8\cdot T + c_8\cdot T^2 + d_8\cdot T^3\right)dT + H_{r_8}\right]\ldots$$

$$+ n_{o_9}\cdot\left[\int_{T_r}^{T_o}\left(a_9 + b_9\cdot T + c_9\cdot T^2 + d_9\cdot T^3\right)dT + H_{r_9}\right] + n_{o_{10}}\cdot\left[\int_{T_r}^{T_o}\left(a_{10} + b_{10}\cdot T + c_{10}\cdot T^2 + d_{10}\cdot T^3\right)dT + H\right.$$

$$+ n_{o_{11}}\cdot\left[\int_{T_r}^{T_o}\left(a_{11} + b_{11}\cdot T + c_{11}\cdot T^2 + d_{11}\cdot T^3\right)dT + H_{r_{10}}\right]$$

$$\Delta H_o = -1.065\times 10^{10}\,\frac{kJ}{day}$$

Total energy out: $\Delta H_{out} := \Delta H_o$

$$\Delta H_{out} = -1.065\times 10^{10}\,\frac{kJ}{day}$$

Heat load: $\Delta H_4 := \Delta H_{out} - \Delta H_{in}$

$$\Delta H_4 = 2.334\times 10^{10}\,\frac{kJ}{day}$$

4.5 Energy Balances on Cooler

Material flows of the cooler

$$n := \begin{pmatrix} 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 25401.50 & 0.00 & 0.00 & 25401.50 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 \end{pmatrix}\cdot\frac{kmol}{day}$$

Temperature

$$\begin{pmatrix} T_i \\ T_a \\ T_l \\ T_o \end{pmatrix} := \begin{pmatrix} 379 \\ 0 \\ 0 \\ 309 \end{pmatrix}\cdot K$$

$n_i := n^{\langle 1 \rangle}$ $\qquad n_a := n^{\langle 2 \rangle}$ $\qquad n_l := n^{\langle 3 \rangle}$ $\qquad n_o := n^{\langle 4 \rangle}$

$T_i = 379\,\mathrm{K}$ $\qquad T_a = 0\,\mathrm{K}$ $\qquad T_l = 0\,\mathrm{K}$ $\qquad T_o = 309\,\mathrm{K}$

$\Delta T_{cooler} := T_o - T_i$ $\qquad \Delta T_{cooler} = -70\,\mathrm{K}$

Energy In

Energy of input

$$
\begin{aligned}
\Delta H_i := {} & n_{i_1} \cdot \left[\int_{T_r}^{T_i} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{i_2} \cdot \left[\int_{T_r}^{T_i} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{i_3} \cdot \left[\int_{T_r}^{T_i} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{i_4} \cdot \left[\int_{T_r}^{T_i} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{i_5} \cdot \left[\int_{T_r}^{T_i} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{i_6} \cdot \left[\int_{T_r}^{T_i} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{i_7} \cdot \int_{T_r}^{T_i} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{i_8} \int_{T_r}^{T_i} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{i_9} \cdot \int_{T_r}^{T_i} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{i_{10}} \cdot \int_{T_r}^{T_i} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{i_{11}} \cdot \int_{T_r}^{T_i} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}
\qquad \frac{\mathrm{kJ}}{\mathrm{day}}
$$

Energy of addition

$T_a = 0\,\mathrm{K}$

$$
\begin{aligned}
\Delta H_a := {} & n_{a_1} \cdot \left[\int_{T_r}^{T_a} \left(a_1 + b_1 \cdot T + c_1 \cdot T^2 + d_1 \cdot T^3\right) dT\right] + n_{a_2} \cdot \left[\int_{T_r}^{T_a} \left(a_2 + b_2 \cdot T + c_2 \cdot T^2 + d_2 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_3} \cdot \left[\int_{T_r}^{T_a} \left(a_3 + b_3 \cdot T + c_3 \cdot T^2 + d_3 \cdot T^3\right) dT\right] + n_{a_4} \cdot \left[\int_{T_r}^{T_a} \left(a_4 + b_4 \cdot T + c_4 \cdot T^2 + d_4 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_5} \cdot \left[\int_{T_r}^{T_a} \left(a_5 + b_5 \cdot T + c_5 \cdot T^2 + d_5 \cdot T^3\right) dT\right] + n_{a_6} \cdot \left[\int_{T_r}^{T_a} \left(a_6 + b_6 \cdot T + c_6 \cdot T^2 + d_6 \cdot T^3\right) dT\right] \ldots \\
& + n_{a_7} \cdot \int_{T_r}^{T_a} \left(a_7 + b_7 \cdot T + c_7 \cdot T^2 + d_7 \cdot T^3\right) dT + n_{a_8} \cdot \int_{T_r}^{T_a} \left(a_8 + b_8 \cdot T + c_8 \cdot T^2 + d_8 \cdot T^3\right) dT \ldots \\
& + n_{a_9} \cdot \int_{T_r}^{T_a} \left(a_9 + b_9 \cdot T + c_9 \cdot T^2 + d_9 \cdot T^3\right) dT + n_{a_{10}} \cdot \int_{T_r}^{T_a} \left(a_{10} + b_{10} \cdot T + c_{10} \cdot T^2 + d_{10} \cdot T^3\right) dT \ldots \\
& + n_{a_{11}} \cdot \int_{T_r}^{T_a} \left(a_{11} + b_{11} \cdot T + c_{11} \cdot T^2 + d_{11} \cdot T^3\right) dT
\end{aligned}
$$

day

Total energy in: $\Delta H_{in} := \Delta H_i + \Delta H_a$

$$\Delta H_{in} = 1.089\times 10^{8}\,\frac{kJ}{day}$$

Energy Out

Energy of Loss

$T_l = 0\,K$

$$\begin{aligned}\Delta H_l := {} & n_{l_1}\cdot\left[\int_{T_r}^{T_l}\left(a_1 + b_1\cdot T + c_1\cdot T^2 + d_1\cdot T^3\right)dT\right] + n_{l_2}\cdot\left[\int_{T_r}^{T_l}\left(a_2 + b_2\cdot T + c_2\cdot T^2 + d_2\cdot T^3\right)dT\right]\ldots\\ & + n_{l_3}\cdot\left[\int_{T_r}^{T_l}\left(a_3 + b_3\cdot T + c_3\cdot T^2 + d_3\cdot T^3\right)dT\right] + n_{l_4}\cdot\left[\int_{T_r}^{T_l}\left(a_4 + b_4\cdot T + c_4\cdot T^2 + d_4\cdot T^3\right)dT\right]\ldots\\ & + n_{l_5}\cdot\left[\int_{T_r}^{T_l}\left(a_5 + b_5\cdot T + c_5\cdot T^2 + d_5\cdot T^3\right)dT\right] + n_{l_6}\cdot\left[\int_{T_r}^{T_l}\left(a_6 + b_6\cdot T + c_6\cdot T^2 + d_6\cdot T^3\right)dT\right]\ldots\\ & + n_{l_7}\cdot\int_{T_r}^{T_l}\left(a_7 + b_7\cdot T + c_7\cdot T^2 + d_7\cdot T^3\right)dT + n_{l_8}\cdot\int_{T_r}^{T_l}\left(a_8 + b_8\cdot T + c_8\cdot T^2 + d_8\cdot T^3\right)dT\ldots\\ & + n_{l_9}\cdot\int_{T_r}^{T_l}\left(a_9 + b_9\cdot T + c_9\cdot T^2 + d_9\cdot T^3\right)dT + n_{l_{10}}\cdot\int_{T_r}^{T_l}\left(a_{10} + b_{10}\cdot T + c_{10}\cdot T^2 + d_{10}\cdot T^3\right)dT\ldots\\ & + n_{l_{11}}\cdot\int_{T_r}^{T_l}\left(a_{11} + b_{11}\cdot T + c_{11}\cdot T^2 + d_{11}\cdot T^3\right)dT\end{aligned}$$

$$\Delta H_l = 0\,\frac{kJ}{day}$$

Energy of Output

$T_o = 309\,K$

$$\begin{aligned}\Delta H_o := {} & n_{o_1}\cdot\left[\int_{T_r}^{T_o}\left(a_1 + b_1\cdot T + c_1\cdot T^2 + d_1\cdot T^3\right)dT\right] + n_{o_2}\cdot\left[\int_{T_r}^{T_o}\left(a_2 + b_2\cdot T + c_2\cdot T^2 + d_2\cdot T^3\right)dT\right]\ldots\\ & + n_{o_3}\cdot\left[\int_{T_r}^{T_o}\left(a_3 + b_3\cdot T + c_3\cdot T^2 + d_3\cdot T^3\right)dT\right] + n_{o_4}\cdot\left[\int_{T_r}^{T_o}\left(a_4 + b_4\cdot T + c_4\cdot T^2 + d_4\cdot T^3\right)dT\right]\ldots\\ & + n_{o_5}\cdot\left[\int_{T_r}^{T_o}\left(a_5 + b_5\cdot T + c_5\cdot T^2 + d_5\cdot T^3\right)dT\right] + n_{o_6}\cdot\left[\int_{T_r}^{T_o}\left(a_6 + b_6\cdot T + c_6\cdot T^2 + d_6\cdot T^3\right)dT\right]\ldots\\ & + n_{o_7}\cdot\int_{T_r}^{T_o}\left(a_7 + b_7\cdot T + c_7\cdot T^2 + d_7\cdot T^3\right)dT + n_{o_8}\cdot\int_{T_r}^{T_o}\left(a_8 + b_8\cdot T + c_8\cdot T^2 + d_8\cdot T^3\right)dT\ldots\\ & + n_{o_9}\cdot\int_{T_r}^{T_o}\left(a_9 + b_9\cdot T + c_9\cdot T^2 + d_9\cdot T^3\right)dT + n_{o_{10}}\cdot\int_{T_r}^{T_o}\left(a_{10} + b_{10}\cdot T + c_{10}\cdot T^2 + d_{10}\cdot T^3\right)dT\ldots\\ & + n_{o_{11}}\cdot\int_{T_r}^{T_o}\left(a_{11} + b_{11}\cdot T + c_{11}\cdot T^2 + d_{11}\cdot T^3\right)dT\end{aligned}$$

$$\Delta H_o = 1.432\times 10^{7}\,\frac{kJ}{day}$$

Total energy out: $\Delta H_{out} := \Delta H_l + \Delta H_o$

$$\Delta H_{out} = 1.432 \times 10^7 \frac{kJ}{day}$$

Heat load: $\Delta H_6 := \Delta H_{out} - \Delta H_{in}$

$$\Delta H_6 = -9.46 \times 10^7 \frac{kJ}{day}$$

$Q_{cooler} := \Delta H_6$

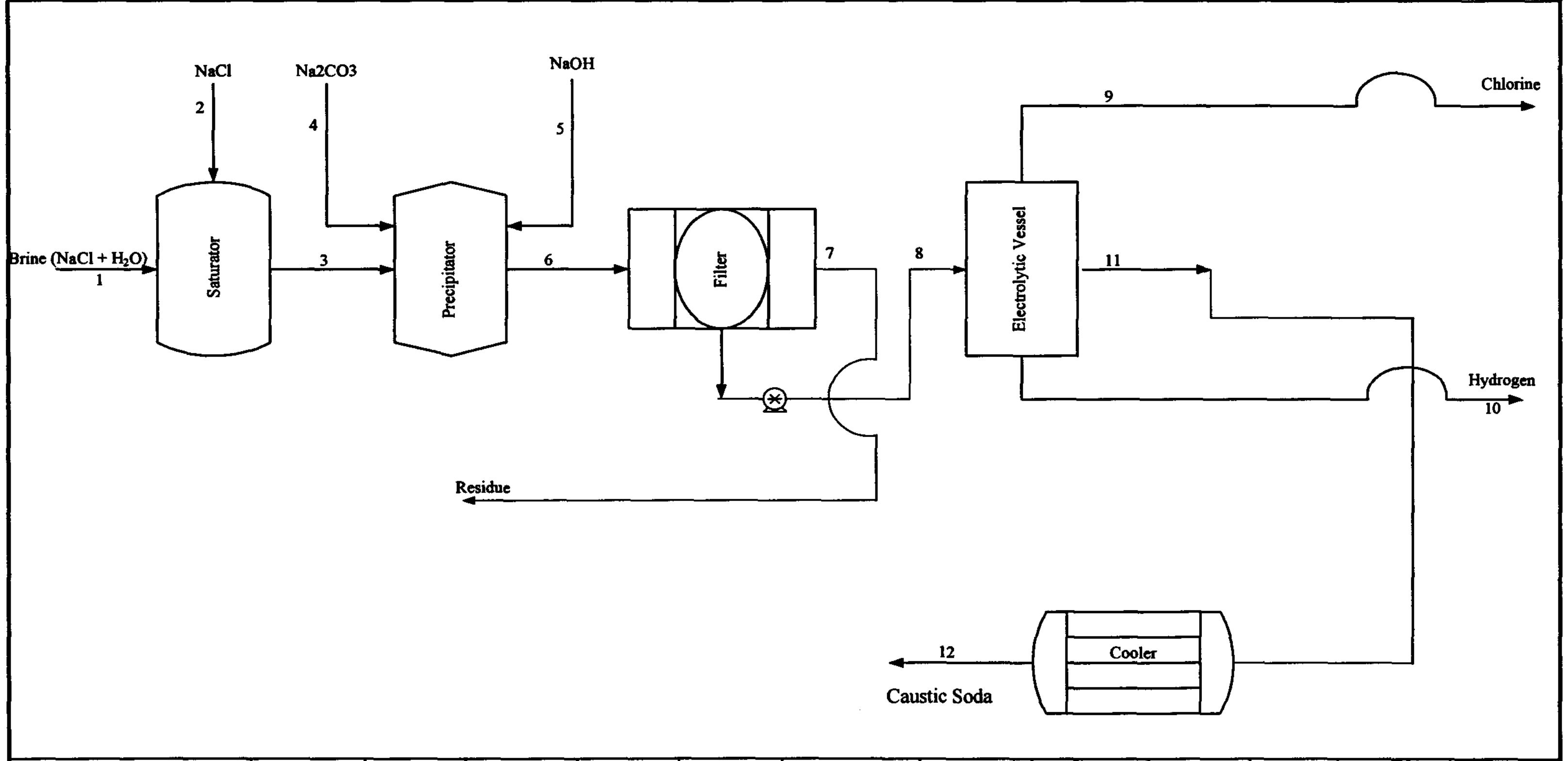
$$Q_{cooler} = -9.46 \times 10^7 \frac{kJ}{day}$$

CHAPTER FIVE

5.0 FLOW SHEET/DIAGRAM

5.1 FLOWSHEETING

GROUP B PLANT DESIGN	**Title: Caustic Soda** **Client: Chemical Engineering Department, FUT, Minna**	**Drawn By: Group B Plant Design** **Checked By: Professor K. R. Onifade**	**Date: October, 2006**



Flow No.	1	2	3	4	5	6	7	8	9	10	11	12
Component	Flows (kg/day)											
NaCl	891592.65	594395.10	1485987.75	0.00	0.00	1485987.75	0.00	1485987.75	0.00	0.00	0.00	0.00
H2O	1490560.02	0.00	1490560.02	0.00	0.00	1490560.02	0.00	1490560.02	0.00	0.00	0.00	0.00
Ca+	81284.80	0.00	81284.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg+	36578.16	0.00	36578.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na2CO3	0.00	0.00	0.00	215404.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NaOH	0.00	0.00	0.00	0.00	121927.20	0.00	0.00	0.00	0.00	0.00	1016060.00	1016060.00
CaCO3	0.00	0.00	0.00	0.00	0.00	203212.00	203212.00	0.00	0.00	0.00	0.00	0.00
Mg(OH)2	0.00	0.00	0.00	0.00	0.00	88397.22	88397.22	0.00	0.00	0.00	0.00	0.00
Cl2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	901753.25	0.00	901753.25	0.00
[illegible]	0.00	[illegible]	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00	25401.50	25401.50	0.00

CHAPTER SIX

6.0 DESIGN OF EQUIPMENT

molecular weights

Densities

$$\begin{pmatrix} NaCl \\ H_2O \\ Ca \\ Mg \\ Na_2CO_3 \\ NaOH \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \\ Na \end{pmatrix} \qquad mw := \begin{pmatrix} 58.5 \\ 18 \\ 40 \\ 24 \\ 106 \\ 40 \\ 100 \\ 58 \\ 71 \\ 2 \\ 23 \end{pmatrix} \cdot \frac{kg}{kmol} \qquad \rho := \begin{pmatrix} 2.16 \cdot 10^3 \\ 1.00 \cdot 10^3 \\ 1550 \\ 1740 \\ 2930 \\ 2.13 \cdot 10^3 \\ 2.53 \cdot 10^3 \\ 2400 \\ 1394.3056 \\ -311.9326 \\ 9.70 \cdot 10^2 \end{pmatrix} \cdot \frac{kg}{m^3}$$

6.1 Design of Saturator

Given the amount to be

$$\begin{pmatrix} NaCl \\ H_2O \\ Ca \\ Mg \\ Na_2CO_3 \\ NaOH \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \\ Na \end{pmatrix} \qquad n := \left[\begin{pmatrix} 15240.90 \\ 82808.89 \\ 2032.12 \\ 1524.09 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} + \begin{pmatrix} 10160.60 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \right] \cdot \frac{kmol}{day}$$

The average density is calculated as:

$$\rho_{av} := \frac{n}{\sum n} \cdot \rho$$

$$\rho_{av} = 1.284 \times 10^3 \frac{kg}{m^3}$$

The total mass of the components is calculated to be

$$M := \sum \overrightarrow{(n \cdot mw)} \qquad M = 1.13 \times 10^9 \frac{kg}{yr}$$

The volumes of the components are calculated using the relationship which is given as

$$\mathrm{Vol} := \frac{M}{\rho_{av}}$$

$$\mathrm{Vol} = 2.41 \times 10^{3}\,\frac{m^{3}}{day}$$

Given the clearance to be equal to $\mathrm{Allowance} := 10\% \cdot \mathrm{Vol}$

$$\mathrm{Allowance} = 241.049\,\frac{m^{3}}{day}$$

The actual volume of the saturator is then equal to

$$V_{saturator} := \mathrm{Vol} + \mathrm{Allowance}$$

$$V_{saturator} = 2.652 \times 10^{3}\,\frac{m^{3}}{day}$$

Mathematically, the volume of the saturator is given as

$$V_{saturator} = \pi \cdot R_{saturator}^{\;2} \cdot H_{saturator}$$

and

$$R_{saturator} = \frac{D_{saturator}}{2}$$

$$saturator = \pi \cdot \left(\frac{D_{saturator}}{2}\right)^{2} \cdot H_{saturator}$$

$$V_{saturator} = \pi \cdot \frac{D_{saturator}^{\;2}}{4} \cdot H_{saturator}$$

assuming that

$$\frac{H_{saturator}}{D_{saturator}} = k$$

then,

$$H_{saturator} = k \cdot D_{saturator}$$

substituting for H,

$$saturator = \pi \cdot \frac{D_{saturator}^{\;2}}{4} \cdot \left(k \cdot D_{saturator}\right)$$

$$4 \cdot saturator = k \cdot \pi \cdot D_{saturator}^{\;3}$$

$$D_{saturator}^{\;3} = \left(\frac{4 \cdot saturator}{k \cdot \pi}\right)$$

$$D_{saturator} = \left(\frac{4 \cdot V_{saturator}}{k \cdot \pi}\right)^{\frac{1}{3}}$$

Assuming that $k := 1.7$

$$D_{saturator} := \left(\frac{4 \cdot V_{saturator} \cdot hr}{k \cdot \pi}\right)^{\frac{1}{3}} \qquad D_{saturator} = 4.358\,m$$

$$H_{saturator} := k \cdot D_{saturator} \qquad H_{saturator} = 7.408\,m$$

The area is calculated to be

$$A_{saturator} := 2\pi \cdot \frac{D_{saturator}}{2} \cdot H_{saturator} + 2\pi \cdot \left(\frac{D_{saturator}}{2}\right)^2 \qquad A_{saturator} = 131.241\,m^2$$

6.2 Design of Precipitator

Given the amount to be

$$\begin{pmatrix} NaCl \\ H_2O \\ Ca \\ Mg \\ Na_2CO_3 \\ NaOH \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \\ Na \end{pmatrix} \qquad n := \left[\begin{pmatrix} 25401.50 \\ 82808.89 \\ 2032.12 \\ 1524.09 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} + \begin{pmatrix} 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 2032.12 \\ 3048.18 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{pmatrix}\right] \cdot \frac{kmol}{day}$$

The average density is calculated as:

$$\rho_{av} := \frac{n}{\sum n} \cdot \rho \qquad \rho_{av} = 1.334 \times 10^3 \frac{kg}{m^3}$$

The total mass of the components is calculated to be

$$M := \sum \overrightarrow{(n \cdot mw)} \qquad M = 1.253 \times 10^9 \frac{kg}{yr}$$

The volumes of the components are calculated using the relationship which is given as

$$\underline{Vol} := \frac{\underline{M}}{\underline{\rho_{av}}}$$

$$\underline{Vol} = 2.572 \times 10^{3}\,\frac{\underline{m}^{3}}{\underline{day}}$$

Given the clearance to be equal to $\underline{Allowance} := 10\underline{\%} \cdot \underline{Vol}$

$$\underline{Allowance} = 257.168\,\frac{\underline{m}^{3}}{\underline{day}}$$

The actual volume of the precipitator is then equal to

$$\underline{V_{precipitator}} := \underline{Vol} + \underline{Allowance}$$

$$\underline{V_{precipitator}} = 2.829 \times 10^{3}\,\frac{\underline{m}^{3}}{\underline{day}}$$

Mathematically, the volume of the precipitator is given as

$$\underline{V_{precipitator}} = \underline{\pi} \cdot \underline{R_{precipitator}}^{2} \cdot \underline{H_{precipitator}}$$

and

$$\underline{R_{precipitator}} = \frac{\underline{D_{precipitator}}}{2}$$

$$\underline{precipitator} = \underline{\pi} \cdot \left(\frac{\underline{D_{precipitator}}}{2}\right)^{2} \cdot \underline{H_{precipitator}}$$

$$\underline{V_{precipitator}} = \underline{\pi} \cdot \frac{\underline{D_{precipitator}}^{2}}{4} \cdot \underline{H_{precipitator}}$$

assuming that

$$\frac{\underline{H_{precipitator}}}{\underline{D_{precipitator}}} = \underline{k}$$

then,

$$\underline{H_{precipitator}} = \underline{k} \cdot \underline{D_{precipitator}}$$

substituting for H,

$$\underline{precipitator} = \underline{\pi} \cdot \frac{\underline{D_{precipitator}}^{2}}{4} \cdot \left(\underline{k} \cdot \underline{D_{precipitator}}\right)$$

$$4 \cdot \underline{precipitator} = \underline{k} \cdot \underline{\pi} \cdot \underline{D_{precipitator}}^{3}$$

$$\underline{D_{precipitator}}^{3} = \left(\frac{4 \cdot \underline{precipitator}}{\underline{k} \cdot \underline{\pi}}\right)$$

$$D_{precipitator} = \left(\frac{4 \cdot V_{precipitator}}{k \cdot \pi}\right)^{\frac{1}{3}}$$

Assuming that $k := 1.5$

$$D_{precipitator} := \left(\frac{4 \cdot V_{precipitator} \cdot hr}{k \cdot \pi}\right)^{\frac{1}{3}}$$

$D_{precipitator} = 4.642\,m$

$$H_{precipitator} := k \cdot D_{precipitator}$$

$H_{precipitator} = 6.964\,m$

The area is calculated to be

$$A_{precipitator} := 2\pi \cdot \frac{D_{precipitator}}{2} \cdot H_{precipitator} + 2\pi \cdot \left(\frac{D_{precipitator}}{2}\right)^2$$

$A_{precipitator} = 135.412\,m^2$

6.3 Design of Filter

Type: Rotary drum

Material: Steel

Equipment physical factors:

maximum effective submergence = 28% (i.e., $sub_{max} := 28\%$)

maximum portion of filter cycle available for dewatering = 45% (i.e., $cyc_{max} := 45\%$)

Scale up factors on rate = 0.5 (i.e., $suf_{rate} := 0.5$)

Scale up factors on area = 0.5 (i.e., $suf_{area} := 0.5$)

Scale up factors on discharge = 0.6 (i.e., $suf_{discharge} := 0.6$)

Scale up factor for the plant, $suf := 1016.01$

Choosing solid thickness to be 1.5cm

From Fig. 18-98 of Perry, dry cake/(m^2 rev), (i.e. $W_c := 291609.22 \frac{kg}{m^2 \cdot rev}$)

From Fig. 18-99, form time, $f := 1.50\,min$

Using simplified moisture content correlating factor in Fig. 18-102, $d/W_c = 0.04$ at average moisture content of $moist := 35\%$)

Dry time is therefore equal to

$\text{dry\_time} := 0.05 \cdot \frac{m^2}{kg} \cdot W_c \cdot min$ $\qquad$ $\text{dry\_time} = 1.458 \times 10^4\, min$

The cycle time (CT) both on the basis of form time and dry time to determine is controlling is:

$$CT_{form} := \frac{f}{sub_{max}} \qquad CT_{form} = 5.357 \frac{min}{rev}$$

$$CT_{dry} := \frac{\text{dry\_time}}{cyc_{max}} \qquad CT_{dry} = 3.24 \times 10^4 \frac{min}{rev}$$

Therefore, residue formation is controlling and a cycle time of $CT_{form} = 5.357 \frac{min}{rev}$ must be used

Overall scale up factor based on the factors presented previously is calculated to be

$$suf_{overall} := suf_{rate} \cdot suf_{area} \cdot suf_{discharge} \qquad suf_{overall} = 0.15$$

Design filtering rate is therefore,

$$\text{filtering\_rate} := \left(\frac{W_c}{CT_{form}}\right) \cdot \left(suf_{overall}\right) \qquad \text{filtering\_rate} = 4.899 \times 10^5 \frac{kg}{hr \cdot m^2}$$

Area required to filter $\qquad m_{filter} := 3431742.65 \cdot \frac{kg}{day}$

$$A_{filter} := \frac{m_{filter}}{\text{filtering\_rate}} \qquad A_{filter} = 0.292\, m^2$$

Dry time is assumed to be 45% of cycle time. That is,

$$\text{dry\_time} := 35\% \cdot CT_{form} \qquad \text{dry\_time} = 1.875\, min$$

6.4 Design of Electrolytic Cell

Given the amount to be

$$\begin{pmatrix} NaCl \\ H_2O \\ Ca \\ Mg \\ Na_2CO_3 \\ NaOH \\ CaCO_3 \\ Mg(OH)_2 \\ Cl_2 \\ H_2 \end{pmatrix} \qquad n := \begin{pmatrix} 25401.50 \\ 82808.89 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \\ 0.00 \end{pmatrix} \cdot \frac{kmol}{day}$$

$\left(\; Na \; \right)$

The average density is calculated as:

$$\rho_{av} := \frac{n}{\sum n} \cdot \rho$$

$$\rho_{av} = 1.272 \times 10^{3} \frac{kg}{m^{3}}$$

The total mass of the components is calculated to be

$$M := \sum \overrightarrow{(n \cdot mw)} \qquad M = 1.087 \times 10^{9} \frac{kg}{yr}$$

The volumes of the components are calculated using the relationship which is given as

$$Vol := \frac{M}{\rho_{av}}$$

$$Vol = 2.34 \times 10^{3} \frac{m^{3}}{day}$$

Given the clearance to be equal to $Allowance := 10\% \cdot Vol$

$$Allowance = 233.95 \frac{m^{3}}{day}$$

The actual volume of the electrolytic cell is then equal to

$$V_{electrolytic\_cell} := Vol + Allowance$$

$$V_{electrolytic\_cell} = 2.573 \times 10^{3} \frac{m^{3}}{day}$$

Mathematically, the volume of the electrolytic cell is given as

$$V_{electrolytic\_cell} = \pi \cdot R_{electrolytic\_cell}^{2} \cdot H_{electrolytic\_cell}$$

and

$$R_{electrolytic\_cell} = \frac{D_{electrolytic\_cell}}{2}$$

$$electrolytic\_cell = \pi \cdot \left(\frac{D_{electrolytic\_cell}}{2} \right)^{2} \cdot H_{electrolytic\_cell}$$

$$V_{electrolytic\_cell} = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{4} \cdot H_{electrolytic\_cell}$$

assuming that

$$\frac{H_{electrolytic\_cell}}{D_{electrolytic\_cell}} = k$$

then,

$$H_{electrolytic\_cell} = k \cdot D_{electrolytic\_cell}$$

substituting for H,

$$electrolytic\_cell = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{4} \cdot \left(k \cdot D_{electrolytic\_cell}\right)$$

$$4 \cdot electrolytic\_cell = k \cdot \pi \cdot D_{electrolytic\_cell}^{3}$$

$$D_{electrolytic\_cell}^{3} = \left(\frac{4 \cdot electrolytic\_cell}{k \cdot \pi}\right)$$

$$D_{electrolytic\_cell} = \left(\frac{4 \cdot V_{electrolytic\_cell}}{k \cdot \pi}\right)^{\frac{1}{3}}$$

Assuming that $k := 1.25$

$$D_{electrolytic\_cell} := \left(\frac{4 \cdot V_{electrolytic\_cell} \cdot hr}{k \cdot \pi}\right)^{\frac{1}{3}} \qquad D_{electrolytic\_cell} = 4.78\,m$$

$$H_{electrolytic\_cell} := k \cdot D_{electrolytic\_cell}$$

$$H_{electrolytic\_cell} = 5.975\,m$$

The area is calculated to be

$$A_{electrolytic\_cell} := 2\pi \cdot \frac{D_{electrolytic\_cell}}{2} \cdot H_{electrolytic\_cell} + 2\pi \cdot \left(\frac{D_{electrolytic\_cell}}{2}\right)^{2}$$

$$A_{electrolytic\_cell} = 125.62\,m^{2}$$

6.5 Design of Cooler

Mass of caustic soda to be cooled, $m_a := 1016060 \cdot \frac{kg}{day}$

Given:

The fluids are:

Water:

Inlet temperature, $T_{in\_1} := (25 + 273) \cdot K$

Outlet temperature, $T_{out\_1} := (40 + 273) \cdot K$

caustic soda:

Inlet temperature, $T_{in\_2} := (112 + 273) \cdot K$

Outlet temperature, $T_{out\_2} := (30 + 273) \cdot K$

The caustic soda is cooled from a high temperature to a lower temperature in a Shell and Tube Type Heat Exchanger. Water which enters the heat exchanger at room temperature is heated to $T_{out\_1} = 313\,K$ and comes out of the system.

Bulk temperature of water: $T_{bw} := \dfrac{T_{in\_1} + T_{out\_1}}{2}$ $\qquad T_{bw} = 305.5\,K$

Bulk temperature of the caustic soda: $T_{ba} := \dfrac{T_{in\_2} + T_{out\_2}}{2}$ $\qquad T_{ba} = 344\,K$

Properties of components at bulk temperature:

$$\begin{pmatrix} T_b \\ \rho \\ C_p \\ K \\ \mu \end{pmatrix} = \begin{pmatrix} \text{"Bulk temperature"} \\ \text{Density} \\ \text{"Specific heat capacity"} \\ \text{"Thermal conductivity"} \\ \text{Viscosity} \end{pmatrix}$$

:Water :

$$\begin{pmatrix} T_{bw} \\ \rho_w \\ C_{pw} \\ K_w \\ \mu_w \end{pmatrix} := \begin{pmatrix} \dfrac{T_{in\_1} + T_{out\_1}}{2} \\ 994.86 \cdot \dfrac{kg}{m^3} \\ 4.184 \cdot \dfrac{kJ}{kg \cdot K} \\ 0.623 \cdot \dfrac{W}{m \cdot K} \\ 0.8 \cdot cP \end{pmatrix}$$

caustic soda:

$$\begin{pmatrix} T_{ba} \\ \rho_a \\ C_{pa} \\ K_a \\ \mu_a \end{pmatrix} := \begin{pmatrix} \dfrac{T_{in\_2} + T_{out\_2}}{2} \\ 1950 \cdot \dfrac{kg}{m^3} \\ 1.5435 \cdot \dfrac{kJ}{kg \cdot K} \\ 0.555 \cdot \dfrac{W}{m \cdot K} \end{pmatrix}$$

1. Heat load:

The heat load on teh heat exchanger is calculated from the energy balance to be,

$$Q_{cooler} = -9.46 \times 10^{7} \frac{kJ}{day}$$

Mass of water requuired is calculated as

$$m_w := \frac{|Q_{cooler}|}{C_{pw} \cdot (T_{out\_1} - T_{in\_1})}$$

$$m_w = 17.447 \frac{kg}{s}$$

2. Log Mean Temperature Difference, LMTD:

Temperatures	**Inlet**	**Outlet**
Water	$T_{in\_1} = 298\,K$	$T_{out\_1} = 313\,K$
caustic soda	$T_{in\_2} = 385\,K$	$T_{out\_2} = 303\,K$

Temperature Difference

$$LMTD := \frac{(T_{in\_2} - T_{out\_1}) - (T_{out\_2} - T_{in\_1})}{\ln\left[\frac{(T_{in\_2} - T_{out\_1})}{(T_{out\_2} - T_{in\_1})}\right]}$$

$$LMTD = 25.12\,K$$

$$R := \frac{T_{in\_2} - T_{out\_2}}{T_{out\_1} - T_{in\_1}}$$

$$R = 5.467$$

$$S := \frac{T_{out\_1} - T_{in\_1}}{T_{in\_2} - T_{in\_1}}$$

$$S = 0.172$$

Taking the LMTD correction factor to be, $F_T := 0.834$

$$LMTD_c := 0.834 \cdot LMTD$$

$$LMTD_c = 20.95\,K$$

3. Routing:

Shell side = caustic soda

Tube side = Cooling Water

4. Determination of Area:

Assuming $U_o := 630 \cdot \frac{W}{m^2 \cdot K}$

Then, area can be calculated as,

$$A_{cooler} := \frac{|Q_{cooler}|}{U_o \cdot LMTD_c}$$

$A_{cooler} = 82.962\,m^2$

5. Choice of Tubes:

From the tubing characteristics as given in Perry, the following dimensions of the tube are chosen,

1 inch outer diameter tubes with 1.25 inch triangular pitch, 16 BWG

Outer diameter, $D_o := 1.0 \cdot in$ $D_o = 0.025\,m$

Inner diameter, $D_i := 0.87 \cdot in$ $D_i = 0.022\,m$

Pitch, $P := 31.75 \cdot mm$ $P = 0.032\,m$

Assuming the tube to be of length, $L_t := 6 \cdot m$

Number of tubes, $N_t := \frac{A_{cooler}}{\pi \cdot D_o \cdot L_t}$

$N_t = 173$

6. Correction of Heat Transfer Area:

From the tube count table, we have for TEMA P or S (1 - 4 exchanger)

1 Shell Pass and 4 Tube Passes ($N_p := 4$)

Diameter of shell, $D_s := 635 \cdot mm$

Number of tubes, $N_t := N_t - 2.678$

Corrected heat transfer area, $A_{corrected} := \pi \cdot D_o \cdot L_t \cdot N_t$

$A_{corrected} = 81.68\,m^2$

Corrected heat transfer coefficient, U_{oc}

Corrected heat transfer coefficient, U_{oc}

$$U_{oc} := \frac{|Q_{cooler}|}{A_{corrected} \cdot LMTD_c} \qquad U_{oc} = 639.889 \frac{W}{m^2 \cdot K}$$

7. Calculation of Inside Heat Transfer Coefficient:

Area of the tubes, $A_t := \frac{\left(\pi \cdot D_i^2 \cdot N_t\right)}{4 \cdot N_p}$ $\qquad A_t = 0.016\,m^2$

Mass velocity, $G_s := \frac{m_w}{A_t}$ $\qquad G_s = 1.067 \times 10^3 \frac{kg}{m^2 s}$

Velocity inside the tubes, $V_t := \frac{m_w}{\rho_w \cdot A_t}$ $\qquad V_t = 1.072 \frac{m}{s}$

The above velocity is within the acceptable limits.

Reynolds Number, $N_{Re} := \frac{G_s \cdot D_i}{\mu_w}$ $\qquad N_{Re} = 2.946 \times 10^4$

Prandtl Number, $N_{Pr} := \frac{\mu_w \cdot C_{pw}}{K_w}$ $\qquad N_{Pr} = 5.373$

Given that,

$$\frac{h_i \cdot D_i}{K} = j_H \cdot N_{Re} \cdot N_{Pr}^{\frac{1}{3}}$$

$$h_i = \frac{j_H \cdot N_{Re} \cdot N_{Pr}^{\frac{1}{3}} \cdot K}{D_i}$$

Taking $j_H := 0.0036$

$$h_i := \frac{j_H \cdot N_{Re} \cdot N_{Pr}^{\frac{1}{3}} \cdot K_w}{D_i} \qquad h_i = 5.237 \times 10^3 \frac{W}{m^2 \cdot K}$$

8. Calculation of Outside Heat Transfer Coefficient:

Length of tube, $L_t = 6\,m$

Baffle spacing, $L_s := 0.266 \cdot D_s$

$L_s = 0.169\,\mathrm{m}$

Number of baffles, $N_b := \dfrac{L_t}{L_s} - 1$

$N_b = 35$

$$S_m := \frac{L_s \cdot (P - D_o) \cdot D_s}{P}$$

$S_m = 0.021\,\mathrm{m}^2$

$$V_s := \frac{m_a}{S_m \cdot \rho_a}$$

$V_s = 0.281\,\dfrac{\mathrm{m}}{\mathrm{s}}$

The above value of velocity is also in the range of acceptable limits.

Equivalent Diameter, $D_e := 1.1 \cdot \dfrac{\left(P^2 - 0.917 \cdot D_o^{\,2}\right)}{D_o}$

$D_e = 0.018\,\mathrm{m}$

Reynolds Number, $N_{Re} := \dfrac{D_e \cdot G_s}{\mu_a}$

$N_{Re} = 2.776 \times 10^3$

$$N_{Pr} := \frac{\mu_a \cdot C_{pa}}{K_a}$$

$N_{Pr} = 19.273$

From graph, $j_H := 0.019$

$$\frac{h_o \cdot D_e}{K} = j_H \cdot N_{Re} \cdot N_{Pr}^{\frac{1}{3}} \cdot \left(\frac{\mu_a}{\mu_w}\right)^{0.14}$$

$$h_o := j_H \cdot N_{Re} \cdot N_{Pr}^{\frac{1}{3}} \cdot \left(\frac{\mu_a}{\mu_w}\right)^{0.14} \cdot \frac{K_a}{D_e}$$

$h_o = 5.887 \times 10^3\,\dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{D_o}{D_i} \cdot \frac{1}{h_i} + \frac{D_o \cdot \ln\left(\frac{D_o}{D_i}\right)}{2 \cdot K_w} + \frac{1}{h_{od}} + \frac{D_o}{D_i} \cdot \frac{1}{h_{id}}$$

where

Inside film fluid coefficient, $h_i := 8000 \cdot \dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$

[illegible] W

Inside dirt coefficient, $h_{id} := 5000 \cdot \frac{}{m^2 \cdot K}$

Outside dirt coefficient, $h_{od} := 3000 \cdot \frac{W}{m^2 \cdot K}$

$$U_o := \left(\frac{1}{h_o} + \frac{D_o}{D_i} \cdot \frac{1}{h_i} + \frac{D_o \cdot \ln\left(\frac{D_o}{D_i}\right)}{2 \cdot K_w} + \frac{1}{h_{od}} + \frac{D_o}{D_i} \cdot \frac{1}{h_{id}} \right)^{-1}$$

$U_o = 269.132 \frac{W}{m^2 \cdot K}$

9. Pressure Drop Calculation:

For the tube side,

Friction factor, $f := 0.079 \cdot N_{Re}^{-0.25}$

$f = 0.011$

$$\Delta P_L := \frac{4 \cdot f \cdot L_t \cdot V_t^2 \cdot \rho_w}{2 \cdot D_i}$$

$\Delta P_L = 6.758 \times 10^3 \frac{N}{m^2}$

$$\Delta P_t := 2.5 \cdot \rho_w \cdot \frac{V_t^2}{2}$$

$\Delta P_t = 1.429 \times 10^3 \frac{N}{m^2}$

$$\Delta P_{tube} := N_p \cdot (\Delta P_L + \Delta P_t)$$

$\Delta P_{tube} = 3.275 \times 10^4 \frac{N}{m^2}$

For shell side,

Pressur drop in the cross flow section:

$$\Delta P_c = \left[\frac{\left(b \cdot f_k \cdot W'^2 \cdot N_c\right)}{\rho_w \cdot S_m^2} \right] \cdot \frac{\mu_w}{\mu_a^{0.14}}$$

$N_{Re} = 2.776 \times 10^3$

$b := 2 \cdot 10^{-3}$

Baffle cut, $L_c := 25\% \cdot D_s$

$P_p := \frac{\sqrt{3}}{2} \cdot P$

$P_p = 0.027 m$

$f_k := 0.25$

$N \;:= D \cdot \frac{\left[1 - 2 \cdot \left(\frac{L_c}{D_s}\right)\right]}{}$

$_c := {}_s \qquad P_p$ $\qquad N_c = 11.547$

$$\Delta P_c := \left[\frac{\left(b \cdot f_k \cdot m_a^{\,2} \cdot N_c\right)}{\rho_w \cdot S_m^{\,2}}\right] \cdot \left(\frac{\mu_w}{\mu_a}\right)^{0.14} \qquad \Delta P_c = 1.289\,\frac{N}{m^2}$$

Pressure drop in end zones:

$$\Delta P_e = \Delta P_c \cdot \left(1 + \frac{N_{cw}}{N_c}\right)$$

Number of cross flow rows in each window, $N_{cw} := 0.8 \cdot \frac{L_c}{P_p}$ $\qquad N_{cw} = 4.619$

$$\Delta P_e := \Delta P_c \cdot \left(1 + \frac{N_{cw}}{N_c}\right) \qquad \Delta P_e = 1.805\,\frac{N}{m^2}$$

Pressure drop in window zones:

$$\Delta P_w = \frac{b \cdot m_a^{\,2} \cdot \left(2 \cdot 0.6 \cdot N_{cw}\right)}{S_m \cdot S_w \cdot \rho_a}$$

$b := 5 \cdot 10^{-4}$

Area for flow through window zone, $S_w = S_{wg} - S_{wt}$

Gross window area, $S_{wg} := 100 \cdot in^2$ $\qquad S_{wg} = 0.065\,m^2$

Area occupied by tubes, $S_{wt} = \frac{N_t}{8} \cdot \left(1 - F_c\right) \cdot \pi \cdot D_o^{\,2}$

From the graph in Perry, Fig. 10-16, Pg. 10-28,

$F_c := 0.65$

$$S_{wt} := \frac{N_t}{8} \cdot \left(1 - F_c\right) \cdot \pi \cdot D_o^{\,2}$$

$S_{wt} = 0.015\,m^2$

$S_w := S_{wg} - S_{wt}$ $\qquad S_w = 0.049\,m^2$

$$\Delta P_w := \frac{b \cdot m_a^{\,2} \cdot \left(2 \cdot 0.6 \cdot N_{cw}\right)}{S_m \cdot S_w \cdot \rho_a} \qquad \Delta P_w = 0.186\,\frac{N}{}$$

$- \qquad \mathrm{m}^2$

Therefore, the total pressur drop on the shell side is calculated by the following relation:

$$\Delta P_{shell} := 2 \cdot \Delta P_e + (N_b - 1) \cdot \Delta P_c + N_b \cdot \Delta P_w$$

$$\Delta P_{shell} = 53.228 \frac{N}{m^2}$$

Summary of process design for heat exchanger

Mass flow rate of caustic soda, $m_a = 11.76 \frac{kg}{s}$

Mass flow rate of water, $m_w = 17.447 \frac{kg}{s}$

Shell outer diameter, $D_s = 0.635\,m$

Number of tubes, $N_t = 170.6$

Tube outer diameter, $D_o = 0.025\,m$

Pitch, $P = 0.032\,m$

Tube length, $L_t = 6\,m$

Shell side pressure drop, $\Delta P_{shell} = 53.228 \frac{N}{m^2}$

Tube side pressure drop, $\Delta P_{tube} = 3.275 \times 10^4 \frac{N}{m^2}$

CHAPTER SEVEN

7.0 EQUIPMENT OPTIMIZATION

7.1 Optimization of electrolytic cell

In optimizing, the first step is clearly to define the objective; that is, the criterion to be used to judge the performance of the system. In engineering design, the objective of optimizing any equipment must be an economical one. This is because for any chemical plant set up, the primary objective is to maximize the profit.This can be approached based on the fact that, in order to minimize cost of construction, the dimensions (Volume and Area) of the equipment must be kept at minimum. For the electrolytic cell, the total surface area is given as

$$A_{electrolytic\_cell} = 2 \cdot \pi \cdot R_{electrolytic\_cell}^{2} + 2 \cdot \pi \cdot R_{electrolytic\_cell} \cdot H_{electrolytic\_cell}$$

and $R_{electrolytic\_cell} = \frac{D_{electrolytic\_cell}}{2}$

where $R_{electrolytic\_cell}$ = "radius of the electrolytic_cell tube"

$D_{electrolytic\_cell}$ = "diameter of the electrolytic_cell"

$H_{electrolytic\_cell}$ = "height of the electrolytic_cell"

π = "pie, a constant"

So, the formula becomes

$$A_{electrolytic\_cell} = 2 \cdot \pi \cdot \left(\frac{D_{electrolytic\_cell}}{2}\right)^{2} + 2\pi \cdot \frac{D_{electrolytic\_cell}}{2} \cdot H_{electrolytic\_cell}$$

$$A_{electrolytic\_cell} = 2 \cdot \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{4} + 2 \cdot \pi \cdot \frac{D_{electrolytic\_cell}}{2} \cdot H_{electrolytic\_cell}$$

$$A_{electrolytic\_cell} = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot D_{electrolytic\_cell} \cdot H_{electrolytic\_cell}$$

At this point, it is clear that area of the equipment is a function of the diameter and length of the equipment. Mathematically,

$$A_{electrolytic\_cell} = f\left(D_{electrolytic\_cell}, H_{electrolytic\_cell}\right)$$

where the objective function is

$$A_{electrolytic\_cell} = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot D_{electrolytic\_cell} \cdot H_{electrolytic\_cell}$$

and the constraints are

$$D = D_{minimum} \quad \text{and} \quad H = H_{minimum}$$

so that the equation of $A_{electrolytic\_cell}$ becomes

$$f(D_{electrolytic\_cell}, H_{electrolytic\_cell}) = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot D_{electrolytic\_cell} \cdot H_{electrolytic\_cell}$$

Noting that the volume of the equiupment is given as

$$V_{electrolytic\_cell} = \pi \cdot R_{electrolytic\_cell}^{2} \cdot H_{electrolytic\_cell}$$

with $R_{electrolytic\_cell} = \frac{D_{electrolytic\_cell}}{2}$

$$V_{electrolytic\_cell} = \pi \cdot \left(\frac{D_{electrolytic\_cell}}{2}\right)^{2} \cdot H_{electrolytic\_cell}$$

$$V_{electrolytic\_cell} = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{4} \cdot H_{electrolytic\_cell}$$

Making the height of the equipment the subject of the formula in the above equation,

$$H_{electrolytic\_cell} = \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot D_{electrolytic\_cell}^{2}}$$

So,

$$f(D_{electrolytic\_cell}, H_{electrolytic\_cell}) = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot D_{electrolytic\_cell} \cdot \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot D_{electrolytic\_cell}^{2}}$$

Simplifying,

$$f(d_{electrolytic\_cell}, h_{electrolytic\_cell}) = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot D_{electrolytic\_cell}}$$

It can now be observed from the above equation that the area is a function of the diameter if the volume is kept constant.

$$f\left(D_{electrolytic\_cell}\right) = \pi \cdot \frac{D_{electrolytic\_cell}^{2}}{2} + \pi \cdot \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot D_{electrolytic\_cell}}$$

Differentiating the above equation yields,

$$\frac{d}{d\left(D_{electrolytic\_cell}\right)} f\left(D_{electrolytic\_cell}\right) = \pi \cdot D_{electrolytic\_cell} - \frac{4}{D_{electrolytic\_cell}^{2}} \cdot V_{electrolytic\_cell}$$

At optimum point, the derivative is equated to zero. That is,

$$\frac{d}{dd_{electrolytic\_cell}} f\left(D_{electrolytic\_cell}\right) = \pi \cdot D_{electrolytic\_cell} - \frac{4}{D_{electrolytic\_cell}^{2}} \cdot V_{electrolytic\_cell} = 0$$

Taking the last two expressions,

$$\pi \cdot D_{electrolytic\_cell} - \frac{4}{D_{electrolytic\_cell}^{2}} \cdot V_{electrolytic\_cell} = 0$$

$$\pi \cdot D_{electrolytic\_cell} = \frac{4}{D_{electrolytic\_cell}^{2}} \cdot V_{electrolytic\_cell}$$

$$D_{electrolytic\_cell}^{2} \cdot D_{electrolytic\_cell} = \frac{4 \cdot V_{electrolytic\_cell}}{\pi}$$

$$D_{electrolytic\_cell}^{3} = \frac{4 \cdot V_{electrolytic\_cell}}{\pi}$$

$$D_{electrolytic\_cell} = \sqrt[3]{\frac{4 \cdot V_{electrolytic\_cell}}{\pi}}$$

The above expression is now the optimized diameter of the equipment.

From,

$$H_{electrolytic\_cell} = \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot D_{electrolytic\_cell}^{2}}$$

Substituting for $D_{electrolytic\ cell}$ in this expression yields

$$H_{electrolytic\_cell} = \frac{4 \cdot V_{electrolytic\_cell}}{\pi \cdot \left(\sqrt[3]{\frac{4 \cdot V_{electrolytic\_cell}}{\pi}}\right)^2}$$

Simplifying,

$$H_{electrolytic\_cell} = \frac{V_{electrolytic\_cell}^{\left(\frac{1}{3}\right)}}{\pi^{\left(\frac{1}{3}\right)}} \cdot \sqrt[3]{2^2}$$

Numerically, with

$$V_{electrolytic\_cell} = 2.573 \times 10^3 \frac{m^3}{day}$$

$$D_{electrolytic\_cell} := \sqrt[3]{\frac{4 \cdot V_{electrolytic\_cell} \cdot hr}{\pi}} \qquad D_{electrolytic\_cell} = 5.149\,m$$

$$H_{electrolytic\_cell} := \frac{\left(V_{electrolytic\_cell} \cdot hr\right)^{\left(\frac{1}{3}\right)}}{\pi^{\left(\frac{1}{3}\right)}} \cdot \sqrt[3]{2^2} \qquad H_{electrolytic\_cell} = 5.149\,m$$

It, therefore, means that the optimum diameter and height of the equipment are $D_{electrolytic\_cell} = 5.149\,m$ and $H_{electrolytic\_cell} = 5.149\,m$.

CHAPTER EIGHT

8.0 SAFETY AND QUALITY CONTROL

8.1 Safety

Safety is an area of engineering and public health that deals with the protection of workers' health, through control of the work environment to reduce or eliminate hazards. Industrial accidents and unsafe working conditions can result in temporary or permanent injury, illness, or even death. They also take a toll in reduced efficiency and loss of productivity. (Encarta, 2004)

8.1.1 General Safety Rules

Follow relevant instructions

a) Before attempting to operate the plant, all relevant manufacturers' instructions and local regulations should be understood and implemented.

b) It is irresponsible and dangerous to misuse equipment or ignore instructions, regulations or warnings.

c) The specified maximum operating conditions must not be exceeded. (Odigure, 1998)

Operation

a) It must be ensured that all staff must be fully aware of the potential hazards when the plant is being operated.

b) Serious injury can result from touching apparently stationary equipment or rotating belt.

c) No metallic object should be allowed into the plant. Otherwise, the gear motor of the affected conveyor must be set in the reverse direction and the entrained materials should be discharged. (Odigure, 1998)

Maintenance

a) A badly maintained plant is a potential hazard. It must be ensured that competent members of staff is responsible for organizing maintenance and repairs on a planned basis.

b) Faulty equipment must be permitted to be operated. Repairs must be carried out competently and the operation must be checked. (Odigure, 1998)

Using electricity

a) At least once a month, the electrical cables should be checked to ensure that they are operating normally.

b) Electricity is the commonest cause of accidents in the factory, it must be respected.

c) It must be ensured that electricity supply has been disconnected from the equipment before attempting repairs or adjustment.

d) It must be known that water and electricity are not compatible and can cause serious injury if they come into contact.

e) The plant must always be disconnected from electricity when not in use. (Odigure, 1998)

Avoiding fire or explosion

a) It must be ensured that the factory is provided with adequate fire extinguishers appropriate to the potential dangers.

b) It must be known that empty vessels having inflammable liquids can contain vapours and explode if ignited.

Handling poisons or toxic materials

a) Food must not be allowed to be brought into or consumed in the factory.

b) Smoking should not be allowed in the factory premises. Notices should be so displayed and enforced. (Odigure, 1998)

Avoiding cuts and burns

a) Care must be taken when handling sharp edged components. Undue force must not be exerted on glass or fragile items.

b) Hot surfaces cannot, in most cases, be totally shielded and can produce severe burns even when not "visibly hot". Common sense must be used always!

Eye protection

a) Facilities for eye irritation should always be available

Ear protection

a) Ear protectors must be worn when operating the plant.

Guard and safety devices

a) Guards and safety devices must be installed on the plant to protect the operators. The equipment must not be operated with such devices removed.

b) Safety gauges, cut-out and other safety devices must be set to protect the equipment. Interference with these devices may create a potential hazard.

c) It is impossible to guard the operator against all contingencies. Common sense muse be used.

d) Before starting a machine, it must be ensured that the members of staff are aware of how it (the machine) should be stopped in an emergency. (Odigure, 1998)

First aid

a) It is essential that first aid equipment is available and that the supervisor knows how to use it.

b) A notice giving details of a proficient first aider should be prominently displayed. (Odigure, 1998)

8.2 Quality Control

Quality simply means “fitness for use”. But, according to the International Standard Organisation (ISO), quality is defined as the totality of the characteristics of an entity that bear on its ability to satisfy stated and intended needs. It is more costly to exceed a specification than to meet it. Therefore, there is the need to get quality goal or target for effective quality control.

Maintaining product quality in accordance with acceptable standard has been a major role for industrial instrumentation since its inception decades ago. With the ever-increasing interest in speeding up production, one becomes aware of the fact that rejectable as well as acceptable products can be produced at high rates.

8.2.1 Quality assurance

Quality assurance is defined by ISO as all the planned and systematic activities implemented within the quality system and demonstration is needed to provide adequate confidence on entity will fulfil requirement for quality.

8.2.1.1 Principles of quality assurance

The principles of quality assurance include the following:

i. Management involvements and objective (management) involvement is very essential to ensure quality.

ii. Programming and planning.

iii. Application of quality control principles.

iv. Design and specification control.

v. Purchasing control and vendor appraisal.

vi. Production control.

vii. Marketing and service quality functions.

viii. Proper documentation.

ix. Non-conformance control.

x. Remedial action.

xi. Defect and failure analysis.

8.2.1.2 Quality management

Quality management involves all activities of the overall management functions that determine the quality policy, objective and responsibilities and implement then by means, such as quality planning control assurance and improvement within the quality system. Responsibility of quality lies at all level of all. To successfully implement quality management, the organisation structure, procedure process and resources are requisite.

CHAPTER NINE

9.0 PROCESS CONTROL AND INSTRUMENTATION

It is proposed that most of the plant equipments in this plant are to be operated using automatic control with the indicating instruments being located in a control room. This is the general practice for a plant of this type which is not labour intensive. With the exception of the reactor system, the plant operates at atmospheric pressure and therefore the process control and instrumentation will be based upon temperature, flow and level measurements. Measurements of these parameters will be made using thermocouples, orifice plates and float type indicators respectively. (Austin & Jeffrey, 1991)

9.1 Types of control instruments

The control instruments are of four major categories

a) Temperature controllers (TC)
b) Pressure controller (PC)
c) Flow controller (FC)
d) Level controller (LC)

9.2 Control Mechanism

The pneumatic control hardware is recommended for this process it will be powered by instrument air supplies.

The control mechanism for this process consist of a sensor to detect the process variables; a transmitter to convert the sensor into an equivalent "signal" a controller that compares this process signal with a desired set point value and produces an appropriate controller output signal and a final control element (pneumatic activator) tat changes the manipulated variable with the use of a mechanical action.

9.3 Control Sensors

The devices to be used for the on-line measurement of the process variables are:

1) Flow sensor: The orifice meter can be employed in the process since it is simple and of low cost.
2) Temperature sensor: The recommended temperature sensors are resistance thermometer detectors (RTDS) and Thermocouples. The 100v pt (-2000C to 850C) and type N (0-13000) are both sufficient for RTDS and thermocouples respectively.
3) Pressure sensors: Bourdon – Tube pressure gauge can be used.
4) Level sensor: float activated devices are sufficient.

Alarms are to be employed to alert the process operator to a process that requires immediate action and attention. Instead of individually issuing point alarms, all alarms associated with a certain aspect of the process are to be simply wired to give a single trouble alarm.

9.4 Transmitters, Controllers and Control Valves

The transmitter is the inter-phase between the process and it's control system. The transmitter converts the sensors signal into a control signal. The pilot – acting controllers should be employed in the process. The pilot – acting controllers are capable of greater degree of sensitivity since they eliminate of the lags which would be inherent in sel – acting mechanism activated by the force of a large volume of fluid. The fluid control element is an automatic control which throttles the flow of the manipulated variable.

CHAPTER TEN

10.0 ENVIRONMENTAL ACCEPTABILITY

Any new project or technology involving hazardous materials requires a rational approach of assessing the suitability and acceptability to the environment and man (Giwa, 2004).

Various legislations govern the emission of pollutants into the environment. The environmental friendliness of the process choice adopted from the design process is of utmost importance to the relevant government agencies responsible for environmental protection. Awareness of the relevant federal regulations is an essential component of a legally acceptable plant design (Giwa, 2004).

10.1 Identification of Possible Pollutants

10.1.1 Air emissions

Air emissions consist of asbestos and fugitive emissions of chlorine from the cells and in the process tail gases (IPPC, 2001).

10.1.2 Asbestos

Air emissions can appear during production of the diaphragms and, excluding potential accidental releases during transportation, unloading and storage, the major potential sources of air emission are during bag handling and opening and the disposal of spent asbestos (IPPC, 2001).

Three sources of asbestos emission can be identified in the cell room maintenance area:

- from the off-gas compressor,

- from the off-gas drying oven,
- from the off-gas asbestos weighing room.

The fibre concentration in the cell room maintenance area is estimated by the industry to be less than 100000 fibres/m^3.

Asbestos emissions from the baking furnace were calculated as being about 5 g per year, corresponding to an emission of 0.036 mg of asbestos per tonne of chlorine capacity in a plant of 140000 tonnes annual chlorine capacity [Dutch report, 1998].

Dry asbestos fibres can cause serious health problems if not properly used and handled in the diaphragm process. Asbestos fibres are thin and sharp crystals, which can be split into even thinner crystals. Due to its physical properties, asbestos is considered to be carcinogenic. The fibres are insoluble in body fluids and easily penetrate cell membranes. They can enter the human body by either inhalation or ingestion.

10.1.3 Water emissions

Waste water streams from the diaphragm cell process mainly originate from the condenser during caustic soda evaporation, chlorine drying, and brine purification of salt recovered from the evaporators. These waste water streams are described in the relevant paragraphs about auxiliary processes.

At the end of the lifetime of an asbestos diaphragm, the asbestos is removed from the cathode can by means of high pressure water-jet cleaning. Asbestos is collected with the rinsing water and can be discharged. A filter press can be installed to remove asbestos from the rinsing water. Reported emissions give values of under or equal to 30 mg/l (IPPC, 2001).

10.2 Suggestions on the Treatment of the Pollutants

10.2.1 Conversion to membranes

The important changes to an existing plant when converting from diaphragm cells to membrane technology are:

- Additional brine purification, including hardness removal ion exchange techniques. Modifications to brine treatment to control other impurities, such as sulphate, may also be required.
- Additional brine dechlorination to protect the ion exchange resin. It is necessary to complete the brine recirculation loop by adding primary and secondary dechlorination and possibly resaturation.
- Inclusion of a cell room caustic soda recirculation system. If 50% product is required, the existing diaphragm cell caustic soda evaporator must be modified and simplified to accept high-strength, salt-free caustic soda.
- Change of electrolysers and details of the cell room system (IPPC, 2001).

10.2.2 Conversion to asbestos-free diaphragms

In some cases the Tephram diaphragms can directly replace the old diaphragms and the Polyramix diaphragms can replace the old diaphragms if the cathodes are also replaced (IPPC, 2001).

CHAPTER ELEVEN

11.0 START UP AND SHUT DOWN PROCEDURE

Start up time may be defined as the time span between end of construction and the beginning of normal operations. Start up and shut down procedure must proceed safely and be flexible enough to be carried out in various ways. In other words, the start up and shut down of the plant should be such that it can be easily and safely operated. The operating limits of the plant should not be exceeded and dangerous mixtures must not be formed as a result of abnormal states of concentration, composition, temperature, phase, pressure, reactants and products.

It should be noted that some items of actions must be completed before even the start up of the plant in order to prepare the plant for the start up operation. The items of actions are:

i. All scaffolds and temporary piping and supports should be removed.
ii. Lines and equipment should be flushed out.
iii. Pumps, motors/turbines and compressors should be run.
iv. Hydrostatic or pneumatic lines and equipment should be tested.
v. Laboratory and sampling schedule should be prepared.
vi. All instruments should be inspected and tested.

11.1 Start Up Procedures

For the plant designed, the following are the start up procedures:

i. The heat exchanger should be started up using auxiliary fuel to begin steam production.
ii. The reactors should be heated up and maintained at their operating temperatures and pressures.

iii. The inlet and outlet valves of the electrolytic cell should be opened up.

iv. All the inlet and outlet valves to the reactor should be shut as soon as the feed enters the reactor in order to achieve maximum conversion.

v. The outlet value of the reactor should be opened for the evacuation of the reactor contents.

vi. The outlet valve of the reactor should be locked before opening the inlet valve before further entering of the feed into the reactor.

11.2 Shut Down Procedures

The shut down procedures for the plant are as outlined below

i. The supply of brine into the saturator should be stopped

ii. The supply of the concentrated salt to the saturator should be cut off.

CHAPTER TWELVE

12.0 SITE FOR PLANT LOCATION

The location of the plant can have a crucial effect on the profitability of the project and the scope for future expansion. Many factors must be considered when selecting a suitable site, and they are as outlined below:

i. Location, with respect to the marketing area.

ii. Raw materials supply.

iii. Transport facilities.

iv. Availability of labour.

v. Availability of utilities.

vi. Availability of suitable land.

vii. Environmental impact and effluent disposal.

viii. Local community considerations.

ix. Climate.

x. Political and strategic considerations.

12.1 Factors Considered for Site and Plant Location

The factors considered for site and plant location are as described thus.

12.1.1 Location, with respect to the marketing area

For a material produced in bulk quantities such as the caustic soda where the cost of the product per tonne is relatively low and the cost of transport is a significant fraction of the sales price, the plant should be located close to the primary market. This consideration will be less important for low volume production, high-priced products; such as pharmaceuticals.

12.1.2 Raw materials

The availability and price of suitable raw materials will often determine the site location. Plants producing bulk chemical such as the caustic soda plant are best located close to the source of the major raw materials where this is also close to the marketing area.

12.1.3 Transport

The transport of materials and products to and from the plant will be an overriding consideration for site selection.

If practicable, a site should be selected that is close to at least tow major forms of transport: road, rail, waterway (canal or river), or a sea port. Road transport is being increasingly used, and is suitable for local distribution from a central warehouse. Rail transport will be cheaper for the long-distance transport of bulk chemicals.

Air transport is convenient and efficient for the movement of personnel and essential equipment and supplies, and the proximity of the site to a major airport should be considered.

12.1.4 Availability of labour

Labour will be needed for construction of the plant and its operation. Skilled construction workers will usually be brought in from outside the site area, but there should be an adequate pool of unskilled labour available locally; and labour suitable for training to operate the plant. Skilled tradesmen will be needed for plant maintenance. Local trade union customs and restrictive practices will have to be considered when assessing the availability and suitability of the local labour for recruitment and training.

12.1.5 Utilities (Services)

Chemical processes invariably require large quantities of water for cooling and general process use, and the plant must be located near a source of water of suitable quality. Process water may be drawn from a river, from wells, or purchased from a local authority.

At some sites, the cooling water required can be taken from a river or lake, or from the sea; at other locations cooling towers will be needed. Electrical power will be needed at all sites.

12.1.6 Environmental impact and effluent disposal

All industrial processes produce waste products, and full consideration must be given to the difficulties and coat of their disposal. The disposal of toxic and harmful effluents will be covered by local regulations, and the appropriate authorities must be consulted during the initial site survey to determine the standards that must be met.

12.1.7 Local community considerations

The proposed plant must be fit in with and be acceptable to the local community. Full consideration must be given to the safe location of the plant so that it does not impose a significant additional risk to the community.

12.1.8 Availability of suitable land

Sufficient suitable land must be available for the proposed plant and for future expansion. The land should be ideally flat, well drained and have suitable load bearing capacity. A full site evaluation should be made to determine the need for pining or other special foundations. It should also be available at low cost.

12.1.9 Climate

Adverse climatic conditions at a site will increase costs. Abnormally low temperatures will require the provision of additional insulation & special heating for equipment & pipe runs. Stronger structures will be needed at locations subject to high winds or earthquakes.

12.1.10 Political and strategic consideration

Capital grants, tax concessions and other incentives provided by governments to direct new investment to preferred locations, such as areas of high un-employment should be the overriding considerations in the site selection.

12.2 Selection of Site

Careful consideration of the factors for the site selection outlined above reveals that the best site for this project is the Lagos metropolis, Lagos State, Nigeria.

12.3 Justification of the Selected Site

Actually, the site selected based on the fact that it satisfied more than 75% of the factors considered. For instance, it is close to the source and market apart from having good road network.

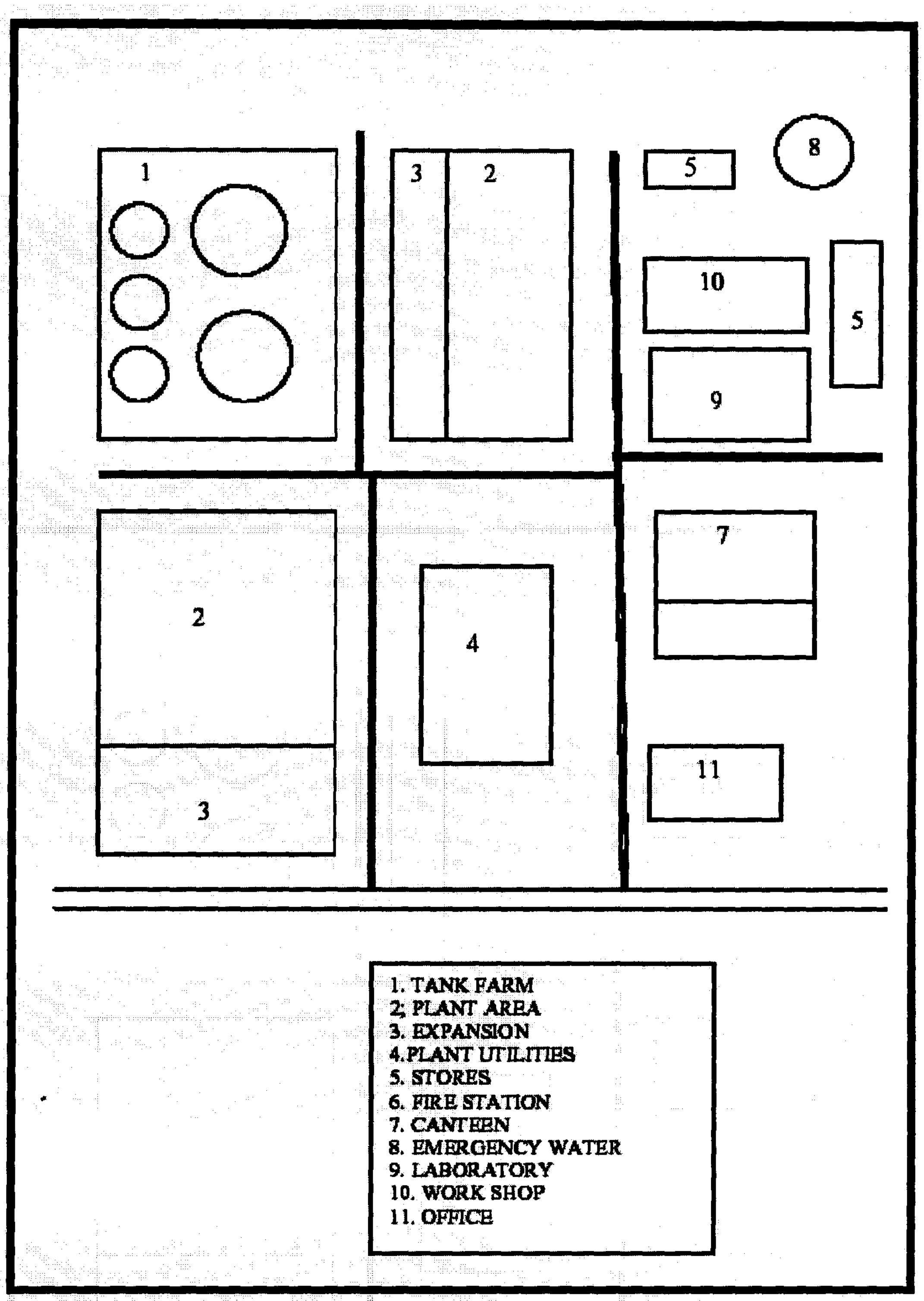


Fig. 12.1: Plant layout

CHAPTER THIRTEEN

13.0 ECONOMIC ANALYSIS

13.1 Purchased Equipment Cost

13.1.1 Purchased equipment cost of saturator

Given that,

$M\_S := 1100 \qquad F_m := 3.67 \qquad F_p := 1.15 \qquad F_c := F_m \cdot F_p$

$$PC_{saturator} := \left(\frac{M\_S}{280}\right) \cdot \left[101.9 \cdot \left(\frac{D_{saturator}}{ft}\right)^{1.066} \cdot \left(\frac{H_{saturator}}{ft}\right)^{0.802} \cdot F_c\right] \cdot er \cdot Naira$$

$PC_{saturator} = 4.836 \times 10^7 \, Naira$

13.1.2 Purchased equipment cost of precipitator

Given that,

$M\_S := 1100 \qquad F_m := 3.67 \qquad F_p := 1.15 \qquad F_c := F_m \cdot F_p$

$$PC_{precipitator} := \left(\frac{M\_S}{280}\right) \cdot \left[101.9 \cdot \left(\frac{D_{precipitator}}{ft}\right)^{1.066} \cdot \left(\frac{H_{precipitator}}{ft}\right)^{0.802} \cdot F_c\right] \cdot er \cdot Naira$$

$PC_{precipitator} = 4.923 \times 10^7 \, Naira$

13.1.3 Purchased equipment cost of filter

Given that,

$M\_S := 1100 \qquad F_m := 1.00 \qquad F_p := 1.00 \qquad F_c := F_m \cdot F_p$

$$PC_{filter} := \left(\frac{M\_S}{280}\right) \cdot \left[101.3 \cdot \left(\frac{A_{filter}}{ft^2}\right)^{0.65} \cdot F_c\right] \cdot er \cdot Naira$$

$PC_{filter} = 1.089 \times 10^5 \, Naira$

13.1.4 Purchased equipment cost of electrolytic cell

Given that,

$M\_S := 1100 \qquad F_m := 3.67 \qquad F_p := 1.15 \qquad F_c := F_m \cdot F_p$

$$PC_{electrolytic\_cell} := \left(\frac{M\_S}{280}\right) \cdot \left[101.9 \cdot \left(\frac{D_{electrolytic\_cell}}{ft}\right)^{1.066} \cdot \left(\frac{H_{electrolytic\_cell}}{ft}\right)^{0.802} \cdot F_c\right] \cdot er \cdot Naira$$

$PC_{electrolytic\_cell} = 4.316 \times 10^7 Naira$

13.1.5 Purchased equipment cost of cooler

Given that,

$M\_S := 1100 \qquad F_m := 3.67 \qquad F_p := 1.15 \qquad F_c := F_m \cdot F_p$

$$PC_{cooler} := \left(\frac{M\_S}{280}\right) \cdot \left[101.3 \cdot \left(\frac{A_{cooler}}{ft^2}\right)^{0.65} \cdot F_c\right] \cdot er \cdot Naira$$

$PC_{cooler} = 1.808 \times 10^7 Naira$

Total purchase cost of equipment:

$$PC_{total} := PC_{saturator} + PC_{precipitator} + PC_{filter} + PC_{electrolytic\_cell} + PC_{cooler}$$

$PC_{total} = 1.589 \times 10^8 Naira$

Estimation of Total Capital Investment

I. Direct Costs

A. Equipment + installation + instrumentation + piping + electrical + insulation + painting

1. **Purchased equipment cost (PEC),** 15-40% of fixed capital investment

As calculated, $PEC := PC_{total}$ $\qquad PEC = 1.589 \times 10^8 Naira$

2. **Installation, including insulation and painting,** 25-55% of purchased equipment cost

Assuming $Insta := 40\% \cdot PEC$ $\qquad Insta = 6.358 \times 10^7 Naira$

3. **Instrumentation and controls, installed,** 6-30% of purchased equipment cost

Assume $\underline{Instr} := 11\% \cdot \underline{PEC}$ $\underline{Instr} = 1.748 \times 10^{7}\,\underline{Naira}$

4. **Piping installed,** 10-80% of purchased equipment cost

Assume $\underline{Pip} := 30\% \cdot \underline{PEC}$ $\underline{Pip} = 4.768 \times 10^{7}\,\underline{Naira}$

5. **Electrical, installed,** 10-40% of purchased equipment cost

Assume $\underline{Elect} := 15\% \cdot \underline{PEC}$ $\underline{Elect} = 2.384 \times 10^{7}\,\underline{Naira}$

So, the cost of equipment, installation, instrumentation, piping, electrical, insulation and painting is given as

$\underline{CA} := \underline{PEC} + \underline{Insta} + \underline{Instr} + \underline{Pip} + \underline{Elect}$ $\underline{CA} = 3.115 \times 10^{8}\,\underline{Naira}$

B. Buildings, process and auxiliary, 10-70% of purchased equipment cost

Assume $\underline{Build} := 20\% \cdot \underline{PEC}$ $\underline{Build} = 3.179 \times 10^{7}\,\underline{Naira}$

C. Service facilities and yard improvements, 40-100% of purchased equipment cost

Assuming $\underline{Servi} := 50\% \cdot \underline{PEC}$ $\underline{Servi} = 7.947 \times 10^{7}\,\underline{Naira}$

D. Land, 1-2% of fixed capital investment or 4-8% of purchased equipment cost)

Assuming $\underline{Lan} := 5\% \cdot \underline{PEC}$ $\underline{Lan} = 7.947 \times 10^{6}\,\underline{Naira}$

Thus, the direct cost is equal to

$\underline{Direct\_Cost} := \underline{CA} + \underline{Build} + \underline{Servi} + \underline{Lan}$ $\underline{Direct\_Cost} = 4.308 \times 10^{8}\,\underline{Naira}$

II. Indirect costs: expenses which are not directly involved with material and labour of actual installation of complete facility (15-30% of fixed capital investment)

A. Engineering and supervision, 5-30% of direct cost

Assuming $\underline{Engin} := 13\% \cdot \underline{Direct\_Cost}$ $\underline{Engin} = 5.6 \times 10^{7}\,\underline{Naira}$

B. Construction expense and contractor's fee, 6-30% of direct cost

Assuming $\underline{Const} := 15\% \cdot \underline{Direct\_Cost}$ $\underline{Const} = 6.461 \times 10^{7}\,\underline{Naira}$

C. Contingency, 5-15% of direct cost

Assuming $\underline{Conti} := 7\% \cdot \underline{Direct\_Cost}$ $\underline{Conti} = 3.015 \times 10^{7}\,\underline{Naira}$

Thus, indirect cost is equal to

$\mathrm{Indirect\_Cost} := \mathrm{Engin} + \mathrm{Const} + \mathrm{Conti}$ $\qquad$ $\mathrm{Indirect\_Cost} = 1.508 \times 10^{8}\,\mathrm{Naira}$

III. Fixed Capital Investment:

Fixed capital investment = Direct cost + Indirect cost

$\mathrm{Fixed\_CI} := \mathrm{Direct\_Cost} + \mathrm{Indirect\_Cost}$ $\qquad$ $\mathrm{Fixed\_CI} = 581514365.70\,\mathrm{Naira}$

IV. Working Capital, 11-20% of fixed capital investment

Assuming $\mathrm{Working\_C} := 11\% \cdot \mathrm{Fixed\_CI}$ $\qquad$ $\mathrm{Working\_C} = 6.397 \times 10^{7}\,\mathrm{Naira}$

13.1 V. Total Capital Investment (TCI):

Total capital investment to be Fixed capital investment + Working capital

Assuming $\mathrm{TCI} := \mathrm{Fixed\_CI} + \mathrm{Working\_C}$ $\qquad$ $\mathrm{TCI} = 6.455 \times 10^{8}\,\mathrm{Naira}$

Estimation of Total Product Cost:

I. Manufacturing Cost = Direct production cost + Fixed charges + Plant overhead cost

A. Fixed Charges, 10-20% of total product cost)

i. Depreciation, This depends on life period, salvage value and method of calculation

- about 13% of FCI for machinery and equiupment and 2-3% of building value for buildings

Assuming $\mathrm{Depre} := 10\% \cdot \mathrm{Fixed\_CI} + 3\% \cdot \mathrm{Build}$ $\qquad$ $\mathrm{Depre} = 5.911 \times 10^{7}\,\mathrm{Naira}$

ii. Local Taxes, 1-4% of fixed capital investment

Assuming $\mathrm{Tax} := 3.5\% \cdot \mathrm{Fixed\_CI}$ $\qquad$ $\mathrm{Tax} = 2.035 \times 10^{7}\,\mathrm{Naira}$

iii. Insurance, 0.4-1% of fixed capital investment)

Assuming $\mathrm{Insur} := 0.6\% \cdot \mathrm{Fixed\_CI}$ $\qquad$ $\mathrm{Insur} = 3.489 \times 10^{6}\,\mathrm{Naira}$

iv. Rent, 8-12% of value of fixed capital investment

Assuming $\mathrm{Ren} := 10\% \cdot \mathrm{Fixed\_CI}$ $\qquad$ $\mathrm{Ren} = 5.815 \times 10^{7}\,\mathrm{Naira}$

Thus, fixed charges is given as

$\mathrm{Fixed\_Charges} := \mathrm{Depre} + \mathrm{Tax} + \mathrm{Insur} + \mathrm{Ren}$

$\mathrm{Fixed\_Charges} = 1.411 \times 10^{8}\,\mathrm{Naira}$

13.2 B. Direct Production Cost (Operating Cost):

Fixed charges is 10-20% of total product cost

Assuming $\underline{\text{Fixed\_Charges}} = 15\underline{\%} \cdot \underline{\text{TPC}}$

making total product cost, TPC, the subject of the formula,

$$\underline{\text{TPC}} = \frac{\underline{\text{FC}}}{15\underline{\%}}$$

$$\underline{\text{TPC}} := \frac{\underline{\text{Fixed\_Charges}}}{15\underline{\%}} \qquad \underline{\text{TPC}} = 9.407 \times 10^{8}\,\underline{\text{Naira}}$$

i. **Raw materials,** 10-50% of total product cost)
Assuming

$\underline{\text{Raw\_mat}} := 15\underline{\%} \cdot \underline{\text{TPC}}$ $\qquad \underline{\text{Raw\_mat}} = 1.411 \times 10^{8}\,\underline{\text{Naira}}$

ii. **Operating Labour (OL),** 10-20% of total product cost

Assuming $\underline{\text{OperL}} := 10\underline{\%} \cdot \underline{\text{TPC}}$ $\qquad \underline{\text{OperL}} = 9.407 \times 10^{7}\,\underline{\text{Naira}}$

iii. **Direct Supervisory and Clerical Labour (DS & CL),** 10-25% of OL

Assuming $\underline{\text{DireS}} := 15\underline{\%} \cdot \underline{\text{OperL}}$ $\qquad \underline{\text{DireS}} = 1.411 \times 10^{7}\,\underline{\text{Naira}}$

iv. **Utilities,** 10-20% of total product cost

Assuming $\underline{\text{Util}} := 12.5\underline{\%} \cdot \underline{\text{TPC}}$ $\qquad \underline{\text{Util}} = 1.176 \times 10^{8}\,\underline{\text{Naira}}$

v. **Maintenance and repairs (M & R),** 2-10% of fixed capital investment

Assuming $\underline{\text{Maint}} := 3.7\underline{\%} \cdot \underline{\text{Fixed\_CI}}$ $\qquad \underline{\text{Maint}} = 2.152 \times 10^{7}\,\underline{\text{Naira}}$

vi. **Operating Supplies,** 10-20% of M & R or 0.5-1% of FCI

Assuming $\underline{\text{OperS}} := 17\underline{\%} \cdot \underline{\text{Maint}}$ $\qquad \underline{\text{OperS}} = 3.658 \times 10^{6}\,\underline{\text{Naira}}$

vii. **Laboratory Charges,** 10-20% of OL

Assuming $\underline{\text{Lab}} := 15\underline{\%} \cdot \underline{\text{OperS}}$ $\qquad \underline{\text{Lab}} = 5.487 \times 10^{5}\,\underline{\text{Naira}}$

viii. **Patent and Royalties,** 0-6% of total product cost

Assuming $\underline{\text{Paten}} := 4.5\underline{\%} \cdot \underline{\text{TPC}}$ $\qquad \underline{\text{Paten}} = 4.233 \times 10^{7}\,\underline{\text{Naira}}$

Thus, direct production cost is

$$\text{DPC} := \text{Raw\_mat} + \text{OperL} + \text{DireS} + \text{Util} + \text{Maint} + \text{OperS} + \text{Lab} + \text{Paten}$$

$$\text{DPC} = 4.349 \times 10^{8}\,\text{Naira}$$

C. Plant Overhead Costs, 50-70% of operating labour, supervision, and maintenance or 5-15% of total product cost); includes for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, salvage, laboratories, and storage facilities.

Considering the plant overhead cost to be 55% of OL, DS & CL and M & R

Therefore,

$$\text{Plant\_Overhead} := 55\% \cdot (\text{OperL} + \text{DireS} + \text{Maint}) \qquad \text{Plant\_Overhead} = 7.133 \times 10^{7}\,\text{Naira}$$

Manufacture cost = Direct production cost + Fixed charges + Plant overhead cost

$$\text{Manuf} := \text{DPC} + \text{Fixed\_Charges} + \text{Plant\_Overhead} \qquad \text{Manuf} = 6.473 \times 10^{8}\,\text{Naira}$$

II. General Expenses = Administrative costs + distribution and selling costs + research and development costs

A. Administrative costs, 2-6% of total product cost

Assuming $\text{Admin} := 3\% \cdot \text{TPC}$ $\qquad \text{Admin} = 2.822 \times 10^{7}\,\text{Naira}$

B. Distribution and Selling Costs, 2-20% of total product cost; includes costs for sales offices, salesmen, shipping, and advertising.

Assuming $\text{Distr} := 11\% \cdot \text{TPC}$ $\qquad \text{Distr} = 1.035 \times 10^{8}\,\text{Naira}$

C. Research and Development Costs, about 5% of total product cost

Assuming $\text{Resea} := 5\% \cdot \text{TPC}$ $\qquad \text{Resea} = 4.703 \times 10^{7}\,\text{Naira}$

D. Financing (Interest), 0 - 10% of total capital investment

Assuming $\text{Interest} := 5\% \cdot \text{TCI}$ $\qquad \text{Interest} = 3.227 \times 10^{7}\,\text{Naira}$

Thus, general expenses,

$$\text{Gener} := \text{Admin} + \text{Distr} + \text{Resea} + \text{Interest} \qquad \text{Gener} = 2.11 \times 10^{8}\,\text{Naira}$$

III. Total Product Cost = Manufacture Cost + General Expenses

$\underline{TProdC} := \underline{Manuf} + \underline{Gener}$ $\underline{TProdC} = 8.583 \times 10^{8}\,\underline{Naira}$

13.3 V. Gross Earnings/Income (Revenue Expectations):

The selling price of the product is

$$\underline{Selling\_price} := 2.825 \cdot \frac{\underline{Naira}}{\underline{kg}}$$

$$\underline{Quantity\_Produced} := 1016060.00 \cdot \frac{\underline{kg}}{\underline{day}}$$

Assuming that the attainment is $\underline{Attainment} := 329 \cdot \underline{day}$

Total income = Selling price x quantity of product manufactured

Assume $\underline{Total\_income} := \underline{Selling\_price} \cdot \underline{Quantity\_Produced} \cdot \underline{Attainment}$

$\underline{Total\_income} = 9.444 \times 10^{8}\,\underline{Naira}$

Gross income = Total income - Total Product Cost

That is, $\underline{Gross\_income} := \underline{Total\_income} - \underline{TPC}$ $\underline{Gross\_income} = 3.694 \times 10^{6}\,\underline{Naira}$

Tax rate = 45% of gross income, $\underline{Tax\_rate} := 45\underline{\%}$

$\underline{Taxes} := 45\underline{\%} \cdot \underline{Gross\_income}$ $\underline{Taxes} = 1.662 \times 10^{6}\,\underline{Naira}$

Net profit = Gross income - Taxes

$\underline{Net\_profit} := \underline{Gross\_income} - \underline{Taxes}$

$\underline{Net\_profit} = 2.032 \times 10^{6}\,\underline{Naira}$

Calculation of Rate of Return:

$$\underline{Rate\_of\_return} = \frac{\underline{Net\_profit}}{\underline{Total\_CI}} \cdot 100$$

Therefore,

$$\underline{Rate\_of\_return} := \frac{\underline{Net\_profit}}{\underline{TCI}} \cdot 100$$

$\underline{Rate\_of\_return} = 31.475\underline{\%}$

13.4 Cash Flow

Cash flow is the difference between the amount earned and the amount expended.

$\underline{Cash\_Flow} := \underline{Total\_income} - \underline{TProdC}$ $\underline{Cash\_Flow} = 8.601 \times 10^{7}\,\underline{Naira}$

13.5 Pay-Back Period

The pay-back period is calculated as the reciprocal of the rate of return.

Therefore,

$$\text{Pay\_back\_period} := \frac{1}{\text{Rate\_of\_return}} \cdot \text{yr} \qquad \text{Pay\_back\_period} = 3.18\,\text{yr}$$

13.6 Discounted Cash Flow Rate or Return

The discounted cash flow is the interest rate that will make the condition given as

$$\text{DCF} = \sum_{i=1}^{n} \frac{\text{Cash\_Flow}}{(1+r)^{n}} = 0$$

Using trial-and-error calculations as suggested by Sinnot R. K. (Coulson and Richardson's Chemical Engineering, 3rd Edition, pg 277,

$$r := 53 \cdot \% \qquad n := 61 \qquad \text{DCFRR} := r$$

$$\text{DCF} := \sum_{i=1}^{n} \frac{\text{Cash\_Flow}}{(1+r)^{n}} \qquad \text{DCF} = 0$$

Therefore, the Discounted Cash Flow Rate of Return (DCFRR) is equal to $\text{DCFRR} = 53\%$.

13.7 Return on Investment

This is calculated as given thus.

Return on investment (ROI) is given by the expression,

$$\text{ROI} = \frac{\text{Total\_profit\_less\_depreciation}}{\text{Total\_investment}}$$

That is,

$$\text{ROI} := \frac{\text{Total\_income} - \text{Depre}}{\text{Total\_income}} \cdot 100\% \qquad \text{ROI} = 93.741\,\%$$

13.8 Project Income and Expenses Statement for 2006-2009

It is expected that the performance of the plant should increase every year. The projected income and expenses for four consecutive years are as shown below.

Table 13.1: Projected income and expenses statement for the year 2006 to 2009

DESCRIPTION	YEARS			
	2006	2007	2008	2009
kg/day	1016060.00	1161211.43	1306362.86	1451514.29
Capacity (%)	70	80	90	100
REVENUE	**AMOUNT IN NAIRA**			
Net sales	571625195.40	653285937.60	734946679.80	816607422.00
EXPENDITURE				
Raw material	85514087.83	97730386.09	109946684.36	122162982.62
Factory labour	57009391.89	65153590.73	73297789.57	81441988.41
Depreciation	35821186.54	40938498.90	46055811.27	51173123.63
Overhead	43230430.02	49406205.74	55581981.46	61757757.18
TOTAL	221575096.28	253228681.47	284882266.65	316535851.83
PROFIT				
Before tax	350050099.12	400057256.13	450064413.15	500071570.17
Tax	689074.44	787513.64	885952.85	984392.05
Net profit	349361024.68	399269742.49	449178460.31	499087178.12

13.9 Conclusion on the Economic Viability of the Project

The total production cost of the plant which is $\underline{\mathrm{TProdC}} = 8.583\times 10^{8}\,\underline{\mathrm{Naira}}$ and a net profit of $\underline{\mathrm{Net\_profit}} = 2.032\times 10^{6}\,\underline{\mathrm{Naira}}$ have revealed that the project is economically viable with a pay back period of $\underline{\mathrm{Pay\_back\_period}} = 3.177\underline{\mathrm{yr}}$.

CHAPTER FOURTEEN

14.0 RECOMMENDATIONS TO THE INDUSTRIALIST

14.1 General Recommendations

Based on the design work carried out, the following recommendations are made to the industrialists to be noted during the construction, start-up and operating phases of the work:

i. Adequate data and technological parameters should be at the possession of the plant operations at all time to forestall any unwanted accident.

ii. Routine turn around plant maintenance should be of paramount importance in the design. An articulate and organised maintenance team should safeguard quick plant shut down and ensure equipment salvage value. This will also take care of schedule, slippage, cost over-run and possible re-work.

iii. Personnel should undergo routine training about new work ethic and equipments to improve their knowledge of the plant operation and increase overall plant productivity.

iv. Procurement of raw materials and equipments should be based on strict regulation of specification and maximum quality.

v. Plant should not be operated above the design specification to avoid abnormal conditions and explosions.

vi. The implementation of this design work must be adequately supervised by the experts.

vii. The plant should be sited close to the source of raw materials.

viii. Alternative sources of energy should be available at all times to avoid plant failure and possible sources of failure.

ix. The water and air around the plant should be monitored regularly to ensure compliance with the Environmental Protection Agency Standards.

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