

**CUMULATIVE ENERGY CONSUMPTION ANALYSIS
OF THE
ALCELL® AND KRAFT
WOOD PULPING PROCESSES**

by

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ABSTRACT

The production of wood pulp by the Kraft process has proven to be reliable and economically feasible. However, due to recent legislation, the allowable emission limits for certain pollutants produced by the Kraft process have been decreased. These reduced emission limits have encouraged the development of alternative wood pulping methods, such as the ALCELL® process. The decision to build a full scale plant is presently being considered by REPAP Enterprises Incorporated. As part of the decision making process, studies are being performed to evaluate the performance of the ALCELL® process relative to the Kraft process. A major factor in the economics and profitability of one process relative to the other is their energy consumption per unit of product.

The Cumulative Energy Consumption analysis provides a method of determining the energy consumption per unit of product when more than one product is manufactured. This analysis allows for comparison between different processes that produce a common product.

In the present work, a comparison between the Kraft and ALCELL® processes has been carried out on the basis that each has a modern design, relative to the time frame of this study. The examination of these processes by the Cumulative Energy Consumption analysis has required the construction and computer simulation of the mass and energy flows throughout each of these processes. The mass and energy flows have been determined by using projected

stream data, as well as some existing stream data. Computer simulation has been performed by using Microsoft's Excel version 4.0 spreadsheet software.

The effects of using certain byproducts as fuel for a steam and electricity cogeneration system are also investigated with the aid of the computer models. A number of byproduct combustion strategies are presented with the most probable operating strategies giving specific Cumulative Energy Consumption (CEnC) values to the wood pulp of 12.3 MJ/kg for the ALCELL® process and 14.5 MJ/kg for the Kraft process. For these same operating strategies, the total Cumulative Energy per unit of pulp, entering the ALCELL® process is much higher than the amount entering the Kraft process. The lower specific CEnC of wood pulp achieved by the ALCELL® process is a consequence of the non-utilization of byproducts as fuels in the cogeneration system.

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NOMENCLATURE

Latin Symbols

C	Cumulative Energy, kJ
c	Specific cumulative energy, kJ/kg
h_c	Net combustion enthalpy, kJ/kg
E	Energy, kJ
h	Specific Enthalpy, kJ/kg
H_{mix}	Heat of Mixing, kJ/kmol of solution
ΔH_{soln}	Enthalpy of Solution, kJ
M	Mass, kg
P	Production, kg

Greek Symbols

η	Generation efficiency based on cumulative energy consumption, %
η_E	Overall energy efficiency for the production of fuels, % (Boustead & Hancock)

Operators

Δ	Finite change in a state property
Σ	Cumulative summation operator

Subscripts

<i>a</i>	Away or leaving system section
<i>Cogen</i>	Cogeneration Process
<i>Cond</i>	Condensate
<i>Elec</i>	Electrical
<i>i</i>	Species <i>i</i>
<i>j</i>	Product <i>j</i>
<i>Make-up</i>	Make-up
<i>N</i>	Section <i>N</i>
<i>nr</i>	Natural resources
<i>ovelec</i>	Overall electricity use including imports
<i>Rec</i>	Recovered
<i>Steam</i>	Steam
<i>u</i>	Useful
<i>w</i>	Waste

Superscripts

<i>BFW</i>	Boiler Feed Water
<i>E</i>	Energy supply stream
<i>F</i>	Feed stream
<i>Imp</i>	Imported from outside the system's boundary
<i>Prod</i>	Produced
<i>R</i>	Recycle stream

CHAPTER 1

INTRODUCTION

1.1 General

At the present time the most important process by which pulp is produced from wood is the Kraft (or sulfate) process. The Kraft process uses a solution of sodium hydroxide and sodium sulfide to treat the wood so that enough lignin is removed to form a pulp from the remaining cellulosic fiber. These chemicals can cause environmental pollution problems, during the recovery part of this process, unless sufficient emission control systems are installed.

The emission limits for certain pollutants have been reduced by the introduction of appropriate legislation. Due to the required reduction in emission levels, more advanced emission control systems are needed. These control systems have significantly increased the cost of wood pulp that is produced by the Kraft process. This increase in pulp production costs has resulted in the development of alternative pulping processes that require fewer control systems for operation at an acceptable emissions level as dictated by legislation.

An alternative method of producing wood pulp, that has been developed by REPAP Enterprises Incorporated, is known as the ALCELL® process. This process uses an ethyl alcohol based extraction technique that has significant advantages relative to the use of inorganic chemicals in the Kraft process.

The advantages that the ALCELL® process possess in relation to other wood pulping techniques include:

- ① Estimates indicate that a fully commercial ALCELL® mill can be built at a lower capital cost than an equivalently sized new kraft mill because it does not require a recovery boiler or a causticizing cycle.
- ② The ALCELL® process is able to isolate a valuable byproduct, lignin, in a "sulfur-free" form. Existing chemical pulping processes, such as the Kraft and sulfite processes, are unable to do so. This lignin can be sold on markets where Kraft lignins and lignosulfonates cannot compete. [11]
- ③ The ALCELL® process is relatively benign environmentally compared with the Kraft or sulfite processes. There is no odor such as that associated with Kraft pulping and there is a low volume of effluent per tonne of pulp relative to the Kraft or sulfite processes. [11]
- ④ Bleached pulps from the ALCELL® process have been tested as stronger than both sulfite and TMP (Thermo-Mechanical Pulping) pulps and compare well with Kraft pulps. [17]

A pilot plant of the ALCELL® process is currently operating at Newcastle, New Brunswick, Canada. It has operated there since the summer of 1988 with a daily pulp production capability of 30 air dry metric tonnes (ADMT). Experimental and operational data obtained from the pilot plant of the ALCELL® process have resulted in a design for a full scale commercial plant with a daily pulp production capacity of 450 ADMT.

The decision to build a full scale plant is presently being considered by REPAP Enterprises Incorporated. As part of the decision making process, studies are being performed to evaluate the performance of the ALCELL® process relative to the Kraft process. A major factor in the economics and profitability of one process relative to the other is the energy consumption per unit of product. The Cumulative Energy Consumption analysis of a process presents a more sophisticated method of determining the energy consumption per unit of product when more than one product is yielded by a chemical, metallurgical or even physical process.

Computer spreadsheets that simulate the mass and energy flows of the Kraft and ALCELL® processes have been developed using the software package Excel¹. Cumulative energy values for the process streams are determined and presented in the form of tabulated summaries.

It is the purpose of this thesis to present the theory of Cumulative Energy Consumption analysis and to present the results of applying this theory to the Kraft and ALCELL® processes for comparative purposes.

¹ Microsoft Excel Version 4.0

CHAPTER 2

CUMULATIVE ENERGY CONSUMPTION ANALYSIS

2.1 Introduction

Various forms of energy analysis are currently used to evaluate industrial processes and to determine whether or not certain systems within these processes may be improved upon.

The field of energy analysis has been expanded due to three main factors. These factors include; ① environmental considerations due to the release of heat energy into the atmosphere, ② concerns relating to the fact that there are finite quantities of conventional fossil fuels available from the earth, and ③ the rapidly increasing cost of energy. Factor ③ has provided the major impetus for the expansion of the energy analysis field because energy costs have increased to the point where they have become a significant factor in the overall cost associated with the manufacture of products.

The Cumulative Energy Consumption (CEnC) analysis is essentially an accounting procedure in which the cumulative energies associated with all input streams to a process section are distributed to the useful products. This implies that the energy associated with a waste product, discharged to the environment is zero, since this energy is dissipated.

Cumulative Energy Consumption (CEnC) analysis provides a method of assessing different production methods for similar products. The specific CEnC

(Sp. CEnC or c) of the product(s) of a process is a major factor in the economics and profitability of one process relative to another. Cumulative energy values assigned to the product(s) of a process express the sum of the energy of natural resources consumed in all steps of the process.

For the wood pulping processes that were investigated during this study the Cumulative Energy Consumption (CEnC) analysis was chosen, over the Cumulative Exergy Consumption (CExC) analysis, because the removal of lignin from wood is essentially a physical process with little or no change in the chemical constitution of the materials.

For the wood pulping processes analyzed in this thesis it was decided to distribute the Cumulative Energy, C_N , entering the Section N to a product in proportion to the ratio of the mass of that product to the total masses of useful products.

This procedure was satisfactory for the various processing sections except for the energy section. The products of this section are process-steam and electricity, and hence it was necessary to apportion the CEnC input to this section, to the process-steam and electricity in proportion to the energies of these output streams.

2.2 Process Analysis

The analysis of a system by the Cumulative Energy Consumption method is described in the following sections.

2.2.1 Definition of the System

A system is only properly defined when the outputs, inputs and function of the system are defined. Sufficient information pertaining to the process under consideration is necessary in order to determine which sub-systems are to be included within the system's boundary. Figure 2.1 depicts a scenario where the system boundary encloses the main process along with three sub-systems. Also this boundary shows that the energy required to transport the raw materials to the site of the process is to be considered as part of the analysis.

The goal of the energy analysis may also influence the determination of the system's boundary. For instance, it may be necessary to include the energy required to produce and deliver the raw materials and services to the system.

Once the goal of the energy analysis has been determined, the person(s) performing the analysis can make the choice of which sub-systems must be included within the system's boundary. The only limitation on the choice of sub-systems to be included is the availability of data to describe them.

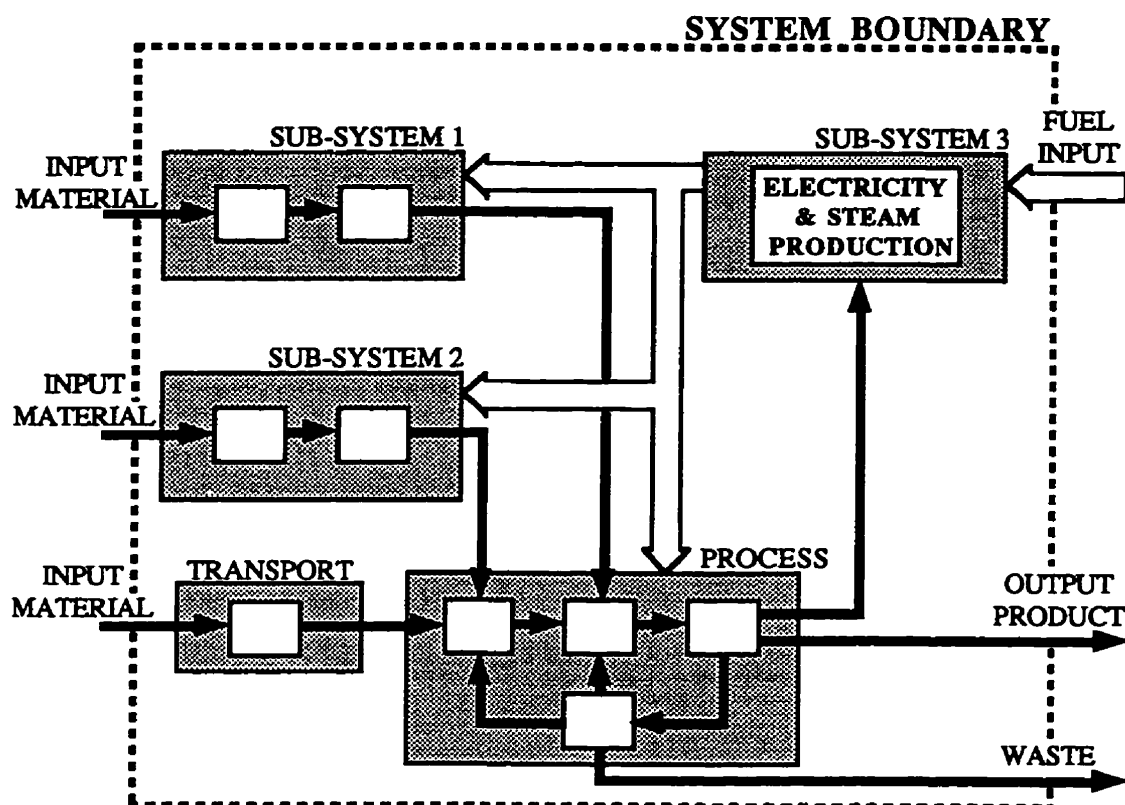


Figure 2.1 — Representation of a Process and Its Sub-Systems

2.2.2 Energy Analysis

Once the boundary for the system under consideration has been determined the process' flowsheet must be divided into suitable sections so that they may be analyzed separately. It may also be necessary to divide the sub-systems, that are contained within the system's boundary, into sections for individual analysis. Processes and sub-systems can be divided into as many sections as is desired, however, sections usually represent a unit operation of the process that represents a specific function such as a set of washers or an entire bleach plant, as was done in this paper.

The first stages of the analysis of the sections comprising the process and sub-systems in question involves the construction of conventional material and energy balances. These balances are based on the Law of Conservation of Mass

and on the First Law of Thermodynamics respectively. Upon completion of these balances the Cumulative Energy Consumption balance equations may be constructed.

2.2.3 Cumulative Energy Consumption Balance Equations

Figure 2.2 depicts a typical section of the system that is under consideration. Possible cumulative energy inputs to this section are as follows:

- ① Feed Streams – CEnC values associated with the intermediate products coming from other sections in the system reflect the amount of energy delivered to the system in all steps prior to this section. In the event that raw materials are fed directly to this section then the energy associated with the processing and transportation of these materials will be reflected in the cumulative energy values of these streams. In the following balance equations, the CEnC values of feed species i entering a section will be represented as C_i^F .
- ② Energy Supply Streams – Energy requirements of the section under consideration are supplied by electricity, steam (both injection and indirect heating) and energy, usually in the form of heat, that is recovered from other sections of the process. The cumulative energy values associated with the energy supply streams of species i are represented and calculated by Equations 2.1 to 2.3.

$$C_{Elec,i}^E = \frac{E_{Elec,i}}{\eta_{ovelec}} \quad (2.1)$$

$$C_{Steam,i}^E = \frac{E_{Steam,i}}{\eta_{Steam}} \quad (2.2)$$

$$C_{Rec,i}^E = E_{Rec,i} \quad (2.3)$$

The efficiency of electricity and steam generation (η_{elec} and η_{Steam} respectively) are determined by Equations 2.25 and 2.22. These efficiencies are calculated on a cumulative energy basis, not on the conventional thermal energy basis.

- ③ **Recycle Streams** – Materials output from one part of a production process that are fed back to some earlier part of the same sequence are known as recycle streams. These streams are recycled for a variety of reasons, however, the cumulative energy values associated with these streams is set equal to their physical energy values as shown in Equation 2.4.

$$C_i^R = E_i \quad (2.4)$$

The reason for setting the cumulative energy value of the recycle stream equal to its physical energy value is a logical decision. As will be seen later in this Section, cumulative energy values are distributed amongst the useful streams of a section in proportion to their mass. Since recycle streams, such as recirculated wash water, often have larger mass flows than the intermediate products of the same section, more cumulative energy would be apportioned to the recycle stream than to the intermediate products. Also recycle streams are often only used as a method of utilizing their physical energy. Therefore a recycle stream should not have a cumulative energy value greater than its physical energy.

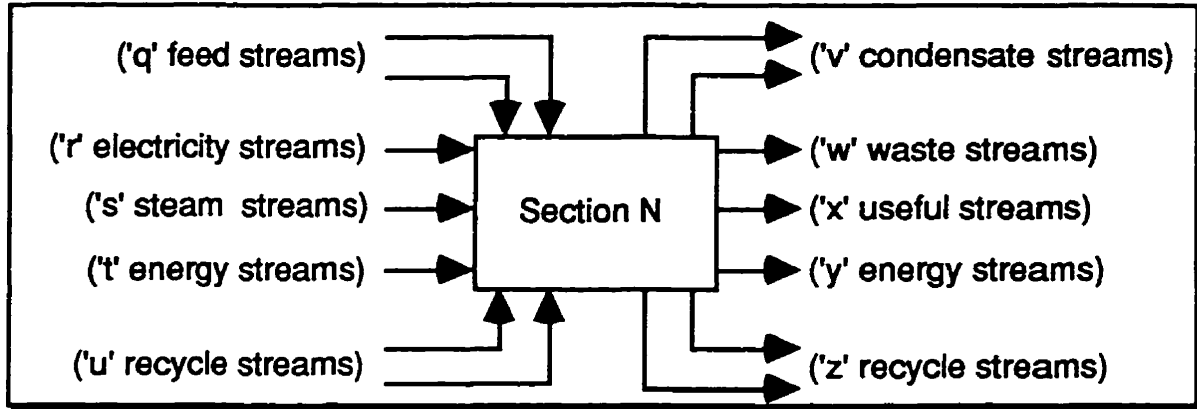


Figure 2.2 — Diagram of Section N

The total cumulative energy entering section N , C_N , is equal to the sum of the cumulative energy delivered to the section with the feed, energy supply and recycle streams. Equation 2.5 represents the total cumulative energy entering section N :

$$C_N = \sum_i C_i = \underbrace{\sum_{i=1}^q C_i^F}_{\text{Feed}} + \underbrace{\sum_{i=1}^r C_{Elec,i}^E + \sum_{i=1}^s C_{Steam,i}^E + \sum_{i=1}^t C_{Rec,i}^E}_{\text{Energy Supply}} + \underbrace{\sum_{i=1}^u C_i^R}_{\text{Recycle}} \quad (2.5)$$

The cumulative energy input to Section N is distributed amongst the section's useful products. The useful streams leaving Section N are denoted by the letter j and they include:

- ① **Recycle and Recovered Energy Streams** — these streams are assigned cumulative energy values equal to the physical energy of the streams, as shown in Equations 2.6 and 2.7.

$$C_j^R = E_j \quad (2.6)$$

$$C_{Rec,j}^E = E_{Rec,j} \quad (2.7)$$

If indirect heating steam is used in section N then the steam condensate is assigned a cumulative energy value according to Equation 2.8.

$$C_{Cond,j}^E = \frac{E_{Cond,j}}{\eta_{Steam}} \quad (2.8)$$

- ② Product Streams — The remainder of the cumulative energy input is apportioned to the useful products of the section in proportion to the mass of the useful products. For each of the product streams, of Section N , equations similar to Equation 2.9a are constructed.

$$C_{u1} = \frac{M_{u1}}{M_{uN}} \times \left(C_N - \sum_{j=1}^Y C_{Rec,j}^E - \sum_j C_{Cond,j}^E - \sum_{j=1}^Z C_j^R \right) \quad (2.9a)$$

$$C_{u2} = \frac{M_{u2}}{M_{uN}} \times \left(C_N - \sum_{j=1}^Y C_{Rec,j}^E - \sum_j C_{Cond,j}^E - \sum_{j=1}^Z C_j^R \right) \quad (2.9b)$$

↓

↓

$$C_{uk} = \frac{M_{uk}}{M_{uN}} \times \left(C_N - \sum_{j=1}^Y C_{Rec,j}^E - \sum_j C_{Cond,j}^E - \sum_{j=1}^Z C_j^R \right) \quad (2.9k)$$

where;

$$M_{uN} = \sum_{j=1}^k M_{uj}$$

For a system involving multiple products from different plant sections and multiple recycle streams, cumulative energy balance equations are written for each section.

The specific cumulative energy consumption for product j , c_j is defined as;

$$c_j = C_j / P_j \quad (2.10)$$

2.2.3.1 CEnC Balance Equations for a Cogeneration System

A cogeneration process can be included within a system's boundary whenever the production process requires the simultaneous generation of thermal (e.g., process-steam) energy and electrical energy. Cogeneration processes for the Kraft and ALCELL® wood pulping processes are shown in Figures 3.13 and 4.11. Figure 2.3 represents a cogeneration system in block formation. Possible cumulative energy inputs to the cogeneration process include:

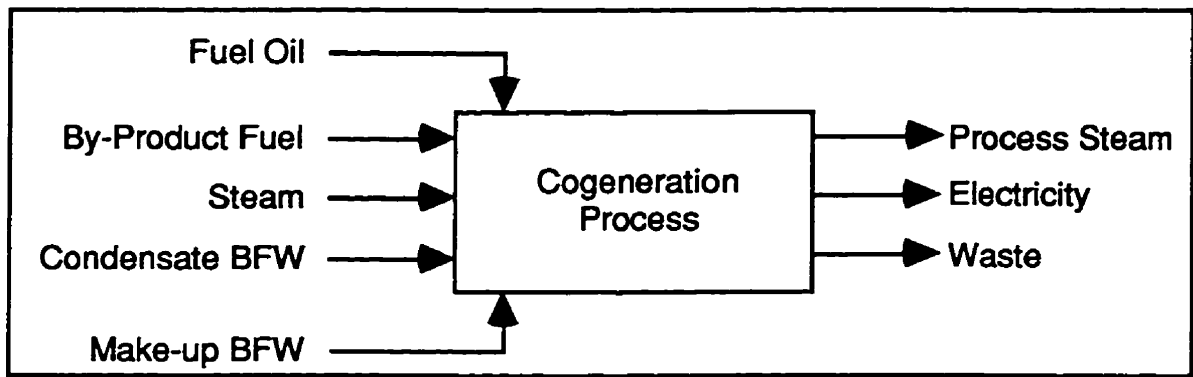


Figure 2.3 — Diagram of the Cogeneration Process

- ① Fuel – Fuel used by the cogeneration process may include byproducts from the production process that is under consideration. The cumulative energy value associated with the combustible byproducts, which are also known as “Hog Fuel”, is equal to the amount of cumulative energy normally apportioned to this byproduct by mass, $C_{Process}$, plus the byproducts combustion energy, $M_{Hog\ Fuel} \cdot h_c$, as shown in Equation 2.11.

$$C_{Hog\ Fuel} = C_{Process} + M_{Hog\ Fuel} \cdot h_c \quad (2.11)$$

Fuels used by the cogeneration process that do not come from the production process, e.g. Bunker C Fuel Oil, have a cumulative energy

value associated with them according to their energetic production efficiency, η_E . Boustead & Hancock [1] define the overall energy efficiency, η_E , for the production of a fuel as;

$$\eta_E = \frac{\text{Total delivered energy available to the consumer}}{\text{Total input energy}} \quad (2.12)$$

The “*Total input energy*” term of Equation 2.12 includes the energy content of the fuel as well as the energy consumption associated with production of the fuels and materials used throughout the processing sequence from extraction of the fuel from the ground and delivery to the consumer.

From Equation 2.12, the cumulative energy of the fuel is:

$$C_{Fuel} = \frac{E_{th}}{\eta_E} \quad (2.13)$$

The “*Total delivered energy available to the consumer*” term of Equation 2.12 is equivalent to the fuel’s thermal energy which is the sum of the fuel’s chemical energy, E_{ch} and its physical energy, E_{ph} as shown in Equation 2.14.

$$E_{th} = E_{ch} + E_{ph} \quad (2.14)$$

Therefore, the cumulative energy value of the fuels used in the process being analyzed is equal to the “*Total input energy*” term of Equation 2.12.

- ② Steam – The Kraft process presents an interesting case where high pressure (≈ 8.72 MPa or 1250 psig) steam is generated in the recovery boiler, which is an integral part of the chemical recovery process. This steam is sent to the cogeneration system for electrical and thermal

energy production and distribution. As discussed in section 4.2.4, the steam is produced by the combustion of organics in the process' black liquor. The cumulative energy value associated with the steam from the recovery boiler is determined by considering it a useful product of the recovery boiler section and by apportioning a cumulative energy value to it in proportion to its mass relative to the other useful products of the recovery boiler. For equations relating to the cogeneration process, the cumulative energy of the steam entering this section will be represented as C_{Steam}^F .

- ③ Make-up Boiler Feed Water – Losses of the working fluid (i.e., water/steam) from the cogeneration process and steam supply system are replenished by make-up boiler feed water (BFW). Figure 2.4 illustrates a possible pre-heating arrangement for the make-up boiler feed water.

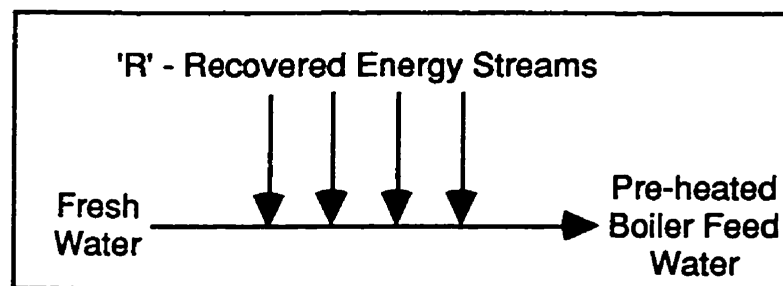


Figure 2.4 — Representation of the Make-up BFW Pre-Heating Train

The fresh water entering the heating train has a cumulative energy value, $C_{Fresh Water}$, that is equal to its physical energy value and the energy required for pumping and purification of the water. Therefore, the cumulative energy value of the preheated boiler feed water may be represented by Equation 2.15 as:

$$C_{Make-up}^{BFW} = \sum_{i=1}^R C_{Rec,i}^E + C_{Fresh\ Water} \quad (2.15)$$

- ④ **Condensate Boiler Feed Water** – The steam supply system for a production process is designed to provide steam at various pressures. Figures 3.14 and 4.12 show the steam supply systems for the ALCELL® and Kraft wood pulping processes respectively.

Application of the Cumulative Energy Consumption (CEnC) analysis to a steam supply system assigns CEnC values to all steam streams according to Equation 2.16.

$$C_{Steam} = \frac{E_{Steam}}{\eta_{Steam}} \quad (2.16)$$

In order to satisfy the CEnC balance on the steam supply system, the cumulative energy values of the steam condensate streams returning to, or leaving, the steam supply system are evaluated in the same manner as the process-steam streams. See Equation 2.17.

$$C_{Cond} = \frac{E_{Cond}}{\eta_{Steam}} \quad (2.17)$$

Therefore, the condensate boiler feed water entering the cogeneration process will have a CEnC value according to Equation 2.18.

$$C_{Cond}^{BFW} = \frac{E_{Cond}^{BFW}}{\eta_{Steam}} \quad (2.18)$$

The total cumulative energy entering the cogeneration process, C_{Cogen} , is distributed amongst the useful products, electricity and process-steam, of the

cogeneration process. Since mass is not a meaningful concept for electricity, the cumulative energy is distributed between the electricity and process-steam in proportion to their energy as opposed to their masses as was done for other sections of the system.

The total cumulative energy entering the cogeneration section, for a case where there are multiple Hog Fuel streams, is represented by Equation 2.19, while the cumulative energy is apportioned to the electricity and process-steam according to Equations 2.20 and 2.21.

$$C_{Cogen} = \sum_i C_{di} = \sum_{i=1}^H C_{Hog\ Fuel, i} + C_{Fuel\ Oil} + C_{Cond}^{BFW} + C_{Make-up}^{BFW} + C_{Steam}^F \quad (2.19)$$

$$C_{Elec}^{Prod} = \frac{E_{Elec}^{Prod}}{\sum E_{Cogen}} \times C_{Cogen} \quad (2.20)$$

$$C_{Steam}^{Prod} = \frac{E_{Steam}^{Prod}}{\sum E_{Cogen}} \times C_{Cogen} \quad (2.21)$$

where;

$$\sum E_{Cogen} = E_{Steam}^{Prod} + E_{Elec}^{Prod}$$

The efficiency of steam production is determined from Equation 2.22.

$$\eta_{Steam} = \frac{E_{Steam}^{Prod}}{C_{Steam}^{Prod}} \quad (2.22)$$

The overall efficiency of electricity generation is determined by considering an “electricity mixing” section as shown in Figure 2.5. This section mixes electricity that is produced in the cogeneration section with electricity that is imported from the grid. Equations 2.23 to 2.25 are the balance equations for the “electricity mixing” section.

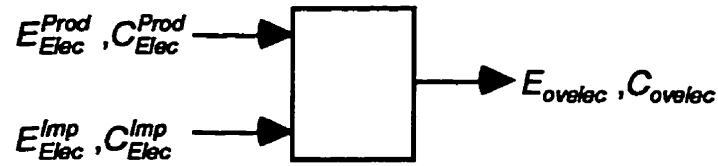


Figure 2.5 — Representation of the “Electricity Mixing” Section

$$E_{ovelec} = E_{Elec}^{Prod} + E_{Elec}^{Imp} \quad (2.23)$$

$$C_{ovelec} = C_{Elec}^{Prod} + C_{Elec}^{Imp} \quad (2.24)$$

where;

$$C_{Elec}^{Imp} = \frac{E_{Elec}^{Imp}}{\eta_{Elec}^{Imp}}$$

The overall electricity generation efficiency is given as:

$$\eta_{ovelec} = \frac{E_{ovelec}}{C_{ovelec}} \quad (2.25)$$

Once all of the cumulative energy equations have been constructed for each plant section it should be found that there are an equal number of unknowns and equations. A solution for these equations may be determined by a suitable method that will solve simultaneous linear equations.

CHAPTER 3

THE ALCELL® PROCESS

3.1 Introduction

The ALCELL® process provides a method of producing wood pulp that is more environmentally friendly than the Kraft (or sulfate) process [17]. While both processes are essentially a physical separation of cellulosic fiber and lignin, the ALCELL® process accomplishes this by using an ethyl alcohol based extraction technique; whereas the Kraft process uses an aqueous solution of sodium hydroxide ($NaOH$) and sodium sulfide (Na_2S). Since the ALCELL® pulping process uses an alcohol based liquor to dissolve the lignin, any losses of the liquor are relatively benign to the environment compared to the emissions from the recovery boiler (see Section 4.2.4) of the Kraft process.

The possibility of delignifying wood using alcohol based extraction agents has been known for some time (Katzen et al, 1980 [6]; Williamson, 1987 [17]). However, the commercial development of this technique has only recently been realized in the construction of a 30 tonne per day commercial scale demonstration plant. This plant was constructed by REPAP Enterprises Incorporated at Newcastle, New Brunswick Canada. It has operated there since the summer of 1988.

The purpose of this ALCELL® demonstration plant has been to verify that the ALCELL® technology is viable. Also, it has provided a site where the

recoverability of the byproducts of the process may be explored and tested. Experimental and operational data obtained from this plant have resulted in a design for a commercial scale plant that will produce an average of 450 ADMT of pulp each day.

The design for this proposed plant has been used to construct a computer spreadsheet program that simulates the mass and energy flows associated with this plant. This spreadsheet has been used to determine the specific Cumulative Energy Consumption (CEnC) for each of the products that are available from the ALCELL® process.

3.2 Process Description

The description of the ALCELL® process is based on the design that was being used at the time of the publication of this thesis. The design for the ALCELL® process has not yet been finalized; however, it is not likely that the design of any major sections of the plant's flowsheet will change enough to affect the results of this study significantly.

In order to perform this study on the ALCELL® process it was necessary to divide the flowsheet of the process into a number of sections. Therefore, it is by these sections that the process will be described in the following pages. Due to the fact that the ALCELL® process has only recently been patented, details of certain sections of the plant, such as the furfural reactor, are not available at this time.

The stream labels that will be referred to in the following descriptions of the various sections of the ALCELL® process may be found in Figure 3.1 and on

the individual schematics that have been included with all sections of the following description of the plant.

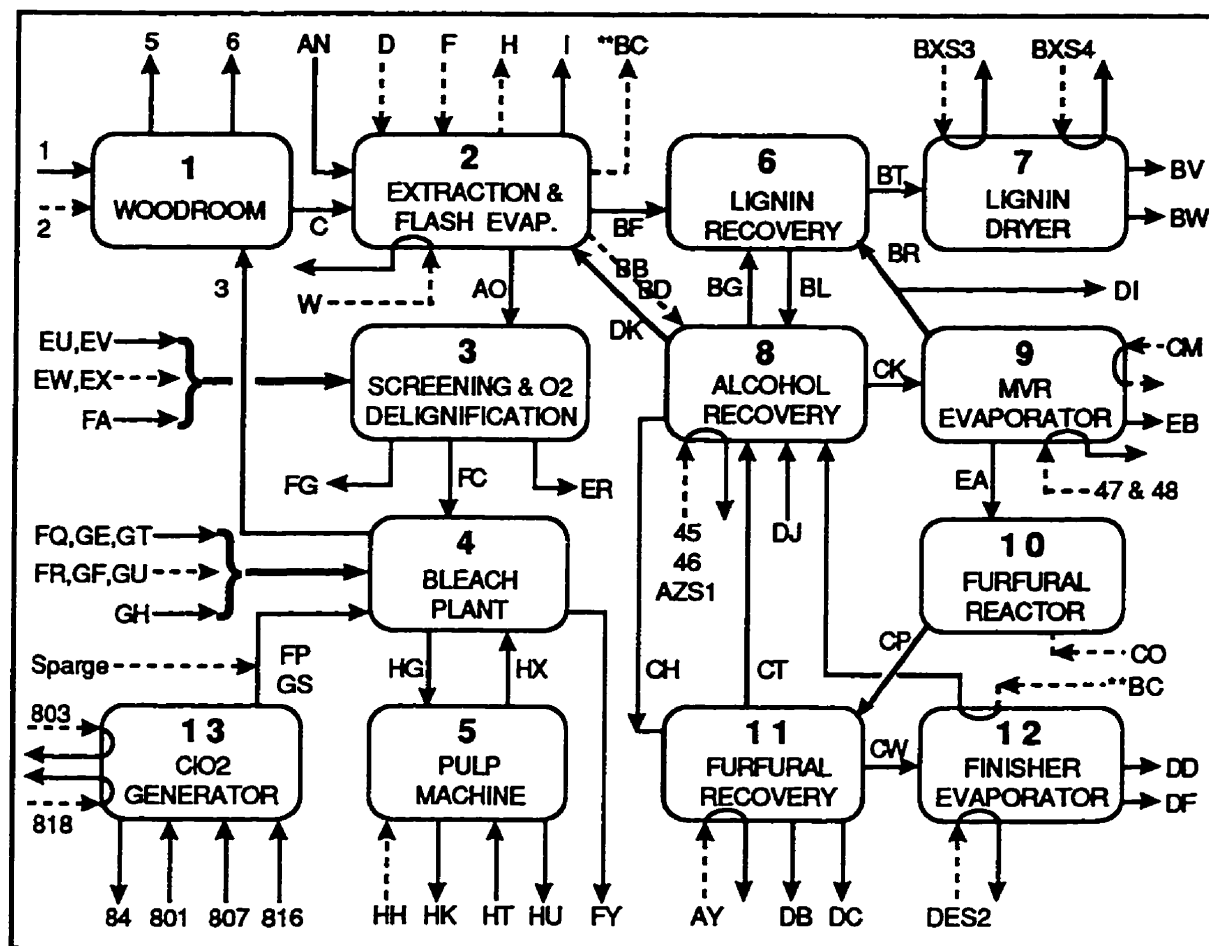


Figure 3.1 — Representation of the ALCELL® Process

Table 3.1 — Stream Labels for the ALCELL® Process

Stream 1 ⇒ Logs	Stream 803 ⇒ Low Pressure Indirect Heating Steam
Stream 2 ⇒ Low Pressure Injection Steam	Stream 807 ⇒ Methanol & Sodium Chlorate Solution
Stream 3 ⇒ Recirculated Wash Water	Stream 816 ⇒ Chilled Water
Stream 5 ⇒ Sewer Water	Stream 818 ⇒ High Pressure Ejector Steam
Stream 6 ⇒ Hog Fuel (Bark & Fines)	Stream AN ⇒ Pre-Heated Wash Water
Stream 45 ⇒ High Pressure Ejector Steam	Stream AO ⇒ Washed Pulp
Stream 46 ⇒ Low Pressure Recirculation Heater Steam	Stream AY ⇒ Medium Pressure Indirect Heating Steam
Stream 47 ⇒ Low Pressure MVR Purge Steam	Stream AZS1 ⇒ Medium Pressure Indirect Heating Steam
Stream 48 ⇒ High Pressure Ejector Steam	Stream BB ⇒ High Pressure Flash Vapor
Stream 84 ⇒ Saltcake (Sodium Sesquisulfate)	Stream BC ⇒ Medium Pressure Flash Vapor
Stream 801 ⇒ Sulfuric Acid Solution	

Stream **BD** ⇒ Low Pressure Flash Vapor
Stream **BF** ⇒ Flashed Black Liquor
Stream **BG** ⇒ Recirculated Stillage
Stream **BL** ⇒ Filtrate/Tower Feed
Stream **BR** ⇒ Recirculated Wash Water
Stream **BT** ⇒ Wet Lignin Cake
Stream **BV** ⇒ Dry Lignin Product
Stream **BW** ⇒ Scrubber Condensate
Stream **BXS3** ⇒ Medium Pressure Indirect Heating Steam
Stream **BXS4** ⇒ High Pressure Indirect Heating Steam
Stream **C** ⇒ Wood Chips
Stream **CH** ⇒ Decanted Furfural
Stream **CK** ⇒ MVR Evaporator Feed
Stream **CM** ⇒ MVR Turbine Inlet Steam
Stream **CO** ⇒ Furfural Reactor Steam
Stream **CP** ⇒ Reacted Furfural
Stream **CT** ⇒ Recovered Alcohol
Stream **CW** ⇒ Finisher Evaporator Feed
Stream **D** ⇒ Low Pressure Heating Steam for the Chip Bin
Stream **DB** ⇒ Furfural Product
Stream **DC** ⇒ Furfural Heavy Residue
Stream **DD** ⇒ Sewer Water
Stream **DES2** ⇒ Medium Pressure Indirect Heating Steam
Stream **DF** ⇒ Concentrated Syrups
Stream **DI** ⇒ Sewer Water
Stream **DJ** ⇒ Make-up Alcohol
Stream **DK** ⇒ Fresh Liquor
Stream **EA** ⇒ Aqueous Layer
Stream **EB** ⇒ Tar Layer
Stream **ER** ⇒ Screen Rejects
Stream **EU** ⇒ Oxygen & Magnesium Sulfate

Stream **EV** ⇒ Sodium Hydroxide Solution
Stream **EW** ⇒ Medium Pressure Injection Steam
Stream **EX** ⇒ High Pressure Injection Steam
Stream **F** ⇒ Medium Pressure Steam for the Steaming Vessel
Stream **FA** ⇒ Pre-Heated Wash Water
Stream **FC** ⇒ Oxygen Delignified Pulp
Stream **FG** ⇒ Sewer Water
Stream **FP** ⇒ Chlorine Dioxide Solution
Stream **FQ** ⇒ Sodium Hydroxide Solution
Stream **FR** ⇒ Medium Pressure Injection Steam
Stream **FY** ⇒ Sewer Water
Stream **GE** ⇒ Sodium Hydroxide Solution
Stream **GF** ⇒ Medium Pressure Injection Steam
Stream **GH** ⇒ Pre-Heated Wash Water
Stream **GS** ⇒ Chlorine Dioxide Solution
Stream **GT** ⇒ Sodium Hydroxide Solution
Stream **GU** ⇒ Medium Pressure Injection Steam
Stream **H** ⇒ Steaming Vessel Purge
Stream **HG** ⇒ Bleached Pulp
Stream **HH** ⇒ Low Pressure Injection Steam
Stream **HK** ⇒ Screen Rejects to Sewer
Stream **HT** ⇒ Pre-Heated Wash Water
Stream **HU** ⇒ Pressed Pulp to Pulp Dryer
Stream **HX** ⇒ Recirculated Wash Water
Stream **I** ⇒ Metering Screw Purge
Stream **W** ⇒ High Pressure Indirect Heating Steam
Stream **Sparge** ⇒ Medium Pressure Injection Steam

3.2.1 Section 1 — The Woodroom

The purpose of the woodroom is to produce wood chips, that are free of “fines” (small wood chips) and bark, from tree length logs. A schematic diagram of the woodroom may be seen in Figure 3.2.

The bark is removed from the logs (Stream 1) in the debarking drum. During the winter months, low pressure injection steam (Stream 2) is used to thaw the logs that enter the debarking drums.

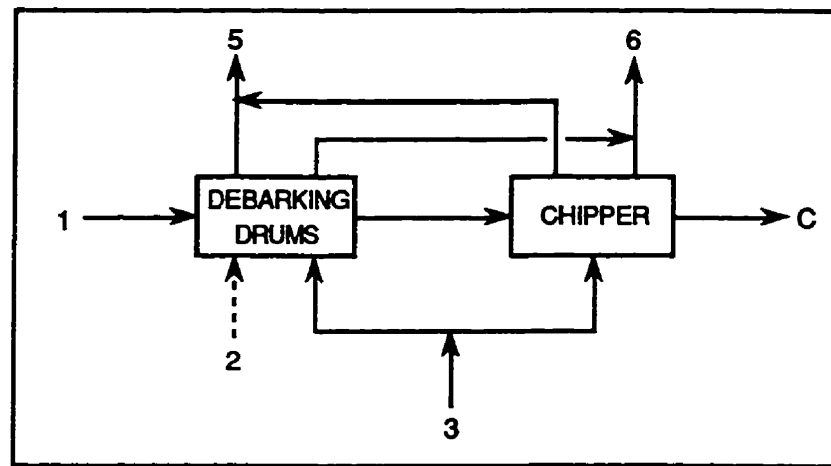
The cleaned logs are passed on to a chipper where they are reduced to wood chips (Stream C). While the logs are being reduced to chips, wood fines or pin chips are also produced. These pin chips are not desirable from an operations perspective in the extraction vessel so they are removed at this stage by a set of screens.

The bark that is removed from the logs in the debarking drums is combined with the “fines” (small wood chips) produced in the chipper. This combined stream is referred to as “Hog fuel” (Stream 6). The “Hog fuel” stream is sent to the “Hog pile” where it is stored until it is burnt in the “Hog boiler” that produces steam for the process. Details about the “Hog boiler” will be discussed in Section 14 of this chapter.

During the debarking and chipping procedure, water for washing and sluicing is often required. This water is available as recycled white water (Stream 3) that comes from the bleach plant (Section 4). However, recent developments in woodroom technology have led to what is known as ‘dry’ woodrooms where very little, if any, water is required for washing or sluicing. For the purpose of this

study, effluent from the woodroom was assumed to be made up entirely of water. However, in reality there is a small amount of wood fiber and bark in this stream.

The wood chips that are produced by the chipper (Stream C) are fed to the extraction vessel located in Section 2.



Stream 1 ⇒ Logs
Stream 2 ⇒ Low Pressure Injection Steam
Stream 3 ⇒ Recirculated Wash Water from the Bleach Plant
Stream 5 ⇒ Sewer Water
Stream 6 ⇒ Hog Fuel (Bark & Fines)
Stream C ⇒ Wood Chips

Figure 3.2 — Diagram of the ALCELL® Woodroom

3.2.2 Section 2 — Extraction & Flash Evaporation

A schematic diagram of the Extraction and Flash Evaporation section is shown in Figure 3.3. Wood chips are introduced to this section by successively passing them through a chip pre-steaming bin and a steaming vessel. The chips are heated with low pressure¹ steam (Stream D) while they are in the chip pre-steaming bin and with medium pressure² steam (Stream F) while they are in the steaming vessel. Purge streams, that are located after both the chip bin and the steaming vessel (Streams I & H respectively), vent condensate and low pressure vapors to the atmosphere.

From here the chips are sent to a mixing tank where they are combined with fresh liquor before being sent to the extraction vessel. The liquor used in the extraction vessel, which is similar to a continuous Kamyr digester, is a solution of ethyl alcohol and water. The pulp mixture is allowed to cook in the extraction vessel at a high temperature, 204°C (400°F) and pressure, 3.55 MPa (500 psig) so that the lignin and cellulosic fibers may be separated from each other. Heat is supplied to the extraction vessel by using high pressure³ indirect heating steam (Stream W).

The wood pulp leaving the extraction vessel is washed with a portion of the recovered alcohol (Stream DK) and with some fresh pre-heated wash water (Stream AN) so that any loosely bound lignin and any residual alcohol may be recovered. The washed wood pulp (Stream AO) is then sent to Section 3 (Screening & Oxygen Delignification).

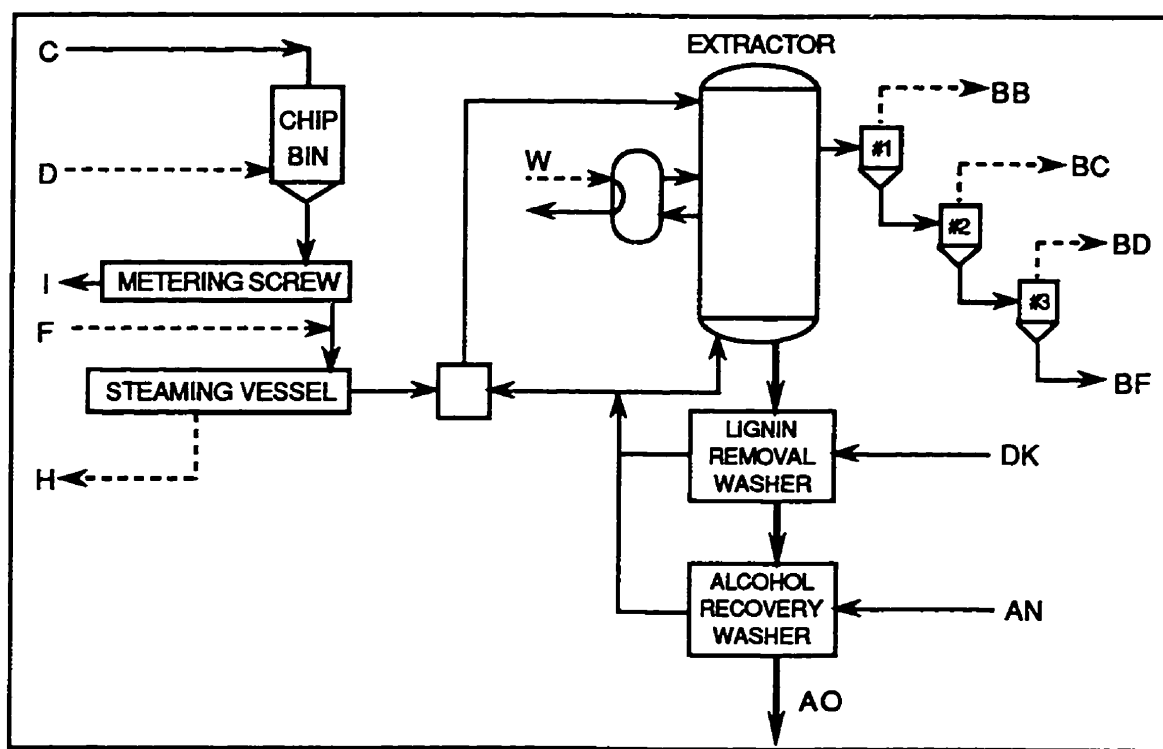
¹ Low Pressure equates to 377 kPa (40 psig) throughout Chapter 3 when referring to steam.

² Medium Pressure equates to 584 kPa (70 psig) throughout Chapter 3 when referring to steam.

³ High Pressure equates to 2515 kPa (350 psig) throughout Chapter 3 when referring to steam.

Black liquor that is removed from the digester is concentrated by sending it through a 3 stage flash tank arrangement. The flash vapors⁴ (Streams BB, BC & BD) produced by these tanks are condensed in two other sections of the plant so that their heats of condensation may be used instead of using steam or some other source of heat. The flash vapor condensates are then recovered in Section 8 (Alcohol Recovery).

The concentrated black liquor (Stream BF) is sent to a mix tank in Section 6 for lignin recovery.



Stream C ⇒ Wood Chips
 Stream D ⇒ Low Pressure Injection Steam
 Stream F ⇒ Medium Pressure Injection Steam
 Stream H ⇒ Steaming Vessel Purge
 Stream I ⇒ Metering Screw Purge
 Stream W ⇒ High Pressure Indirect Heating Steam

Stream AN ⇒ Pre-Heated Wash Water
 Stream AO ⇒ Washed Pulp
 Stream BB ⇒ High Pressure Flash Vapor
 Stream BC ⇒ Medium Pressure Flash Vapor
 Stream BD ⇒ Low Pressure Flash Vapor
 Stream BF ⇒ Flashed Black Liquor
 Stream DK ⇒ Recovered Liquor

Figure 3.3 — Diagram of the Extraction & Flash Evaporation Section

⁴ The Flash Vapors are produced at the following pressures: High Pressure = 997.6 kPa (130.0 psig), Intermediate Pressure = 280.6 kPa (26.0 psig) and Low Pressure = 103.4 kPa (0.3 psig).

3.2.3 Section 3 — Screening and Oxygen Delignification

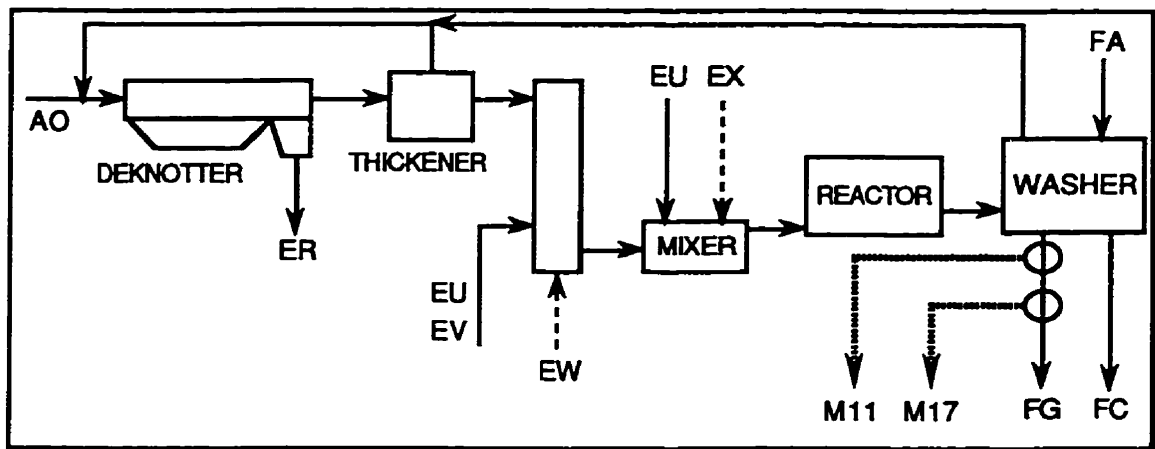
A schematic diagram of the Screening and Oxygen Delignification section is shown in Figure 3.4. The pulp entering the Screening and Oxygen Delignification section is initially deknotted and refined so that any rejects (Stream ER) may be sent to the sewer or used as a fuel in the “Hog boiler”, which is located in Section 14.

After the pulp stream has been screened it enters the Oxygen Delignification section where it is mixed with sodium hydroxide (Stream EV), magnesium sulfate ($MgSO_4$) and oxygen (Stream EU), medium pressure steam (Stream EW) and high pressure steam (Stream EX) before it enters the oxygen reactor. After leaving the reactor the pulp stream (Stream FC) is washed and stored as a high density mixture before being sent to the bleachery (Section 4).

The effluent stream leaving the Oxygen Delignification area is directed to the sewer after heat is removed from it. This heat (Streams M11 & M17) is used to pre-heat the wash water supply in an arrangement that is described in Section 15 of this chapter.

The screening and oxygen delignification section is expected to reduce the Kappa number (which is a measure of the lignin content) of the pulp from approximately 30 to 16.5. This translates into a 45% lignin content reduction. An approximate relation between the Kappa number and the lignin content [7] of wood pulp is shown in Equation 3.1. The Kappa number of a pulp suspension is determined by reacting a known amount of Potassium permanganate ($KMnO_4$) with the lignin in a pulp suspension, the amount consumed by reaction with the lignin is then determined by back titration.

$$Kappa\ Number \times 0.15 = Lignin\ Content\ (\%) \quad (3.1)$$



Stream AO ⇒ Washed Pulp

Stream ER ⇒ Screen Rejects

Stream EU ⇒ Oxygen & Magnesium Sulfate Solution

Stream EV ⇒ Sodium Hydroxide Solution

Stream EW ⇒ Medium Pressure Injection Steam

Stream EX ⇒ High Pressure Injection Steam

Stream FA ⇒ Pre-heated Wash Water

Stream FC ⇒ Oxygen Delignified Pulp

Stream FG ⇒ Sewer Water

Stream M11 ⇒ Recovered Heat to Wash Water

Stream M17 ⇒ Recovered Heat to Wash Water

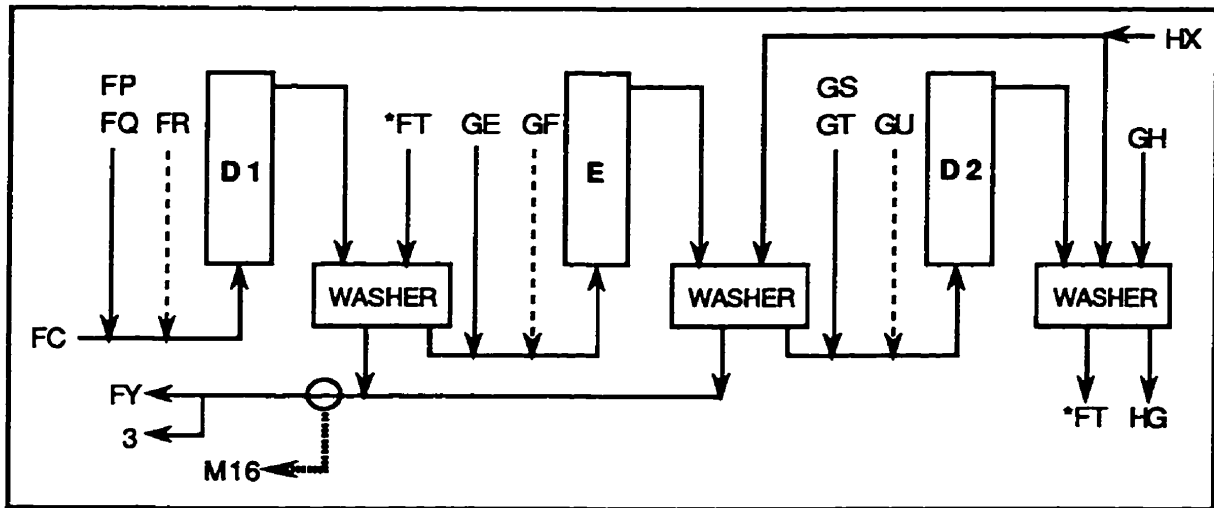
Figure 3.4 — Diagram of the Screening & Oxygen Delignification Area

3.2.4 Section 4 — The Bleach Plant

A schematic diagram of the bleach plant is shown in Figure 3.5. The bleach plant for the proposed ALCELL® process has been designed to bleach hardwood pulp. Presently, hardwood pulp is bleached by using a three stage bleaching sequence as opposed to a four stage sequence that is used for bleaching softwood pulp.

The first stage that the pulp suspension (Stream FC), leaving Section 3, encounters is known as the D₁ stage where chlorine dioxide (Stream FP) is added to the pulp along with sodium hydroxide (Stream FQ) and medium pressure steam (Stream FR). After the pulp has been retained in the D₁ tower for the required amount of time it is washed with the filtrate from the D₂ washer (Stream FT) before it is passed on to the second stage of the bleachery, which is known as the E stage or extraction stage. In the E stage, sodium hydroxide (Stream GE) and medium pressure steam (Stream GF) are mixed with the pulp stream before it enters the E stage retention tower. When the pulp stream leaves this tower it is washed, by using part of the recycled water (Stream HX) that comes from the pulp machine (Section 5), before it is sent to the final bleaching stage. The final bleaching stage is known as the D₂ stage where chlorine dioxide (Stream GS), sodium hydroxide (Stream GT) and medium pressure steam (Stream GU) are again added to the pulp stream before it enters the D₂ retention tower. The pulp stream leaving this retention tower is then washed with the remainder of the recycled water from the pulp machine (Stream HX) and fresh pre-heated water (Stream GH). The washed pulp (Stream HG) is now passed on to the pulp machine (Section 5).

Effluent from the bleachery is split into two streams after heat is recovered from it. This heat (Stream M16) is used to pre-heat the wash water that is used in the ALCELL® process. Part of the effluent stream is used for washing and sluicing in the woodroom (Section 1), while the remainder is sent to the sewer.



Stream 3 ⇒ Recirculated Wash Water to the Woodroom

Stream FC ⇒ Oxygen Delignified Pulp

Stream FP ⇒ Chlorine Dioxide solution

Stream FQ ⇒ Sodium Hydroxide solution

Stream FR ⇒ Medium Pressure Injection Steam

Stream FT ⇒ Recycled Filtrate

Stream FY ⇒ Sewer Water

Stream GE ⇒ Sodium Hydroxide Solution

Stream GF ⇒ Medium Pressure Injection Steam

Stream GH ⇒ Pre-Heated Wash Water

Stream GS ⇒ Chlorine Dioxide solution

Stream GT ⇒ Sodium Hydroxide solution

Stream GU ⇒ Medium Pressure Injection Steam

Stream HG ⇒ Bleached Pulp

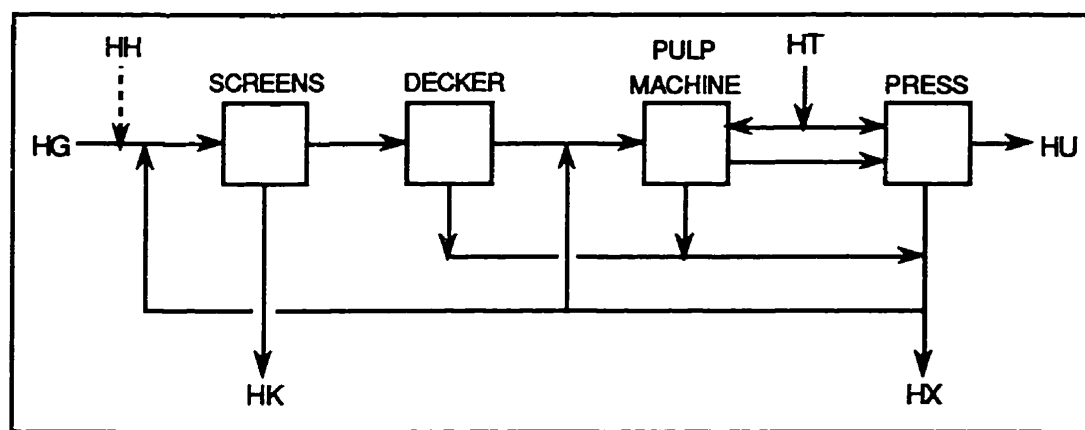
Stream HX ⇒ Recirculated Wash Water from the Pulp Machine

Stream M16 ⇒ Recovered Heat to Wash Water

Figure 3.5 — Diagram of the Bleach Plant of the ALCELL® Process

3.2.5 Section 5 — The Pulp Machine

A schematic diagram of the pulp machine section is shown in Figure 3.6. The pulp (Stream HG) that enters the pulp machine section is at a consistency of approximately 12%. The consistency of wood fiber suspensions is defined as the mass percentage of oven dry wood fiber in a pulp suspension. Initially the pulp machine's screens separate any rejected material from the pulp stream and sends these rejects (Stream HK) to the sewer. The remainder of the pulp stream then passes to a press that squeezes the pulp until its consistency reaches approximately 50%. The water that is displaced by the press is recycled and used as wash water (Stream HX) in the bleachery (Section 4). The pulp of 50% consistency (Stream HU) is considered to be the primary product of the ALCELL® process.



Stream HG ⇒ Bleached Pulp
Stream HH ⇒ Low Pressure Injection Steam
Stream HK ⇒ Screen Rejects to Sewer
Stream HT ⇒ Pre-Heated Wash Water
Stream HU ⇒ Pressed Pulp to Pulp Dryer
Stream HX ⇒ Recirculated Wash Water

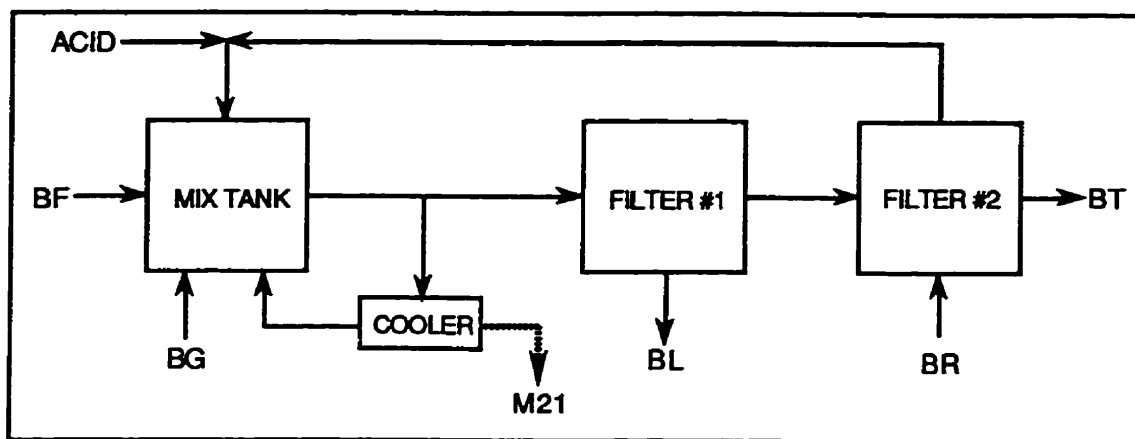
Figure 3.6 — Diagram of the Pulp Machine & Press

3.2.6 Section 6 — Lignin Recovery

A schematic diagram of the Lignin Recovery section is shown in Figure 3.7. The flashed black liquor (Stream BF) from Section 2 enters the section where it is added to a mix tank. While in the mix tank the black liquor is combined with the stillage (Stream BG) that comes from the pressure and vacuum towers located in Section 8 (Alcohol Recovery). Sulfuric acid is also added to the mix tank in small amounts to encourage precipitation of the lignin that is present. From the mix tank the mixture is fed to the lignin concentration sub-section. A filter is used to concentrate the lignin mixture until the lignin concentration reaches 50%. The filtrate (Stream BL) from this filter is sent to the Alcohol Recovery section of the plant where it is fed to the feed tank of the pressure and vacuum distillation towers.

The concentrated lignin stream is now passed on to a second filter where it is washed with condensate (Stream BR) that comes from the mechanical vapor recompression evaporator (Section 9). The filtrate from this filter is fed to the lignin recovery mix tank. The lignin concentrate (Stream BT) from this filter is sent to the lignin dryer (Section 7) at a lignin concentration of approximately 50%.

Excess heat (Stream M21) is removed from the mix tank area of Section 6 and it is used to aid in the pre-heating of the wash water supply.



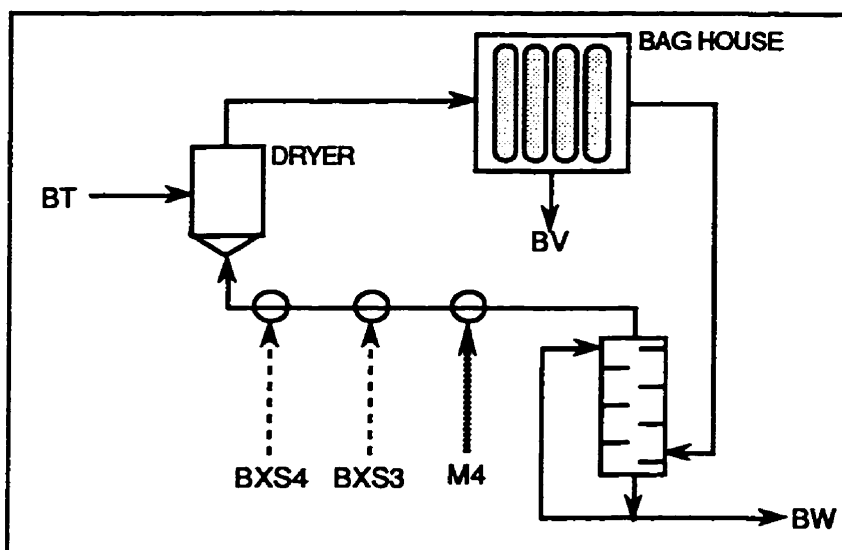
Stream BF ⇒ Flash Black Liquor
Stream BG ⇒ Recirculated Stillage from Alcohol Recovery
Stream BL ⇒ Filtrate/Tower Feed
Stream BR ⇒ Recirculated Wash Water
Stream BT ⇒ Wet Lignin Cake
Stream M21 ⇒ Recovered Heat to Wash Water

Figure 3.7 — Diagram of the Lignin Recovery Section

3.2.7 Section 7 — Lignin Dryer

A schematic diagram of the lignin dryer is provided in Figure 3.8. The wet lignin cake (Stream BT) from Section 6 enters the lignin dryer's drying chamber where it is dried by using hot, 204°C (400°F) nitrogen gas. The nitrogen carries the dried lignin to a baghouse where the lignin (Stream BV) is recovered. The moisture that was present in the wet lignin cake (Stream BT) is carried through the bag house by the nitrogen gas and fed to a scrubber. The scrubber removes any moisture and alcohol from the nitrogen and then sends it to the sewer as scrubber condensate (Stream BW). The nitrogen gas that passes through the scrubber is then heated before it reenters the drying chamber of the lignin dryer. By following the preceding steps it may be deduced that the nitrogen gas is contained in a closed loop from which there are minimal losses. These losses are accounted for by having a make-up nitrogen stream. For the purpose of this study it was assumed that these losses were negligible. However, if make-up nitrogen is required in a plant then it would be added immediately before the loop's heating system.

Heat is supplied to the nitrogen loop by three individual sources. The first source of heat is supplied by recovering heat from the mechanical vapor recompression evaporator's condensate (Stream M4). The nitrogen gas is raised to its required temperature by two indirect contact heat exchangers. These heat exchangers use medium pressure steam (Stream BXS3) and high pressure steam (Stream BXS4) as their heat supplies.



Stream **BT** ⇒ Wet Lignin Cake
 Stream **BV** ⇒ Dry Lignin Product
 Stream **BW** ⇒ Scrubber Condensate
 Stream **BXS3** ⇒ Medium Pressure Indirect Heating Steam
 Stream **BXS4** ⇒ High Pressure Indirect Heating Steam
 Stream **M4** ⇒ Recovered Heat from the MVR Evaporator's Condensate

Figure 3.8 — Diagram of the Lignin Dryer

3.2.8 Section 8 — Alcohol Recovery

The alcohol recovered in this section is fed to the fresh liquor tank; which, as the name implies, supplies fresh liquor (Stream DK) to the extraction vessel that is located in Section 2. A schematic diagram of the Alcohol Recovery section is shown in Figure 3.9.

The supply liquor for the fresh liquor tank comes from the following sources:

- ① Distillate (Stream CT) from the furfural recovery area (Section 11).
- ② Intermediate pressure flash vapor (Stream BC) condensate from the finisher evaporator (Section 12).
- ③ High and low pressure flash vapor (Streams BB & BD) condensates from feed pre-heaters for the distillation towers and from the reboilers of the distillation towers in the alcohol recovery area (Section 8).
- ④ Make-up alcohol (Stream DJ) for the replenishment of any losses throughout the ALCELL® pulping system.
- ⑤ Distillate from the pressure and vacuum towers in the alcohol recovery area (Section 8).

During the alcohol recovery process, furfural may be recovered by removing it from certain stages of the distillation columns. The furfural solution that is drawn off these towers is fed to a decanter where it is allowed to settle so that a furfural rich layer (Stream CH) may be tapped and sent directly to Section 11 (Furfural Recovery).

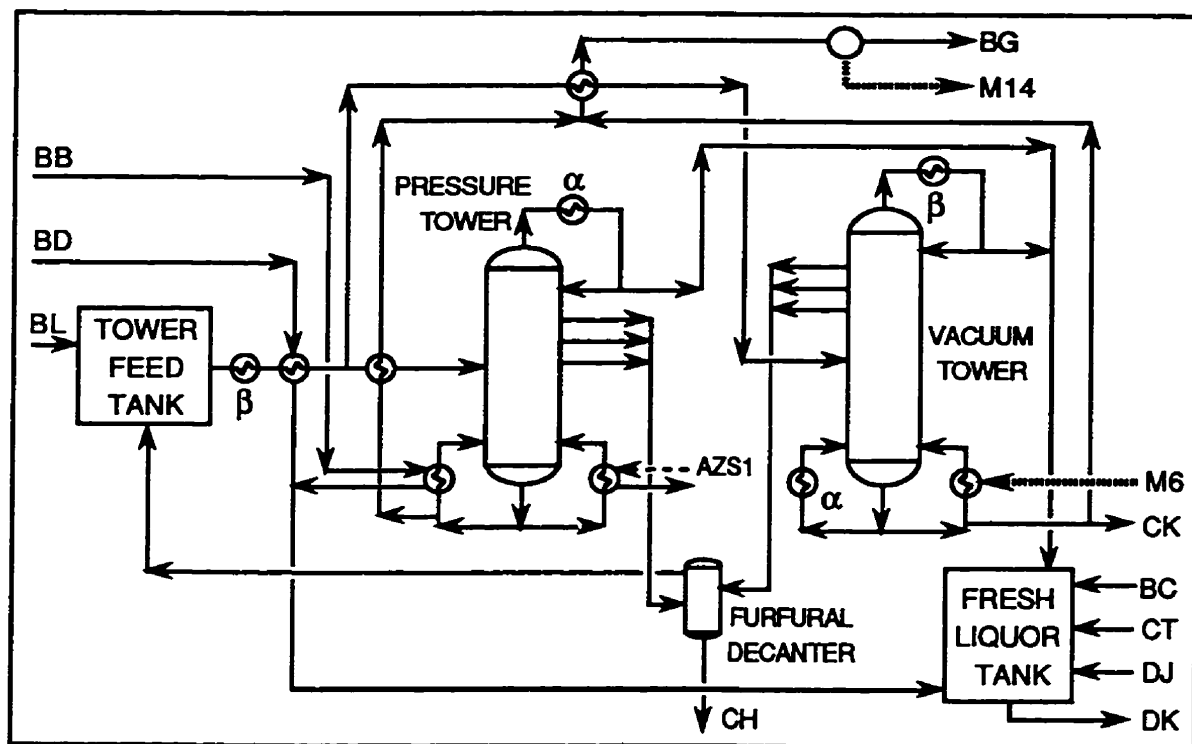
Heat is removed from the pressure distillation tower's stillage before it is combined with the stillage from the vacuum distillation tower. This heat (Stream

M2) is used to pre-heat the make-up boiler feed water, see Figure 3.17b, that enters the cogeneration area (Section 14).

The combined stillage is now divided into two streams. One of these streams (Stream BG) is fed to the mix tank located in Section 6 (Lignin Recovery). The other part of this stillage stream (Stream CK) is sent to Section 9 as the feed for the mechanical vapor recompression (MVR) evaporator.

Before the stillage (Stream BG) enters the mix tank in Section 6, heat is removed from it. This heat (Stream M14) is used to pre-heat wash water that is used in the ALCELL® process.

Heat is supplied to the alcohol recovery section (Section 8) by; condensing the low and high pressure flash vapors, recovering heat (Stream M6) from the finisher evaporator, and supplying heat by using medium pressure steam (Stream AZS1).



Stream AZS1 $\Rightarrow$ Medium Pressure Steam
 Stream BB $\Rightarrow$ High Pressure Flash Vapor
 Stream BC $\Rightarrow$ MP Flash Condensate
 Stream BD $\Rightarrow$ Low Pressure Flash Vapor
 Stream BG $\Rightarrow$ Recirculated Stillage
 Stream BL $\Rightarrow$ Filtrate/Tower Feed
 Stream CH $\Rightarrow$ Decanted Furfural
 Stream CK $\Rightarrow$ MVR Evaporator Feed
 Stream CT $\Rightarrow$ Recovered Alcohol
 Stream DJ $\Rightarrow$ Make-up Alcohol

Stream DK $\Rightarrow$ Fresh Liquor
 Stream M6 $\Rightarrow$ Recovered Heat form Finisher Evaporator
 Stream M14 $\Rightarrow$ Recovered Heat to Wash Water
 Stream α $\Rightarrow$ Heat Transferred from Pressure Tower Condenser to Vacuum Tower Reboiler
 Stream β $\Rightarrow$ Heat Transferred from Vacuum Tower Condenser to Feed Preheater

Figure 3.9 — Diagram of the Alcohol Recovery Section

3.2.9 Section 9 — Mechanical Vapor Recompression Evaporator

Stillage (Stream CK) from Section 8 is fed to the Mechanical Vapor Recompression (MVR) evaporator section of the plant. A schematic diagram of the MVR evaporator is shown in Figure 3.10.

Upon entering Section 9 the stillage is immediately combined with some recycled flash condensate. This mixture is heated with flash vapors that have been compressed by a steam turbine compressor. For the case that has been studied for this thesis, a steam driven compressor was considered. However, there is a possibility that the compressor could be driven by electricity.

The steam (Stream CM) that drives the turbine for the MVR evaporator has an inlet pressure of 4.24 MPa (600 psig). The steam is then expanded and exhausted as high pressure steam that can be used elsewhere in the plant. At this pressure the exhaust steam reenters the steam supply system as shown in Figure 3.16. The inlet and outlet conditions (i.e., temperature, enthalpy and entropy) are subject to the isentropic expansion efficiencies of the main steam turbine and the MVR evaporator turbine.

After heating, the mixture of stillage and recycled flash condensate is sent to a flash tank. The flash vapors produced in this tank are sent to the steam turbine compressor after which they are used to heat more incoming mixture. The flash condensate, some of which is recycled for mixing, is sent to a tar decanter where it is allowed to separate into two layers. One of these layers is referred to as a tar layer (Stream EB) and the other is called the aqueous layer (Stream EA).

The tar layer is sent to Section 14 where it is used as a fuel for generating steam. The aqueous layer is sent to the furfural reactor located in Section 10.

While heating the feed mixture for the flash tank, the compressed flash vapors are condensed. This condensate is now split into two streams. One of these streams is used as wash water (Stream BR) in the lignin recovery area (Section 6). Before this stream enters the lignin recovery area, heat is recovered from it so that the heat can be used in other sections of the plant. Recovered heat from this stream is used for two purposes; the first purpose is to provide heat (Stream M4) to the nitrogen loop in Section 7, the other purpose is to provide heat (Stream M20) for pre-heating the wash water supply.

The other condensate stream (Stream DI) is sent directly to the sewer after some heat is recovered from it. The recovered energy streams are used to pre-heat the caustic solution supply (Stream M12) and to pre-heat the chlorine dioxide solution supply (Stream M13).

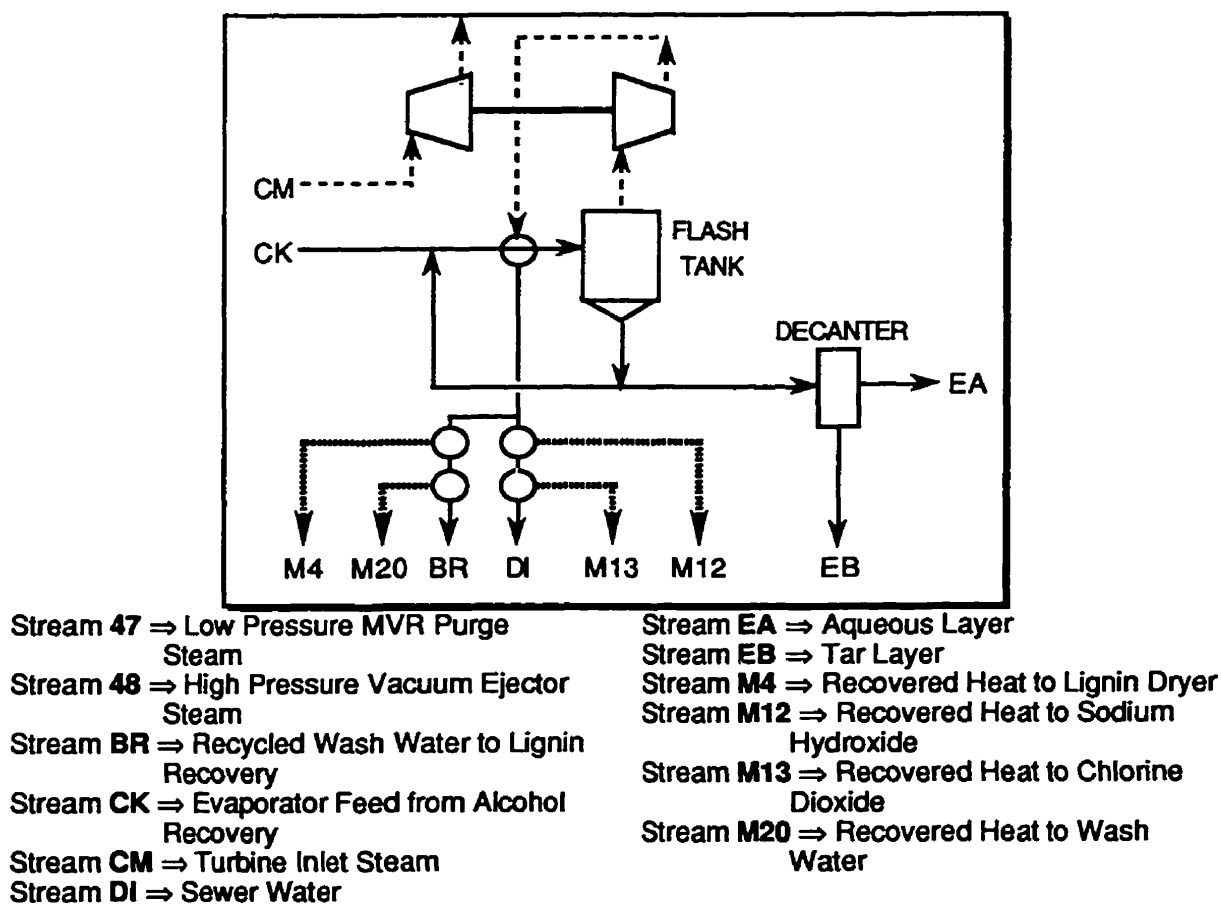
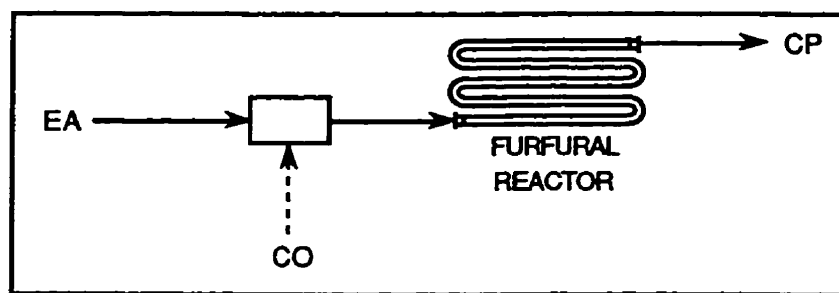


Figure 3.10 — Diagram of the MVR Evaporator

3.2.10 Section 10 — Furfural Reactor

The aqueous layer (Stream EA) that was taken from the tar decanter located in Section 9 is fed to the furfural reactor, as shown in Figure 3.11.

Before the aqueous layer is fed to the furfural reactor it is mixed with 4.24 MPa (600 psig) steam. Once the mixture is in the furfural reactor, some of the syrups that are present are converted to furfural. When the reacted furfural stream (Stream CP) leaves the furfural reactor it is sent directly to Section 11 where the furfural can be recovered.



Stream CO $\Rightarrow$ Furfural Reactor Steam

Stream CP $\Rightarrow$ Reacted Furfural

Stream EA $\Rightarrow$ Aqueous Layer from MVR Evaporator

Figure 3.11 — Diagram of the Furfural Reactor

3.2.11 Section 11 — Furfural Recovery

The reacted furfural stream (Stream CP) entering the furfural recovery area (Section 11) is combined with the decanted furfural stream (Stream CH) from Section 8. This mixture is then fed to the first distillation tower that is located in Section 11. A schematic diagram of the Furfural Recovery section is shown in Figure 3.12.

Any alcohol that is present in the first tower's feed is recovered as distillate (Stream CT) and sent to the fresh liquor tank that is located in Section 8. The stillage leaving the first tower is sent on to more towers where any syrups that are present are removed and sent to the finishing evaporator (Section 12).

The remainder of the stream that was fed to the furfural recovery area is separated into a light furfural fraction and a heavy furfural fraction. The light fraction is a salable product (Stream DB) while the heavy fraction (Stream DC) is used as a fuel for the steam generation in Section 14.

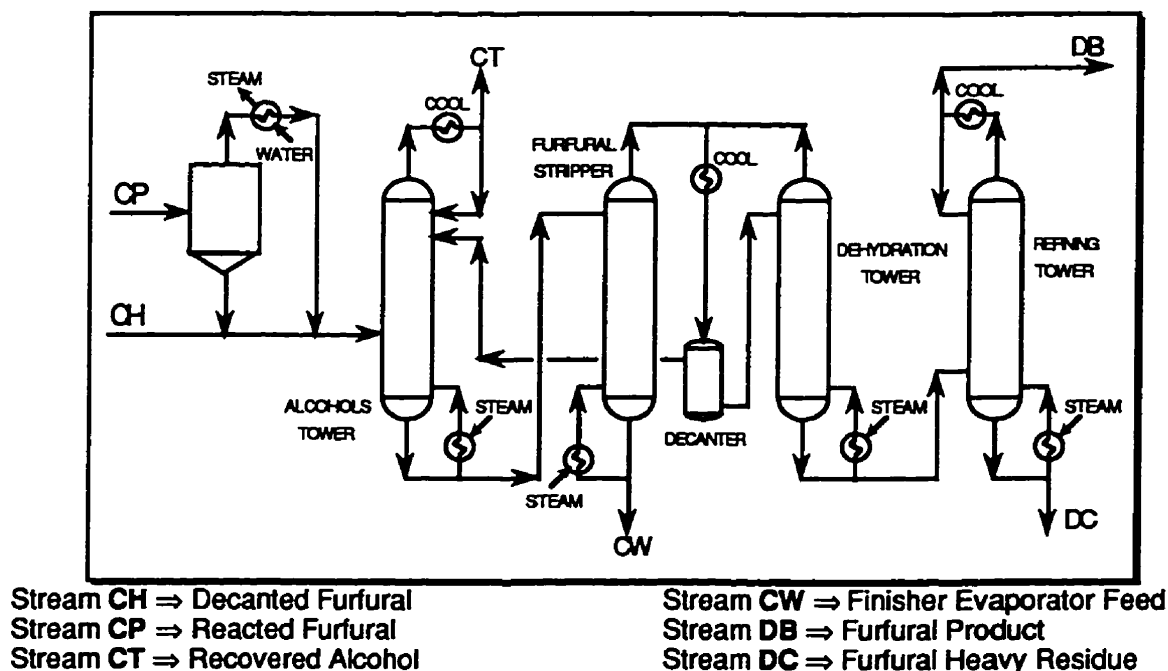


Figure 3.12 — Diagram of the Furfural Recovery Section

3.2.12 Section 12 — Finisher Evaporator

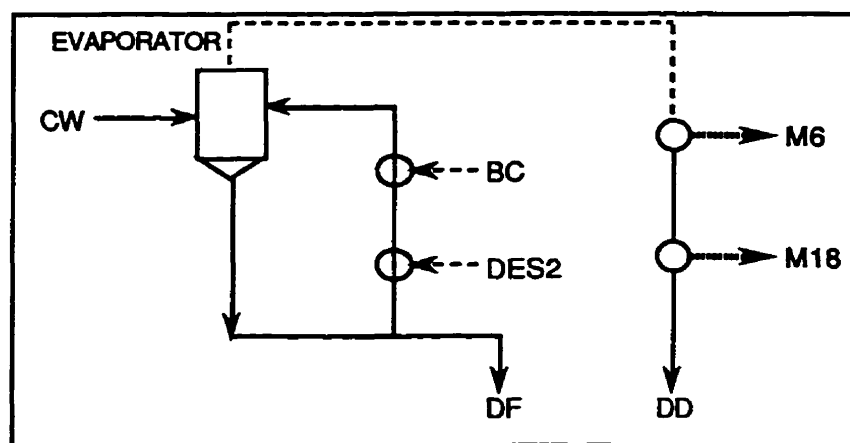
The syrups recovered from Section 11 (Stream CW) are sent to the finisher evaporator located in Section 12. A schematic diagram of the finisher evaporator is shown in Figure 3.13.

The intermediate pressure flash vapor (Stream BC), that is produced in Section 2, is condensed in the finisher evaporator so that the energy released during condensation may be used to reduce the steam requirement of the evaporator. The flash vapor condensate is then sent to the fresh liquor tank located in Section 8.

The evaporator requires more heat than is available from the flash vapor. This additional heat is supplied by medium pressure steam (Stream DES2).

The concentrated syrups (Stream DF) are removed from the evaporator once the desired concentration is reached. These syrups can either be sold as a by-product or used as a fuel for generating steam in section 14.

Condensate (Stream DD) that is produced while concentrating the syrups is sent to the sewer after some useful heat is recovered from it. Recovered energy from the condensate is used for two purposes. One of the energy streams (Stream M18) is used to pre-heat make-up boiler feed water while the other stream (Stream M6) is used in the reboiler of the pressure alcohol recovery distillation tower that is located in Section 8.



Stream **BC** ⇒ Medium Pressure Flash Vapor for Indirect Heating

Stream **CW** ⇒ Finisher Evaporator Feed from Furfural Recovery

Stream **DD** ⇒ Sewer Water

Stream **DES2** ⇒ Medium Pressure Indirect Heating Steam

Stream **DF** ⇒ Concentrated Syrups

Stream **M6** ⇒ Recovered Heat to Alcohol Recovery

Stream **M18** ⇒ Recovered Heat to Make-up Boiler Feed Water

Figure 3.13 — Diagram of the Finisher Evaporator

3.2.13 Section 13 — Chlorine Dioxide Generator

The chlorine dioxide generator design [14] that has been adopted for this study is the *Albright & Wilson (ERCO) R8* model chlorine dioxide generator. This type of generator was chosen because it has advantages over other chlorine dioxide generators that are available at the present time. Some of these advantages are; higher ClO_2 plant generating capacity, faster ClO_2 generation response, higher monthly efficiency in converting sodium chlorate to ClO_2 , and the elimination of Cl_2 by-product handling. These advantages have been noticed by bleached pulp producers throughout the world with the result being that more than 50% of the world's requirement of chlorine dioxide is now produced by the R8 process.

The *Albright & Wilson (ERCO) R8* chlorine dioxide generator is classified as a non-integrated methanol-based chlorine dioxide plant. A flow diagram of this plant is given in Figure 3.14.

The generating system is fed by sodium chlorate & methanol (Stream 807), and sulfuric acid (Stream 801), with sodium sesqui sulfate (Stream 84) being formed as a byproduct. Chlorine dioxide is produced according to the following overall reaction:



The methanol and sodium chlorate are added to the generator's liquor prior to the reboiler where it is heated with indirect low pressure steam (Stream 803). The generator liquor is circulated between the generator and reboiler by using a pump. After the liquor passes through the reboiler sulfuric acid is added. The mixture of liquor and sulfuric acid is now fed to the generator where the

above reaction is allowed to proceed. The chlorine dioxide gas mixture leaving the generator enters an indirect contact cooler where the water vapor that is present condenses. The chlorine dioxide gas stream now passes on to an absorption tower, where chilled water (Stream 816) absorbs the chlorine dioxide. This chlorine dioxide solution (Streams FP & GS) then passes on to a chlorine dioxide solution tank where it is kept until it is required in the bleach plant (Section 4).

The sodium sesqui-sulfate $\{Na_3H(SO_4)_2\}$ slurry (Stream 84) produced in the generator is filtered before it is relegated to a waste storage facility.

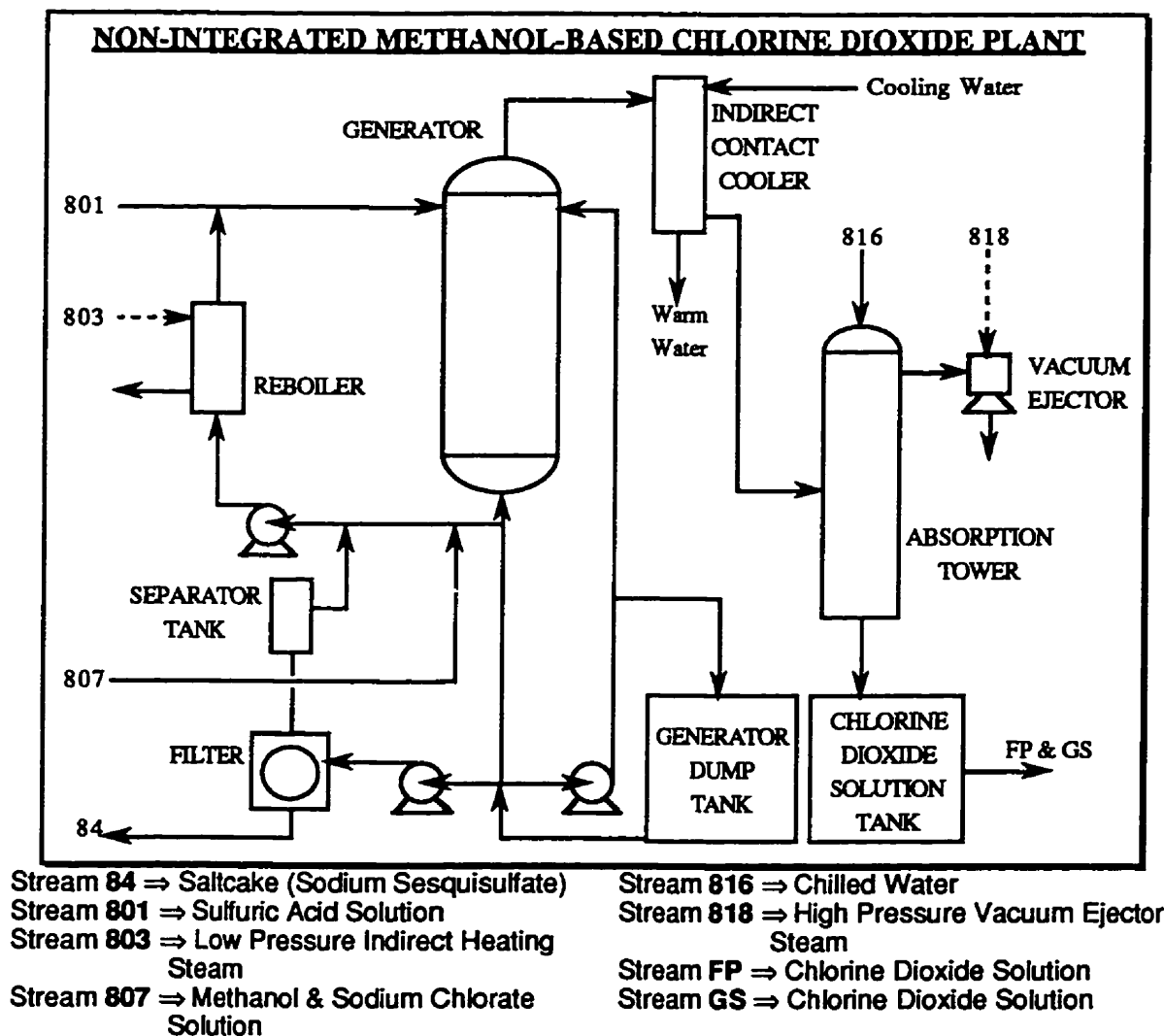


Figure 3.14 — Schematic Diagram of a Chlorine Dioxide Plant

3.2.14 Section 14 — Cogeneration

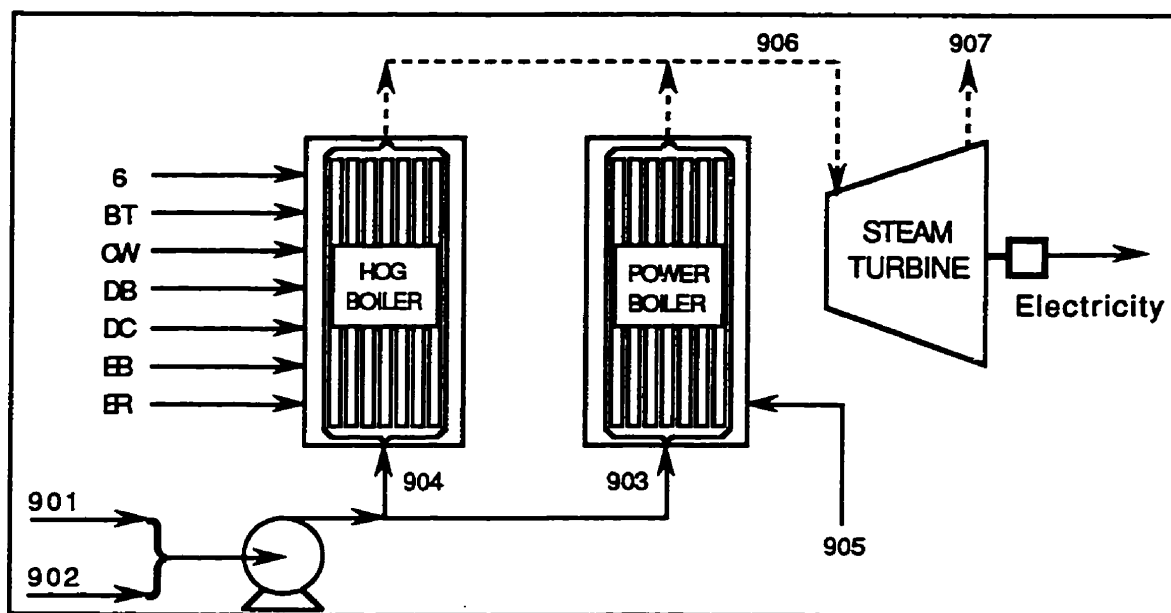
Cogeneration is defined as being “an energy production process involving the simultaneous generation of thermal (e.g., process-steam) and electric energy by using a single primary heat source.” [10]

Schematic diagrams of the steam production arrangement and the steam supply system are shown in Figures 3.15 & 3.16. A cogeneration system has been incorporated into the design of the ALCELL® process in order to take advantage of the possibility that burning some, or all, of the byproducts from the process in a boiler will result in the production of steam that will be used elsewhere in the process. The byproducts that can be used to raise steam in a boiler are as follows: Hog fuel (Stream 6), Wet Lignin Cake (Stream BT), Finisher Evaporator Feed (Stream CW), Furfural Product (Stream DB), Furfural Heavy Residue (Stream DC), Hot Decanter Tar (Stream EB), and the Brownstock Screen Rejects (Stream ER). It is possible to burn any combination of these streams, however, the most probable combination includes streams; 6, DC, EB, and ER.

The “Hog” and “Power” boilers produce steam at high temperature, 510°C (950°F) and pressure, 8.72 MPa (1250 psig) so that it can be expanded through a steam turbine to produce electricity. This electricity will be used to offset the imported electricity requirement of the ALCELL® process.

For the purpose of this study, the cogeneration system has been sized to meet the process steam requirement of the ALCELL® process. Additional electrical energy requirements are purchased from an electric utility. The process-heat requirement of this plant was determined by using the steam supply system that is shown in Figure 3.16. In the event that there is not enough steam

generated by the combustion of the available by-products then the shortfall is generated by burning Bunker C fuel oil in the "Power" boiler. The steam supply system design for the ALCELL® process has not yet been finalized, however, the system shown in Figure 3.16 should closely represent the design that will be constructed if this size plant is built.



Stream 6 ⇒ Hog Fuel from the Woodroom
 Stream 901 ⇒ Make-up Boiler Feed Water
 Stream 902 ⇒ Condensate Boiler Feed Water
 Stream 903 ⇒ Feed Water to Power Boiler
 Stream 904 ⇒ Feed Water to Hog Boiler
 Stream 905 ⇒ Bunker C Fuel Oil
 Stream 906 ⇒ Main Turbine Inlet Steam

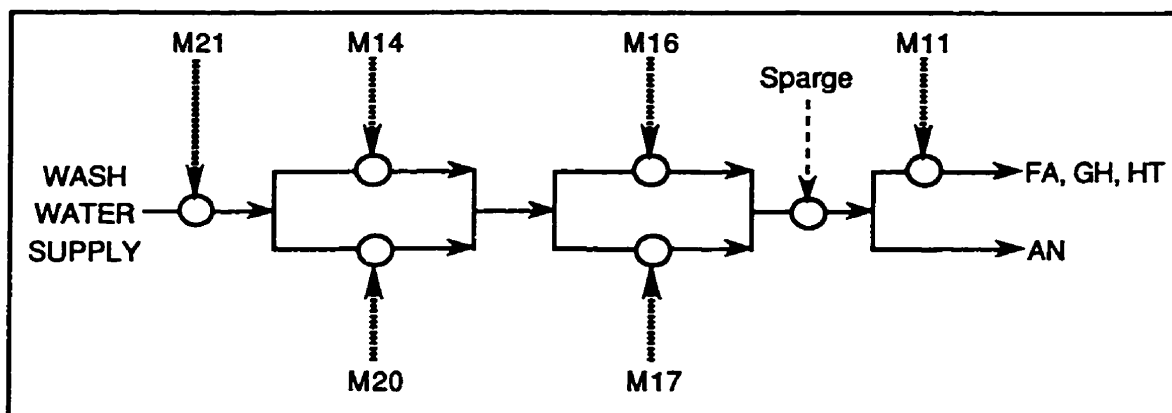
Stream 907 ⇒ Main Turbine Exhaust Steam
 Stream BT ⇒ Wet Lignin Cake
 Stream CW ⇒ Finisher Evaporator Feed
 Stream DB ⇒ Product Furfural (Light Oil)
 Stream DC ⇒ Furfural Heavy Residue
 Stream EB ⇒ Tar Layer from MVR Evaporator
 Stream ER ⇒ Screen Rejects

Figure 3.15 — Steam Production Arrangement for the ALCELL® Process

3.2.15 Section 15 — Water Preheating

The ability to pre-heat wash water, make-up boiler feed water (BFW), the caustic supply and the chlorine dioxide solution supply has been incorporated into the design for the ALCELL® process.

Heat is recovered from several locations throughout the plant and it is added to the make-up wash water and the boiler feed water as shown in Figure 3.17a and in Figure 3.17b. The wash water's temperature is trimmed by using medium pressure sparge steam as shown in Figure 3.17a.



Stream AN $\Rightarrow$ Wash Water for Section 2

Stream FA $\Rightarrow$ Wash Water for Section 3

Stream GH $\Rightarrow$ Wash Water for Section 4

Stream HT $\Rightarrow$ Wash Water for Section 5

Stream M11 $\Rightarrow$ Recovered Heat from Section 3

Stream M14 $\Rightarrow$ Recovered Heat from Section 8

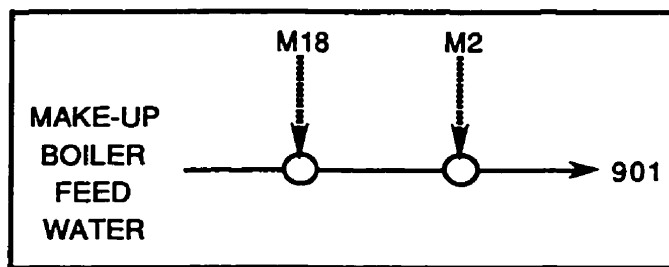
Stream M16 $\Rightarrow$ Recovered Heat from Section 4

Stream M17 $\Rightarrow$ Recovered Heat from Section 3

Stream M20 $\Rightarrow$ Recovered Heat from Section 9

Stream M21 $\Rightarrow$ Recovered Heat from Section 6

Figure 3.17a — Representation of the Wash Water Heating Train



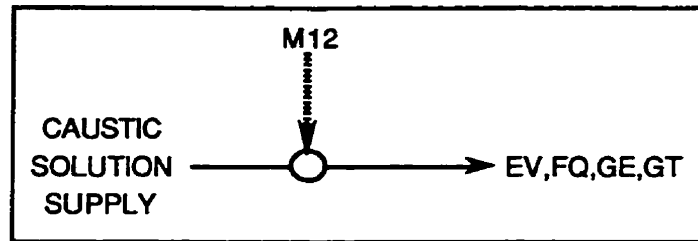
Stream 901 $\Rightarrow$ Make-up Boiler Feed Water

Stream M2 $\Rightarrow$ Recovered Heat from Section 8

Stream M18 $\Rightarrow$ Recovered Heat from Section 12

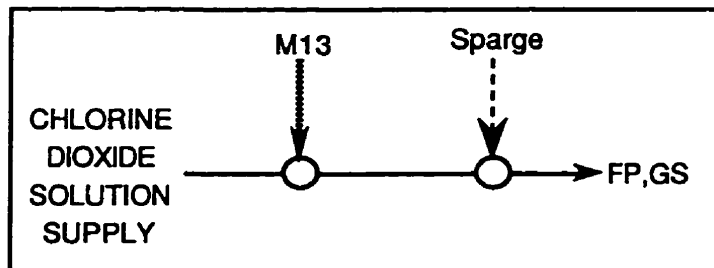
Figure 3.17b — Representation of the Make-up BFW Heating Train

Heat recovered from the MVR's condensate stream (Streams M12 & M13) is used to pre-heat the caustic supply and the chlorine dioxide supply (see Figures 3.17c & 3.17d). Additional heat required for the chlorine dioxide solution is supplied by medium pressure sparge steam as shown in Figure 3.17d.



Stream EV $\Rightarrow$ Sodium Hydroxide Solution
Stream FQ $\Rightarrow$ Sodium Hydroxide Solution
Stream GE $\Rightarrow$ Sodium Hydroxide Solution
Stream GT $\Rightarrow$ Sodium Hydroxide Solution
Stream M12 $\Rightarrow$ Recovered Heat from Section 9

Figure 3.17c — Representation of Caustic Solution Pre-Heating



Stream FP $\Rightarrow$ Chlorine Dioxide Solution
Stream GS $\Rightarrow$ Chlorine Dioxide Solution
Stream M13 $\Rightarrow$ Recovered Heat from Section 9
Stream Sparge $\Rightarrow$ Medium Pressure Injection Steam

Figure 3.17d — Diagram of Chlorine Dioxide Solution Pre-Heating

CHAPTER 4

THE KRAFT PROCESS

4.1 Introduction

The Kraft process was discovered by chance due to an error that occurred while cooking chips to produce pulp at the Munksjö mill in Jönköping, Sweden. These chips were blown prematurely and instead of being dumped into the river they were further processed with the intention of making inferior paper. The result, however, was the production of a paper that, although darker in color, surpassed the strength of any previously made paper. Undercooking of the chips became the regular practice for the production of wrapping paper. This wrapping paper was so much stronger than other wrapping papers that it adopted the name “kraft”, which means “strong” in both the Swedish and German languages. A man by the name of C.F. Dahl of Danzig, Germany, is usually credited with the development of the Kraft, or sulfate, process in 1879. [7]

The Kraft process, which uses a mixture of sodium sulfide (Na_2S) and sodium hydroxide (NaOH) to pulp wood, was first introduced to North America by the Brompton Pulp and Paper Company at East Angus, Quebec, Canada. The Kraft process uses sodium sulfate (Na_2SO_4) as a makeup to replenish any chemical losses from the process. For this reason, this method of producing wood pulp came to be called the “sulfate” process. The sodium sulfate is fed to the recovery boiler where it is reduced to sodium sulfide.

The Kraft process is considered to be a universal pulping process because it can pulp almost any wood species. This provides the Kraft process with a significant advantage over the ALCELL® process because at the present time the ALCELL® process is capable of pulping only certain species of hardwood.

In order to compare the Kraft process to the ALCELL® process certain criteria must be established. These include:

- ① The pulp produced by each of these mills must be made from the same type of wood. This is necessary due to the wide range of component compositions for different wood species. For this study, hardwood is the only acceptable choice because the ALCELL® process is unable to pulp softwood at the present time.
- ② When considering the design for each of these processes, present day technology must be applied so that the comparison is valid for the time frame that coincides with the publication date of this thesis.
- ③ Areas of the two processes that are not directly involved with the cooking/extraction and recovery sections of the plant are considered to be identical to each other. Therefore, the following sections of the two processes are considered to be identical: the Woodroom, Bleach Plant, Pulp Machine and Chlorine Dioxide Plant.

Once a design for the Kraft mill was determined, using the above criteria, a spreadsheet program was constructed so that the mass and energy flows associated with this design could be simulated. The value(s) of the products leaving this plant were then determined from a Cumulative Energy Consumption perspective.

4.2 Process Description

The design of the Kraft mill has been based on a state-of-the-art Kraft mill that is currently under construction in Athabasca, Alberta, Canada.

In order to perform this study on the Kraft process it was necessary to divide the flowsheet of the process into a number of smaller sections. Therefore, it is by these sections that the process will be described in the following pages.

The stream labels that will be referred to in the following descriptions of the various sections of the Kraft process may be found in Figure 4.1 and on the individual schematics that have been included with certain sections of the following description of the plant.

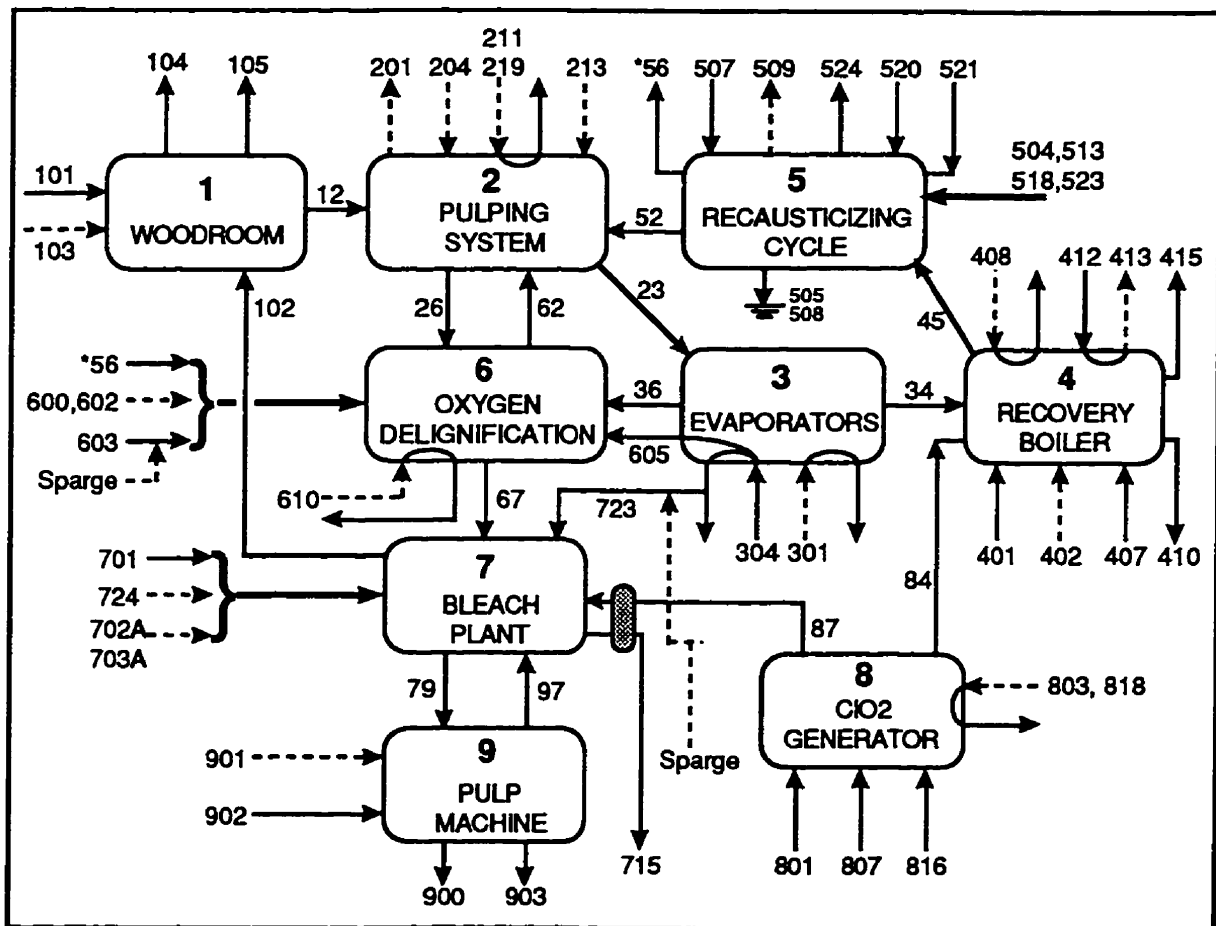


Figure 4.1 — Schematic Representation of the Kraft Process

Table 4.1 — Stream Labels for the Kraft Process

Stream 12 ⇒ Wood Chips	Stream 415 ⇒ Stack Gas
Stream 23 ⇒ Weak Black Liquor	Stream 504 ⇒ Wash Water
Stream 26 ⇒ Screened Pulp	Stream 505 ⇒ Dregs
Stream 34 ⇒ Strong Black Liquor	Stream 507 ⇒ Makeup Lime
Stream 36 ⇒ Evaporator Condensate	Stream 508 ⇒ Grits
Stream 45 ⇒ Smelt	Stream 509 ⇒ Evaporated Water
Stream 52 ⇒ White Liquor	Stream 513 ⇒ Wash Water
Stream 56 ⇒ White Liquor	Stream 518 ⇒ Dilution Water
Stream 62 ⇒ Pre-Oxygen Washer Filtrate	Stream 520 ⇒ Bunker C Fuel Oil
Stream 67 ⇒ Oxygen Delignified Pulp	Stream 521 ⇒ Combustion Air
Stream 79 ⇒ Bleached Pulp	Stream 523 ⇒ Wash Water
Stream 84 ⇒ Saltcake (Sodium Sesquisulfate)	Stream 524 ⇒ Scrubbed Flue Gas
Stream 87 ⇒ Chlorine Dioxide Solution	Stream 600 ⇒ Low Pressure Injection Steam
Stream 97 ⇒ Recirculated Wash Water	Stream 602 ⇒ High Pressure Injection Steam
Stream 101 ⇒ Logs	Stream 603 ⇒ Oxygen & Magnesium Sulfate
Stream 102 ⇒ Recirculated Wash Water	Stream 605 ⇒ Wash Water
Stream 103 ⇒ Low Pressure Injection Steam	Stream 610 ⇒ Low Pressure Indirect Heating Steam
Stream 104 ⇒ Hog Fuel (Bark & Fines)	Stream 701 ⇒ Caustic Solution & Chemicals
Stream 105 ⇒ Sewer Water	Stream 702A ⇒ Eo Stage Low Pressure Indirect Heating Steam
Stream 201 ⇒ Steaming Vessel Purge	Stream 703A ⇒ D2 Stage Low Pressure Indirect Heating Steam
Stream 204 ⇒ Low Pressure Injection Steam	Stream 715 ⇒ Sewer Water
Stream 211 ⇒ High Pressure Indirect Heating Steam	Stream 723 ⇒ Pre-Heated Wash Water
Stream 213 ⇒ High Pressure Injection Steam	Stream 724 ⇒ Low Pressure Injection Steam
Stream 219 ⇒ Low Pressure Indirect Heating Steam	Stream 725 ⇒ Sodium Hydroxide Solution
Stream 301 ⇒ Low Pressure Indirect Heating Steam	Stream 801 ⇒ Sulfuric Acid Solution
Stream 304 ⇒ Cooling Water	Stream 803 ⇒ Low Pressure Indirect Heating Steam
Stream 401 ⇒ Saltcake (Sodium Sulfate)	Stream 807 ⇒ Methanol & Sodium Chlorate
Stream 402 ⇒ High Pressure Injection Steam	Stream 816 ⇒ Chilled Water
Stream 407 ⇒ Combustion Air	Stream 818 ⇒ High Pressure Ejector Steam
Stream 408 ⇒ Low Pressure Indirect Heating Steam	Stream 900 ⇒ Pressed Pulp to Pulp Dryer
Stream 410 ⇒ Steam Drum Blowdown	Stream 901 ⇒ Low Pressure Injection Steam
Stream 412 ⇒ Boiler Feedwater	Stream 902 ⇒ Wash Water
Stream 413 ⇒ Main Steam	Stream 903 ⇒ Screen Rejects to Sewer

4.2.1 Section 1 — The Woodroom

The purpose of the woodroom is to produce wood chips, that are free of “fines” (small wood chips) and bark, from tree length logs. A schematic diagram of the woodroom may be seen in Figure 4.2.

The bark is removed from the logs (Stream 101) in the debarking drum. During the winter months, low pressure injection steam (Stream 103) is used to thaw the logs that are entering the debarking drums.

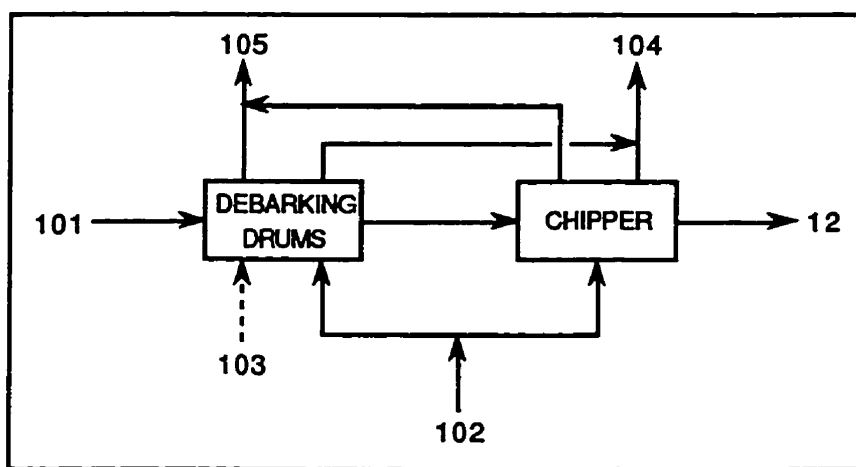
Upon leaving the debarking drums, the cleaned logs are passed on to a chipper where they are reduced to wood chips (Stream 12). While the logs are being reduced to chips, wood fines or pin chips are also produced. These pin chips are not desirable from an operations perspective in the extraction vessel so they are removed at this stage by a set of screens.

The bark that is removed from the logs in the debarking drums is combined with the pin chips produced in the chipper. This combined stream is referred to as “Hog fuel” (Stream 104). The “Hog fuel” stream is sent to the “Hog pile” where it is stored until it is burnt in a boiler that produces steam for the process. The boiler that the bark and pin chips are burnt in is called the “Hog boiler”. Details about the “Hog boiler” will be discussed in Section 10 of this chapter.

During the debarking and chipping procedure, water for washing and sluicing is often required. This water is available as recycled white water (Stream 102) that comes from the bleach plant (Section 7). However, recent developments in woodroom technology has led to what is known as ‘dry’ woodrooms where very little, if any, water is required for washing or sluicing.

Used wash and sluicing water (Stream 105) leaving the woodroom is sent to the sewer.

The wood chips that are produced by the chipper (Stream 12) are now fed to the extraction vessel located in Section 2.



Stream 101 ⇒ Logs
Stream 102 ⇒ Recirculated Wash Water from the Bleach Plant
Stream 103 ⇒ Low Pressure Injection Steam
Stream 104 ⇒ Hog Fuel (Bark & Fines)
Stream 105 ⇒ Sewer Water
Stream 12 ⇒ Wood Chips

Figure 4.2 — Diagram of the Kraft Woodroom

4.2.2 Section 2 — Pulping System

The pulping system for the proposed “modern day” Kraft mill is shown in Figure 4.3. The main unit of the pulping system is known as a Kamyr high-pressure two-vessel vapor/liquid phase continuous digester. This type of digester was determined to be the most likely candidate for the following reasons:

- ① The two-vessel digester system is able to handle lower quality wood finishes than the hydraulic digester.
- ② The separate impregnation vessel of the two-vessel digester system allows increased flexibility in process conditions and improved control over the impregnation and cooking stages than the vapor/liquid phase digester without the impregnation vessel.
- ③ The high pressure version of the two-vessel vapor/liquid digester provides better impregnation of the chips than the low pressure version.
- ④ The high pressure two-vessel digester has a higher cooking efficiency (acceptable pulp/pulp produced) for a given effective alkali charge than other continuous digester systems such as: (1) standard hydraulic system; (2) low pressure impregnation plus vapor/liquid phase; and (3) vapor/liquid without impregnation.

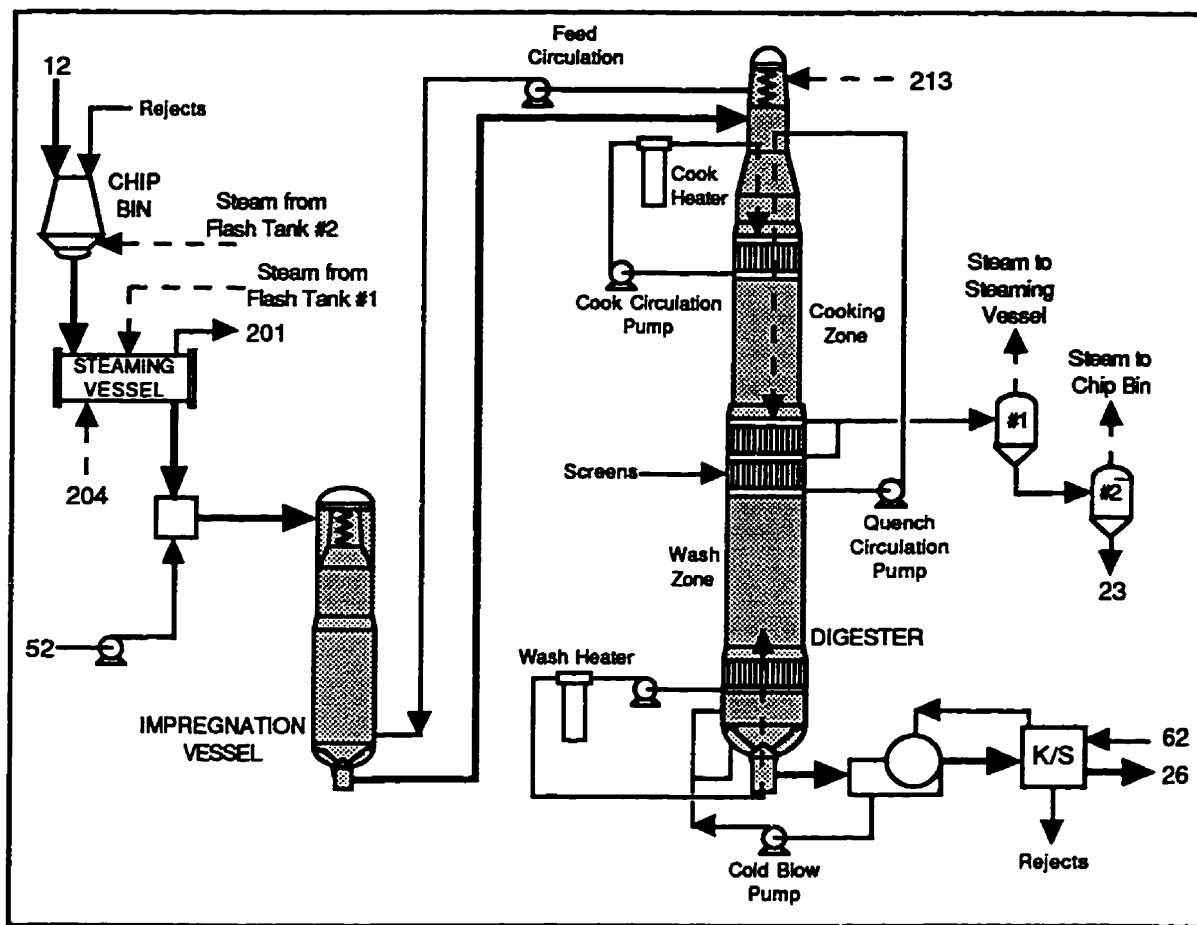
Wood chips (Stream 12), upon entering Section 2, are fed to the chip bin where they are heated with steam from the second black liquor flash tank. The chips remain in the chip bin for approximately 10 minutes before they are passed on to the steaming vessel where they are held for 1-2 minutes. While the chips are in the steaming vessel they are heated with steam from the first black liquor flash tank. Additional heat is supplied by low pressure¹ steam (Stream 204). After

¹ Low Pressure equates to 515 kPa (60 psig) throughout Chapter 4 when referring to steam.

heating is completed the chips are mixed with white liquor before being pumped into the impregnation vessel. The impregnation vessel's operating conditions 1140 kPa (150.65 psig) and 110°C (230°F) provide very good impregnation of the chips. The impregnated chips are fed to the digester where they are cooked to a pulp. Heat is supplied to the digester by high pressure² injection steam (Stream 213) and by using high and low pressure steam in the heaters shown in Figure 4.3. The pulp leaving the digester is passed through an atmospheric diffusion washer before being sent to a set of knotters and screens. The knotters and screens remove any unacceptable material from the pulp stream so that they can be conveyed back to the chip bin for further cooking. The remainder of the pulp stream (Stream 26) is passed on to the Oxygen Delignification section.

Black liquor is extracted from the digester through screens to prevent the pulp from leaving with it. Upon extraction the black liquor is concentrated by passing it through two flash tanks. The flashed black liquor (Stream 23) is sent to the evaporators (Section 3) where further concentration will be achieved.

² High Pressure equates to 1204.5 kPa (160 psig) throughout Chapter 4 when referring to steam.



Stream 12 ⇒ Wood Chips

Stream 23 ⇒ Weak Black Liquor

Stream 26 ⇒ Screened Pulp

Stream 52 ⇒ White Liquor

Stream 62 ⇒ Oxygen Washer Filtrate

Stream 201 ⇒ Steaming Vessel Purge Steam

Stream 204 ⇒ Low Pressure Injection Steam

Stream 213 ⇒ High Pressure Injection Steam

Figure 4.3 — Kamyr Two Vessel Vapor/Liquid Phase Continuous Digester

4.2.3 Section 3 — Black Liquor Evaporators

Flashed black liquor from the digester is fed to a multiple-effect evaporator train as shown in Figure 4.4. The black liquor collected from the pulp washing system is normally in the range of 13% to 17% solids and is referred to as weak black liquor. This must be concentrated to about 65% solids for firing in the recovery boiler. Currently there are three approaches used by the pulp and paper industry to raise the black liquor's concentration to the level required for burning in the recovery boiler.

- ① Concentrate the liquor to about 50% solids in a multiple-effect evaporator train and then bring it to firing strength in a concentrator.
- ② Concentrate the liquor to 65% solids in a multiple-effect train, as shown in Figure 4.4, using evaporators that are not very sensitive to viscosity and fouling problems. Fouling of evaporators occurs readily at concentrations above 50%.
- ③ Concentrate the liquor to about 50% solids in a multiple-effect evaporator train and then bring it to firing strength in a direct contact evaporator.

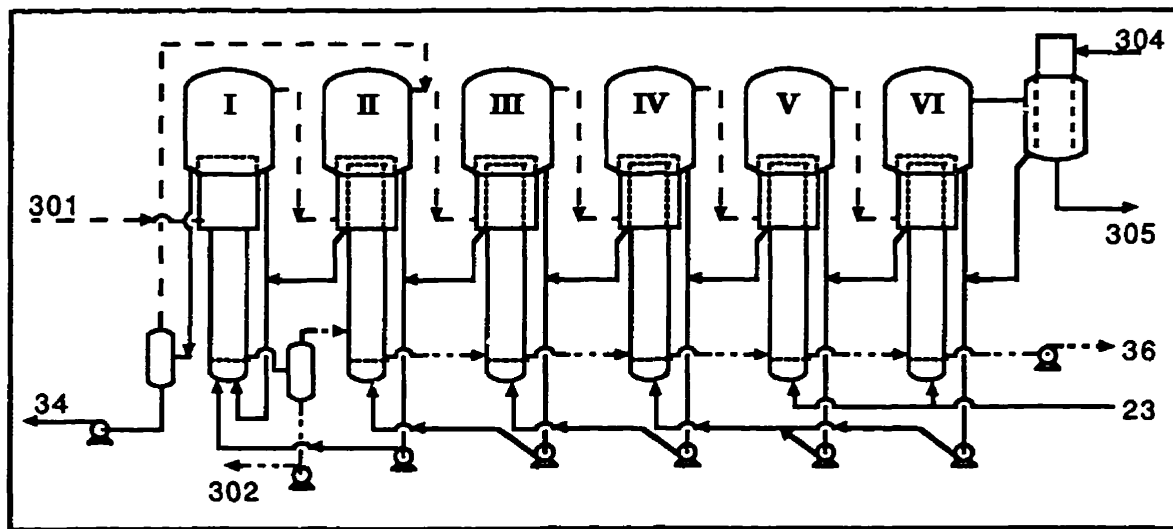
For the purpose of this study it was assumed that the black liquor was brought to its firing conditions by a multiple-effect evaporator train with a given steam economy. Steam economy is defined as the mass ratio of water evaporated to steam used. Heat is supplied to the evaporator train by low pressure indirect heating steam (Stream 301).

The multiple-effect evaporator's condenser uses cooling water to remove heat. The return cooling water (Stream 305) is used elsewhere in the plant for the following purposes:

- ① Make-up feedwater for the steam generation cycle.
- ② Shower water for the washing stages in the Oxygen Delignification area (Section 6).
- ③ Shower water for the washing stages in the Bleach Plant (Section 7).
- ④ Shower water for the washers and filters in the recausticizing cycle (Section 5).

The water evaporated from the weak liquor stream is condensed and combined so that it can be used as shower water in the Oxygen Delignification section (Section 6).

The concentrated black liquor produced by the evaporators is known as strong black liquor (Stream 34). The strong black liquor is fed to the recovery boiler (Section 4) where the chemical recovery process begins.



Stream 23 $\Rightarrow$ Weak Black Liquor (13-17% solids)
 Stream 34 $\Rightarrow$ Strong Black Liquor ($\approx$ 65% solids)
 Stream 36 $\Rightarrow$ Condensate
 Stream 301 $\Rightarrow$ Low Pressure Indirect Heating Steam
 Stream 302 $\Rightarrow$ Low Pressure Steam Condensate
 Stream 304 $\Rightarrow$ Cooling Water

Figure 4.4 — Sample Multiple-Effect Evaporator Sequence

4.2.4 Section 4 — Recovery Boiler

A general schematic diagram of a Kraft recovery boiler is shown in Figure 4.5. Many of the features of the Kraft recovery boiler are similar to other boiler types. These features include the superheater, boiler bank, economizer, electrostatic precipitator and the induced draft (ID) and forced draft (FD) fans. The differences between this recovery boiler and other boiler types are apparent in the lower section of the furnace. The strong black liquor (Stream 34) that is used as fuel is first mixed with make-up chemicals, usually saltcake (Na_2SO_4) and with the dust recycle from the electrostatic precipitator. Part of the make-up saltcake requirement is provided by the chlorine dioxide generator's byproduct stream (Stream 84). The remainder of the saltcake requirement is provided by a fresh supply of saltcake (Stream 401). Make-up saltcake is required due to losses of sodium (or sodium compounds) in; (1) recovery boiler emissions (Stream 415); (2) lime kiln emissions (Stream 524) and (3) the washed pulp stream (Stream 26) entering the Oxygen Delignification unit (Section 3). The mixed liquor is then heated with direct contact steam before it is sprayed into the boiler by nozzles that are known as liquor guns.

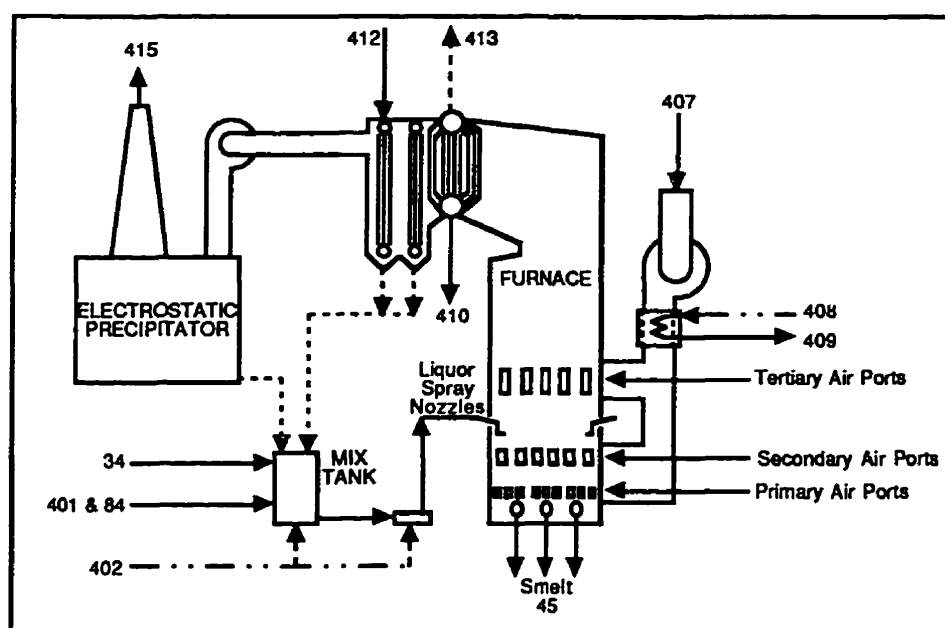
Pre-heated combustion air is introduced by a series of ports located at several elevations in the furnace. Within the boiler an important step in the chemical recovery process is accomplished. The sodium sulfate (Na_2SO_4) is reduced to sodium sulfide (Na_2S) which is the main component of the smelt leaving the boiler. The effectiveness with which a boiler accomplishes this step is known as the boiler's reduction efficiency. A typical value for a boiler's reduction efficiency is 90%.

$$\text{Reduction Efficiency} = \frac{[Na_2S]}{[Na_2S] + [Na_2SO_4]} \times 100\% \quad (4.1)$$

The brackets in Equation 4.1 indicate concentrations of the chemicals that are found in the smelt leaving the recovery boiler and they are expressed on an equivalent sodium oxide (Na_2O) basis.

The smelt (Stream 45) leaving the recovery boiler is fed to the dissolving tank that is located in Section 5.

The steam produced (Stream 413) from the combustion of black liquor is used to generate electricity by passing it through a turbine located in the cogeneration area (Section 10).



- Stream 34 ⇒ Strong Black Liquor
- Stream 45 ⇒ Smelt
- Stream 84 ⇒ Saltcake from ClO_2 Generator (Sodium Sesquisulfate)
- Stream 401 ⇒ Fresh Make-up Saltcake (Sodium Sulfate)
- Stream 402 ⇒ High Pressure Injection Steam
- Stream 407 ⇒ Combustion Air
- Stream 408 ⇒ Low Pressure Indirect Heating Steam
- Stream 410 ⇒ Blowdown
- Stream 412 ⇒ Boiler Feedwater
- Stream 413 ⇒ Main Steam
- Stream 415 ⇒ Stack Gas

Figure 4.5 — Diagram of a Kraft Recovery Boiler

4.2.5 Section 5 — Causticizing Cycle

A schematic diagram of the causticizing cycle is shown in Figure 4.6. The purpose of the recausticizing cycle is to produce acceptable white liquor for the cooking (Stream 52) of wood chips and for chemical addition (Stream 56) to the oxygen delignification section.

The composition of the desired white liquor product is determined by values for the white liquor's sulfidity, total titratable alkali (TTA), active alkali (AA), and by the reduction efficiency of the recovery boiler (Section 4).

$$\text{Sulfidity} = \frac{[Na_2S]}{[Na_2S] + [NaOH]} \text{ or sometimes } \frac{[Na_2S]}{[Na_2S] + [NaOH] + [Na_2CO_3]} \quad (4.2)$$

$$TTA = [NaOH] + [Na_2S] + [Na_2CO_3] + 1/2 [Na_2SO_3] \quad (4.3)$$

$$AA = [NaOH] + [Na_2S] \quad (4.4)$$

The brackets in Equations 4.2 to 4.4 indicate concentrations which are expressed on an equivalent sodium oxide (Na_2O) basis. These concentrations are usually expressed in terms of $g - Na_2O/\ell$ or $lb - Na_2O/ft^3$. The advantage of the Na_2O convention is that the total titratable alkali (TTA) remains constant through the causticizing process.

The first step in producing the white liquor is accomplished in the recovery boiler where sodium sulfate (Na_2SO_4) is reduced to sodium sulfide (Na_2S). The sodium sulfide leaves the recovery boiler, along with sodium carbonate (Na_2CO_3) and small amounts of sodium hydroxide ($NaOH$) and "dregs", in a molten stream known as "smelt" (Stream 45). "Dregs" arise from unburnt carbon, iron salts and other miscellaneous substances that are produced in the recovery boiler.

The “smelt” is fed to the smelt dissolving tank where it is combined with weak wash from the dregs filter and the lime mud washer. This combined stream is then fed to the green liquor clarifier where the dregs are removed and sent to the dregs filter before they are discarded. The overflow is known as clarified green liquor and is fed to the slaker where it is combined with reburned lime (Stream 510) and make-up lime (Stream 507). The reaction of lime (CaO) and water to produce calcium hydroxide (slaked lime) in the slaker is known as the slaking reaction, hence the roots for the name of the slaker is obvious. The slaking reaction is as follows:



Undesirable materials such as overburned and/or unburned lime, sand, and other clinkerous materials are known as “grits”. These “grits” (Stream 508) are removed from the slaker and discarded. The causticized slurry is passed on to the first of a set of three causticizers.

The causticizers provide the retention time and the agitation that is required for the causticizing reaction, which starts in the slaker, to proceed to completion. The causticizing reaction produces sodium hydroxide (NaOH) and calcium carbonate (CaCO_3) according to the following reaction equation.



At this point the two main cooking components of the white liquor have been produced, namely sodium hydroxide (NaOH) and sodium sulfide (Na_2S).

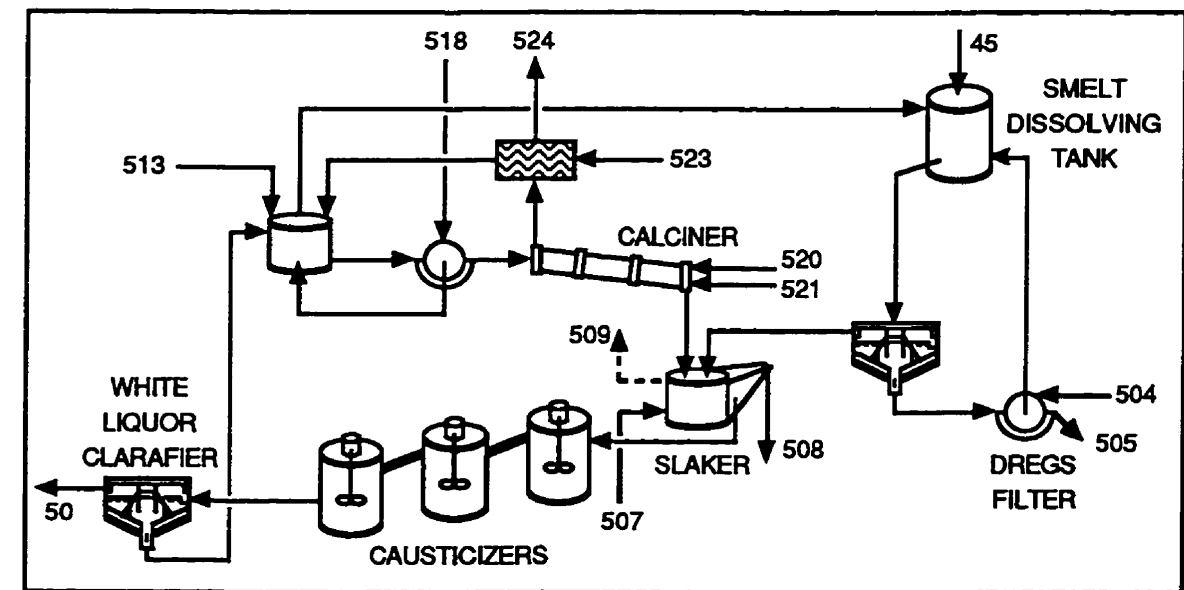
The slurry leaving the causticizers is fed to the white liquor clarifier. The clarifier allows the solids (calcium carbonate) to settle so that they can be removed from the white liquor. White liquor (Stream 50) leaves the clarifier and is

sent to the digester (located in Section 2 as Stream 52) and to the Oxygen Delignification area (Section 6 as Stream 56). The solids that are removed from the white liquor clarifier are known as "lime mud" and they are sent to a lime mud washing and filtering system. After the lime mud is washed and filtered it is fed to a rotary lime kiln where the calcining reaction is allowed to proceed.



The calcium oxide (CaO) produced by the lime kiln is reused in the slaker so that more sodium carbonate (Na_2CO_3) can be regenerated to sodium hydroxide (NaOH).

The calciner's flue gas is fed to a wet flue gas scrubber where any entrained solids are removed before the gases are exhausted to the atmosphere (Stream 524).



Stream 45 $\Rightarrow$ Smelt

Stream 50 $\Rightarrow$ White Liquor

Stream 504 $\Rightarrow$ Wash Water

Stream 505 $\Rightarrow$ Dregs

Stream 507 $\Rightarrow$ Makeup Lime

Stream 508 $\Rightarrow$ Grits

Stream 509 $\Rightarrow$ Evaporated Water

Stream 513 $\Rightarrow$ Wash Water

Stream 518 $\Rightarrow$ Dilution Water

Stream 520 $\Rightarrow$ Bunker C Fuel Oil

Stream 521 $\Rightarrow$ Combustion Air

Stream 523 $\Rightarrow$ Wash Water

Stream 524 $\Rightarrow$ Scrubbed Flue Gas

Figure 4.6 — Diagram of the Causticizing Cycle

4.2.6 Section 6 — Oxygen Delignification

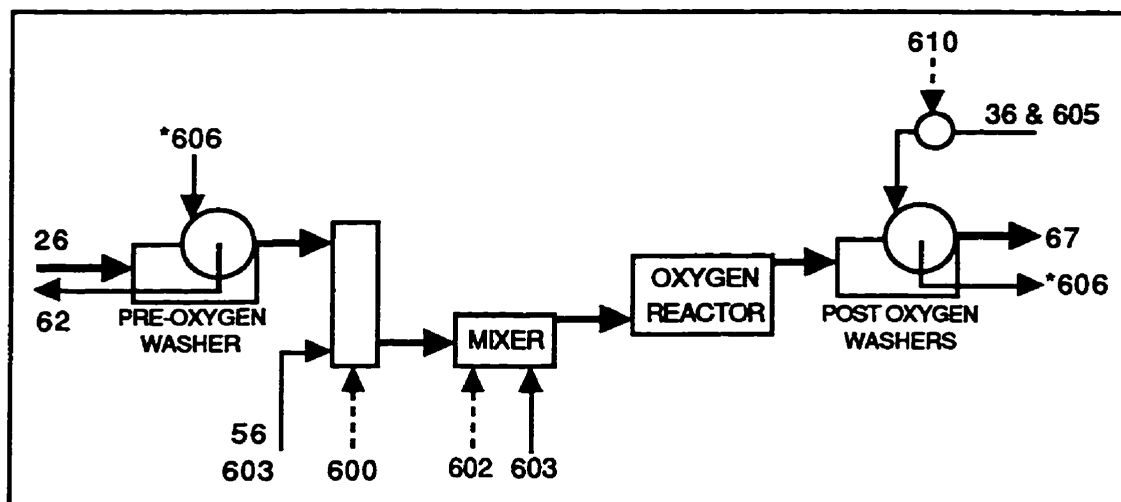
A schematic diagram of the Oxygen Delignification area is shown in Figure 4.7. The pulp stream (Stream 26) entering Section 6 is washed by a pressure washer that uses filtrate from a set of washers located immediately after the oxygen reactor system. The filtrate from the pressure washer (Stream 62) is used as wash water for the pressure screens located in Section 2.

The washed pulp is passed on to a medium consistency mixer where the following streams are added to it: white liquor (Stream 56), magnesium sulfate ($MgSO_4$) (Stream 603), low pressure steam (Stream 600) and high pressure steam (Stream 602). Oxygen (Stream 603) is added to the pulp stream as it enters the oxygen reactor.

The delignification reactions proceed while the pulp mixture is in the oxygen reactor. Upon leaving the reactor, the pulp is washed by a set of washers that use fresh pre-heated water (Stream 605) and condensate (Stream 36), from the black liquor evaporators, as wash water. The washed pulp is stored as a high density mixture before being sent to the bleach plant (Section 7).

The Oxygen Delignification section is expected to reduce the Kappa number (which is a measure of the lignin content) of the pulp from approximately 12 to 8. The relation between the Kappa number and the lignin content [7] of wood pulp is defined as:

$$Kappa\ Number \times 0.15 = Lignin\ Content\ (\%) \quad (4.8)$$



Stream 26 ⇒ Screened Pulp

Stream 36 ⇒ Evaporator Condensate

Stream 56 ⇒ White Liquor

Stream 62 ⇒ Pre-Oxygen Washer Filtrate

Stream 67 ⇒ Oxygen Delignified Pulp

Stream 600 ⇒ Low Pressure Injection Steam

Stream 602 ⇒ High Pressure Injection Steam

Stream 603 ⇒ Oxygen & Magnesium Sulfate

Stream 605 ⇒ Pre-Heated Wash Water

Stream 606 ⇒ Post Oxygen Washer Filtrate

Stream 610 ⇒ Low Pressure Indirect Heating Steam

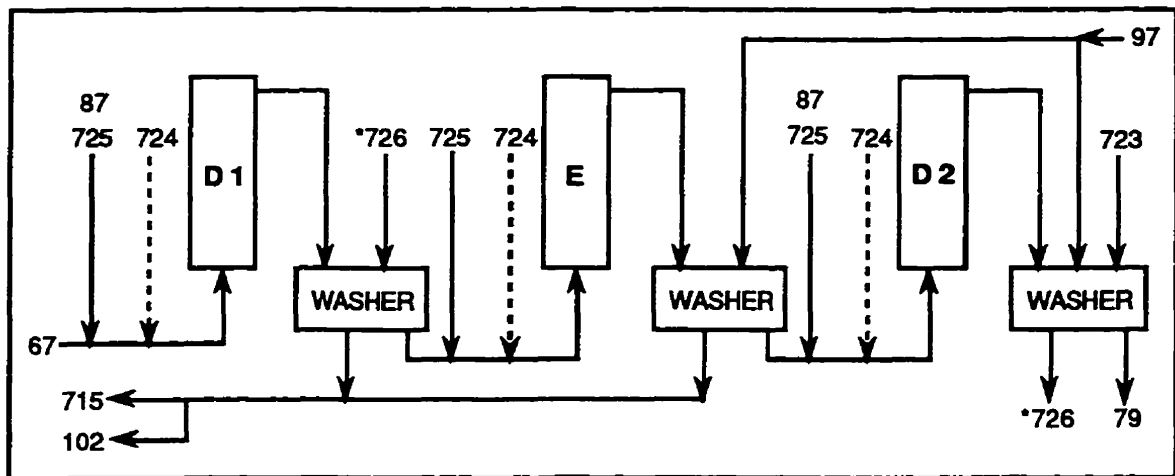
Figure 4.7 — Diagram of the Oxygen Delignification Section

4.2.7 Section 7 — The Bleach Plant

A schematic diagram of the bleach plant used with the Kraft process is shown in Figure 4.8. For this analysis, both the Kraft and ALCELL® processes are pulping hardwood chips. Therefore, the design of the bleach plants used with these processes are identical. Presently, hardwood pulp is bleached using a three stage bleaching sequence as opposed to a four stage sequence that is used for bleaching softwood pulp.

The first stage that the pulp suspension (Stream 67), leaving Section 6, encounters is known as the D₁ stage where chlorine dioxide (Stream 87) is added to the pulp along with sodium hydroxide (Stream 725) and low pressure steam (Stream 724). After the pulp has been retained in the D₁ tower for the required amount of time it is washed, with filtrate from the D₂ stage washer, before being passed on to the second stage of the bleachery, which is known as the E stage or extraction stage. In the E stage sodium hydroxide (Stream 725) and low pressure steam (Stream 724) are mixed with the pulp stream before it enters the E stage retention tower. When the pulp stream leaves this tower it is washed, with part of the recycled water from the pulp machine (Stream 97), and sent to the final bleaching stage. The final bleaching stage is known as the D₂ stage where chlorine dioxide (Stream 87), sodium hydroxide (Stream 725) and low pressure steam (Stream 724) are again added to the pulp stream before it enters the D₂ retention tower. The pulp stream leaving this retention tower is then washed with the remaining portion of the water recycled from the pulp machine (Stream 97) and with fresh pre-heated water (Stream 723). The washed pulp (Stream 79) is now passed on to the pulp machine (Section 9).

Effluent from the bleachery is divided into two streams. One of these streams (Stream 102) is used as wash and sluicing water in the woodroom (Section 1) while the other stream (Stream 715) is sent to the sewer.



Stream 67 ⇒ Oxygen Delignified Pulp
 Stream 87 ⇒ Chlorine Dioxide Solution
 Stream 79 ⇒ Bleached Pulp
 Stream 97 ⇒ Recirculated Wash Water from
 Pulp Machine
 Stream 102 ⇒ Recirculated Wash Water to
 Woodroom

Stream 715 ⇒ Sewer Water
 Stream 723 ⇒ Pre-Heated Wash Water
 Stream 724 ⇒ Low Pressure Injection Steam
 Stream 725 ⇒ Sodium Hydroxide Solution
 Stream 726 ⇒ D2 Stage Washer Filtrate

Figure 4.8 — Diagram of the Bleach Plant of the Kraft Process

4.2.8 Section 8 — Chlorine Dioxide Generator

The chlorine dioxide generator design [14] that has been adopted for this study is the *Albright & Wilson (ERCO) R8* model chlorine dioxide generator. This type of generator was chosen because it has advantages over other chlorine dioxide generators that are available at the present time. Some of these advantages are; higher ClO_2 plant generating capacity, faster ClO_2 generation response, higher monthly efficiency in converting sodium chlorate to ClO_2 , and the elimination of Cl_2 by-product handling. These advantages have been noticed by bleached pulp producers throughout the world with the result being that more than 50% of the world's requirement of chlorine dioxide is now produced by the R8 process.

The *Albright & Wilson (ERCO) R8* chlorine dioxide generator is classified as a non-integrated methanol-based chlorine dioxide plant. A flow diagram of this plant is given in Figure 4.9.

The generating system is fed by sodium chlorate & methanol (Stream 807), and sulfuric acid (Stream 801), with sodium sesqui sulfate (Stream 84) being formed as a byproduct. Chlorine dioxide is produced according to the following overall reaction:



The methanol and sodium chlorate are added to the generator's liquor prior to the reboiler where it is heated with indirect low pressure steam (Stream 803). The generator liquor is circulated between the generator and reboiler by using a pump. After the liquor passes through the reboiler sulfuric acid is added. The mixture of liquor and sulfuric acid is now fed to the generator where the

above reaction is allowed to proceed. The chlorine dioxide gas mixture leaving the generator enters an indirect contact cooler where the water vapor that is present condenses. The chlorine dioxide gas stream now passes on to an absorption tower, where chilled water (Stream 816) absorbs the chlorine dioxide. This chlorine dioxide solution (Streams 87) then passes on to a chlorine dioxide solution tank where it is kept until it is required in the bleach plant (Section 4).

The sodium sesqui sulfate $\{Na_3H(SO_4)_2\}$ slurry produced in the generator is filtered before it is used as make-up saltcake (Stream 84) in the recovery boiler.

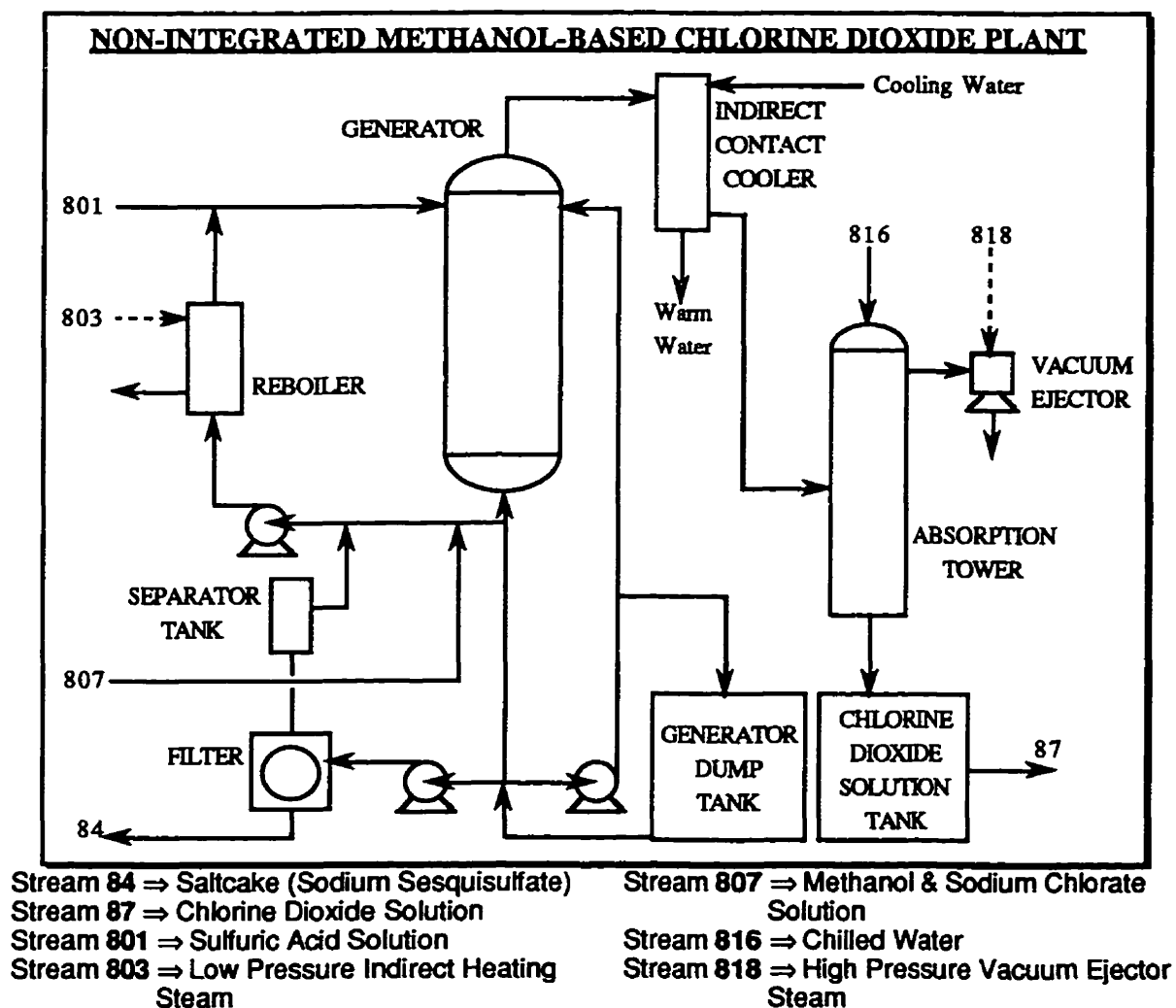
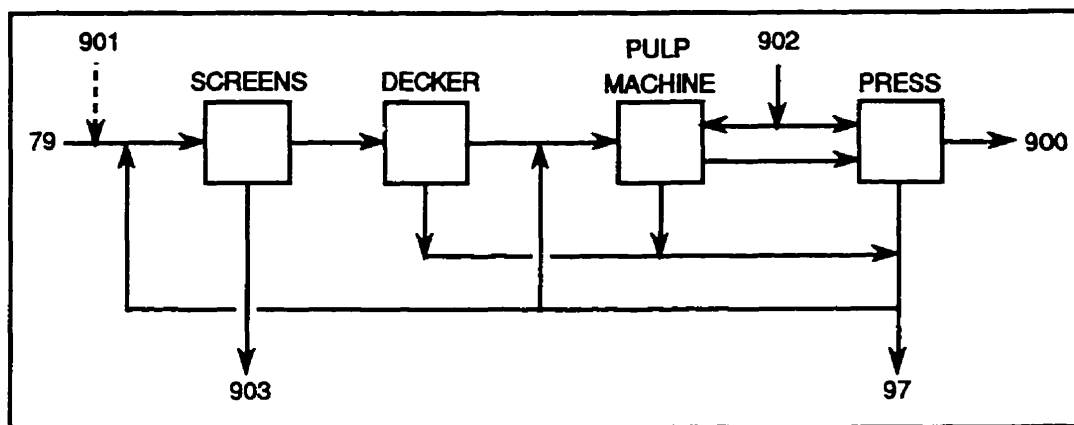


Figure 4.9 — Schematic Diagram of a Chlorine Dioxide Plant

4.2.9 Section 9 — The Pulp Machine

The pulp (Stream 79) that enters the pulp machine area is at a consistency of approximately 12%. Initially the pulp machine's screens separate any rejected material from the pulp stream and sends these rejects (Stream 903) to the sewer. The remainder of the pulp stream then passes on to a press that squeezes the pulp until its consistency reaches approximately 50%. The water that is displaced by the press is recycled and used as wash water (Stream 97) in the bleachery (Section 7). It is the 50% consistency pulp (Stream 900) that is considered to be the primary product of the Kraft process.



Stream 79 ⇒ Bleached Pulp
Stream 97 ⇒ Recirculated Wash Water
Stream 900 ⇒ Pressed Pulp to Pulp Dryer
Stream 901 ⇒ Low Pressure Injection Steam
Stream 902 ⇒ Pre-Heated Wash Water
Stream 903 ⇒ Screen Rejects to Sewer

Figure 4.10 — Diagram of the Pulp Machine & Press

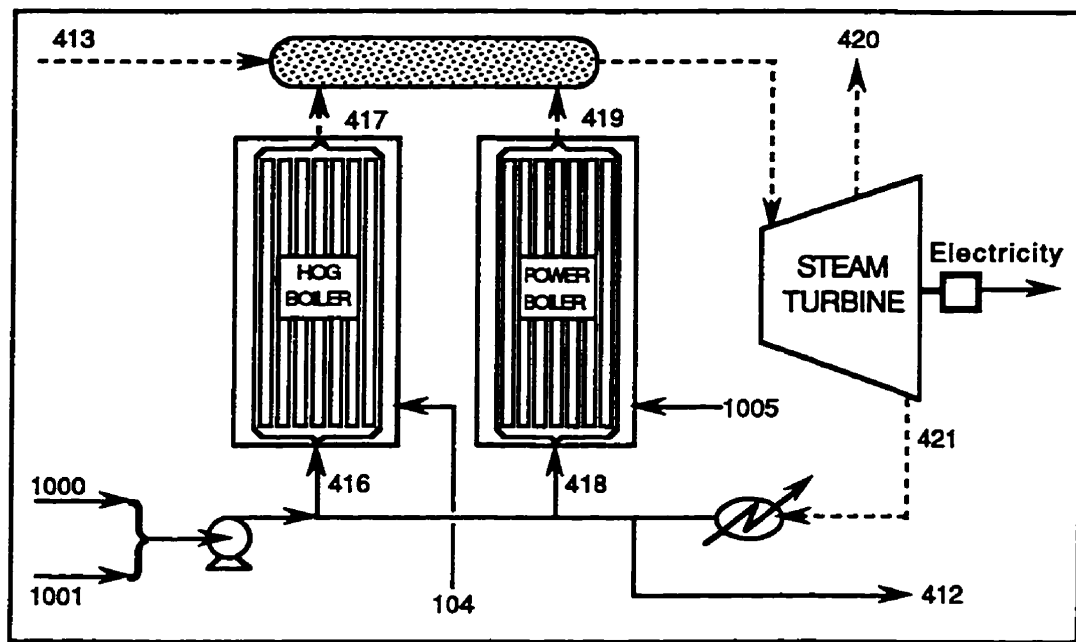
4.2.10 Section 10 — Cogeneration

Cogeneration is defined as being “an energy production process involving the simultaneous generation of thermal (e.g., process-steam) and electric energy by using a single primary heat source.” [10]

Schematic diagrams of the steam production arrangement and the steam supply system are shown in Figures 4.11 & 4.12. A cogeneration system has been incorporated into the design of the Kraft process in order to take advantage of the possibility that burning some, or all, of the “Hog Fuel” from the process in a boiler will result in the production of steam that will be used elsewhere in the process.

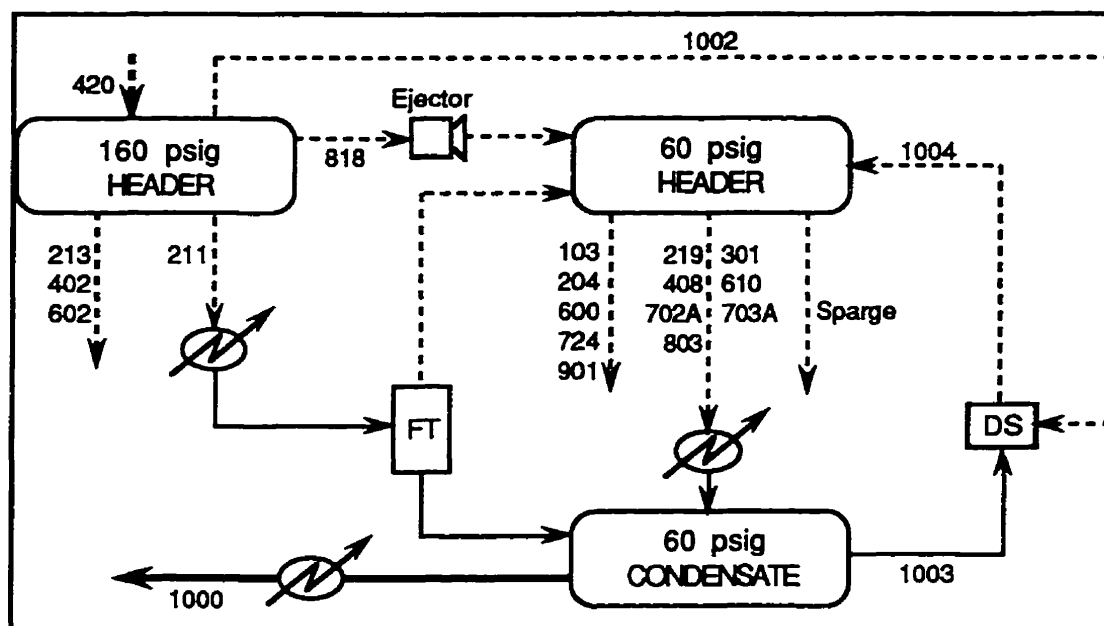
The “Hog”, “Power” and “Recovery” boilers produce steam at high temperature, 510°C (950°F) and pressure, 8.72 MPa (1250 psig) so that it can be expanded through a steam turbine to produce electricity. This electricity will be used to offset the imported electricity requirement of the Kraft process.

For the purpose of this study, the cogeneration system has been sized to meet the process steam requirement of the Kraft process. Additional electrical energy requirements are purchased from an electric utility. The process-heat requirement of this plant was determined by using the steam supply system that is shown in Figure 4.12. In the event that there is not enough steam generated by the combustion of the available “Hog Fuel” then the shortfall is generated by burning Bunker C fuel oil in the “Power” boiler. The steam supply system design for the Kraft may be different than the one shown in Figure 4.12, however it should closely represent the design that will be constructed if this size plant is built.



- | | |
|---|---|
| Stream 104 ⇒ Hog Fuel | Stream 419 ⇒ Steam from Power Boiler |
| Stream 412 ⇒ Feedwater to Recovery Boiler | Stream 420 ⇒ Required Steam to Process |
| Stream 413 ⇒ Steam from Recovery Boiler | Stream 421 ⇒ Surplus Steam |
| Stream 416 ⇒ Feedwater to Hog Boiler | Stream 1000 ⇒ Boiler Feed Water |
| Stream 417 ⇒ Steam from Hog Boiler | Stream 1001 ⇒ Make-up Boiler Feed Water |
| Stream 418 ⇒ Feedwater to Power Boiler | Stream 1005 ⇒ Bunker C Fuel Oil |

Figure 4.11 — Steam Production Arrangement for the Kraft Process



Stream 103 ⇒ Low Pressure Steam to Woodroom

Stream 204 ⇒ Low Pressure Steam to the Steaming Vessel

Stream 211 ⇒ High Pressure Steam to the Digester

Stream 213 ⇒ High Pressure Steam to the Digester

Stream 219 ⇒ Low Pressure Steam to the Digester

Stream 301 ⇒ Low Pressure Steam to the Black Liquor Evaporators

Stream 402 ⇒ High Pressure Steam to the Recovery Boiler

Stream 408 ⇒ Low Pressure Steam to the Recovery Boiler

Stream 420 ⇒ Main Turbine Exhaust Steam

Stream 600 ⇒ Low Pressure Steam to Oxygen Delignification

Stream 602 ⇒ High Pressure Steam to Oxygen Delignification

Stream 610 ⇒ Low Pressure Steam to Oxygen Delignification

Stream 702A ⇒ Low Pressure Steam to the Bleach Plant

Stream 703A ⇒ Low Pressure Steam to the Bleach Plant

Stream 724 ⇒ Low Pressure Steam to the Bleach Plant

Stream 803 ⇒ Low Pressure Steam to the C_lO₂ Plant's Reboiler

Stream 818 ⇒ High Pressure Vacuum Ejector Steam to C_lO₂ Plant

Stream 901 ⇒ Low Pressure Steam to the Pulp Machine

Stream 1000 ⇒ Low Pressure Condensate

Stream 1002 ⇒ High Pressure Steam

Stream 1003 ⇒ Low Pressure Condensate

Stream 1004 ⇒ Low Pressure Steam

Figure 4.12 — Steam Supply System for the Kraft Process

CHAPTER 5

RESULTS

5.1 Introduction

The Cumulative Energy Consumption analysis results were determined by using computer spreadsheet¹ models that were developed for the ALCELL® and Kraft processes individually. These models simulate mass and energy balances around each of the plant sections that are described in Chapters 3 and 4 of this thesis. From the results of the mass and energy balances the Cumulative Energy values of the products of the ALCELL® and Kraft processes were determined.

The Cumulative Energy Consumption analysis results that are presented on the following pages are based on sets of operating parameters that are considered to be representative of the actual plant operating parameters. Some of the operating parameters for the ALCELL® and Kraft processes are listed in Table 5.1. The results of the Cumulative Energy Consumption analysis are presented in Sections 5.2 and 5.3.

¹ Microsoft Excel Version 4.0

Table 5.1 — Operating Parameters for the ALCELL® and Kraft Processes

	ALCELL® Process	Kraft Process
Time of Year	Summer	Summer
Bark Content on Logs (%)	16.0	16.0
Wood Composition (%)		
Wood Fiber	77.70	77.70
Lignin	22.00	22.00
Ash	0.30	0.30
Sectional Yields (%)		
Debarking Drum Fines Loss	2.0	2.0
Chipper Fines Loss	4.0	4.0
Digester Yield	52.0	54.0
Brownstock Screen Yield	99.0	99.0†
Oxygen Delignification Yield	94.0	98.0
Bleach Plant Yield	98.0	96.0
Pulp Machine Yield	99.5	99.5
Kappa# Leaving the Digester	30.0	12.0
Kappa# Leaving Oxygen Delignification	16.5	8.0
Kappa# Leaving Bleach Plant	1.5	1.5
Chemical Addition (% on OD Pulp)		
Oxygen Delignification		
Sodium Hydroxide	4.00	1.50
Oxygen	1.00	1.20
Magnesium Sulfate	0.50	0.00
Bleach Plant		
Chlorine Dioxide	1.60	0.82
Sodium Hydroxide	1.74	1.25
Oxygen	0.44	0.35
Sulfuric Acid	0.56	0.60
Sulfur Dioxide	0.22	0.22
Boiler Efficiencies (%)		
Recovery	—	65.0
Power	85.0	85.0
Hog	65.0	65.0
Heating Value (kJ/kg)		
Woodroom Chip Screen Rejects	19775.0	19775.0
Brownstock Screen Rejects	19775.0	—
Dry Lignin	27900.0	—
Furfural Product	24400.0	—
Furfural Heavy Residue	24400.0	—
Hot Decanter Tar Layer	21400.0	—
Finisher Evaporator Syrups	13960.0	—
Ethyl Alcohol	29850.0	—
Black Liquor Solids	—	15130.0
Bunker C Fuel Oil	43000.0	43000.0

† – Brownstock Screen Rejects are returned to the Chip Bin for further cooking (See Figure 4.3).

5.2 Cumulative Energy Consumption of the ALCELL® Process

The ALCELL® process has been designed to produce quality hardwood pulp as well as a variety of useful byproducts. These byproducts are listed as follows and may be found in Figure 3.1 & Table 3.1:

- ① Woodroom “Chip Screen” Rejects (Stream 6)
- ② Brownstock Screen Rejects (Stream ER)
- ③ Tar Layer from the Hot Decanter (Stream EB)
- ④ Dry Lignin Cake (Stream BV)
- ⑤ Concentrated Syrups (Stream DF)
- ⑥ Furfural Product (light oil) (Stream DB)
- ⑦ Furfural Residue (heavy oil) (Stream DC)

All of the byproducts that have been listed here are able to be used as fuel in the cogeneration process to reduce or eliminate the requirement of Bunker C fuel oil.

If the concentrated syrups and/or the lignin cake are used as fuel in the cogeneration process then it is actually the finisher evaporator feed (Stream CW) and the lignin dryer feed (Stream BT) that are used as the fuels while the steam and electricity consumption of the Finisher Evaporator (Section 12) and Lignin Dryer (Section 7) are set to zero.

Some of the byproducts, such as the Dry Lignin Cake, the Furfural Product (light oil) and the Concentrated Syrups have the potential of becoming salable byproducts of the ALCELL® process. However, the remaining four byproducts have little if any development potential. Therefore, the most probable operating strategy for the ALCELL® process would involve the production of the Dry Lignin Cake, Concentrated Syrups and the Furfural Product while the remaining

byproducts are burnt in the cogeneration process. This combustion strategy is presented as "Combustion Strategy #7" and may be found in Table 5.9.

The computer spreadsheet program that was developed for the ALCELL® process has the capability to determine the CEnC values of the products of the process for any combination of byproduct combustion.

The numerical results which comprise this portion of the analysis are characterized in Table 5.2. This table represents the byproduct combustion strategies that are most likely to be employed at a commercial ALCELL® mill. A detailed set of calculations for "Combustion Strategy #7" (i.e., the most probable operating strategy) is given in Appendix A (pp. 123 to 154).

Table 5.2 — Combustible Byproduct Combinations

Combustible Byproducts	Byproduct Combustion Strategies													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Wet Lignin Cake (BT)‡									✓	✓			✓	✓
Finish Evap. Feed (CW)‡											✓	✓	✓	✓
Furfural Product (DB)‡								✓	✓			✓		✓
Furfural Residue (DC)‡					✓		✓	✓	✓	✓	✓	✓	✓	✓
Hot Decanter Tar (EB)‡						✓	✓	✓	✓	✓	✓	✓	✓	✓
Brownstock Rejects (ER)‡		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Woodroom Rejects (G)‡			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ — indicates combustion of byproduct.

‡ — refers to the stream label used in the computer program.

Tables 5.3 to 5.16 present the overall mass, energy, and Cumulative Energy Consumption balances for the different byproduct combustion strategies that have been considered for this process.

Table 5.3 — Combustion Strategy #1 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #1		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/1	4022.53	0.00	0.00	603.38‡	1.72		
Imported Electricity	—	2160.26	10.22	8331.14§	23.72		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.92	828.36‡	2.36		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.61		
Delignification Chemicals/EU & EV	411.35	14.82	0.07	1167.04‡	3.32		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.47		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.11	153.25‡	0.44		
Combustion Energy							
Byproducts (See Table 5.2)	—	0.00	0.00	0.00	0.00		
Bunker C Fuel Oil	—	18112.43	85.66	21901.37¶	62.36		
Sum	24771.82	21143.47	100.00	35120.50	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.68	21344.55	60.77		
Hog Fuel/6	843.64	0.00	0.00	409.25	1.16		
Dry Lignin/BV	364.13	85.06	0.40	2649.16	7.54		
Furfural Product/DB	62.68	0.00	0.00	451.69	1.29		
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	48.33	0.14		
Concentrated Syrups/DF	411.02	146.58	0.69	9777.86	27.84		
Hot Decanter Tar/EB	51.22	14.15	0.07	374.28	1.07		
Brownstock Rejects/ER	24.80	4.81	0.02	65.38	0.19		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	21.55	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.42	—	—		
Rejected Materials/HK,84 & 817	511.34	67.92	0.32	—	—		
Byproducts Burnt for Cogeneration	0.00	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	4.31	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.46	7.51	—	—		
Section 4 – Bleachery	—	901.62	4.26	—	—		
Section 5 – Pulp Machine	—	339.16	1.60	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.74	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	76.04	0.36	—	—		
Section 10 – Furfural Reactor	—	66.90	0.32	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	3565.65	16.86	—	—		
Cooling Water Enthalpy Increase	—	8145.70	38.53	—	—		
Losses in Electricity Production	—	20.34	0.10	—	—		
Sum	24771.82	21143.47	100.00	35120.50	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.4 — Combustion Strategy #2 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #2	Mass	Energy (Basis = 0°C)	Cumulative Energy		
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38‡	1.72
Imported Electricity	—	2160.26	10.20	8331.14§	23.72
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.91	828.36‡	2.36
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.61
Delignification Chemicals/EU & EV	411.35	14.82	0.07	1167.04‡	3.32
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.47
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.11	153.25‡	0.44
Combustion Energy					
Byproducts (See Table 5.2)	—	162.58	0.77	162.58	0.46
Bunker C Fuel Oil	—	17982.45	84.92	21744.19¶	61.90
Sum	24771.82	21176.07	100.00	35125.90	100.00
Useful Effluents/Stream					
Wood Pulp†/HU	1800.00	355.11	1.68	21376.80	60.86
Hog Fuel/6	843.64	0.00	0.00	409.34	1.16
Dry Lignin/BV	364.13	85.06	0.40	2654.22	7.56
Furfural Product/DB	62.68	0.00	0.00	453.02	1.29
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	48.47	0.14
Concentrated Syrups/DF	411.02	146.58	0.69	9808.67	27.92
Hot Decanter Tar/EB	51.22	14.15	0.07	375.38	1.07
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	21.50	—	—
Purge Streams/H,I & 47cond	219.36	300.88	1.42	—	—
Rejected Materials/HK,84 & 817	511.34	67.92	0.32	—	—
Byproducts Burnt for Cogeneration	24.80	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	4.31	—	—
Section 2 – Extractor	—	0.09	0.00	—	—
Section 3 – Delignification	—	1585.47	7.49	—	—
Section 4 – Bleachery	—	901.62	4.26	—	—
Section 5 – Pulp Machine	—	339.16	1.60	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.74	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	76.04	0.36	—	—
Section 10 – Furfural Reactor	—	66.90	0.32	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	3603.06	17.01	—	—
Cooling Water Enthalpy Increase	—	8145.69	38.47	—	—
Losses in Electricity Production	—	20.34	0.10	—	—
Sum	24771.82	21176.07	100.00	35125.90	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.5 — Combustion Strategy #3 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #3	Mass	Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp [†])	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38 [‡]	1.69
Imported Electricity	—	2160.26	9.27	8331.14 [§]	23.26
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.55	828.36 [‡]	2.31
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04 [‡]	4.52
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04 [‡]	3.26
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92 [‡]	1.44
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25 [‡]	0.43
Combustion Energy					
Byproducts (See Table 5.2)	—	9248.79	39.66	9248.79	25.82
Bunker C Fuel Oil	—	11039.83	47.34	13349.25 [¶]	37.27
Sum	24771.82	23319.66	100.00	35817.17	100.00
Useful Effluents/Stream					
Wood Pulp [†] /HU	1800.00	355.11	1.52	21848.30	61.00
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00
Dry Lignin/BV	364.13	85.06	0.37	2728.14	7.62
Furfural Product/DB	62.68	0.00	0.00	472.57	1.32
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	50.57	0.14
Concentrated Syrups/DF	411.02	146.58	0.63	10259.08	28.64
Hot Decanter Tar/EB	51.22	14.15	0.06	391.52	1.09
Brownstock Rejects/ER	24.80	4.81	0.02	66.99	0.19
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.53	—	—
Purge Streams/H,I & 47 ^{cond}	219.36	300.88	1.29	—	—
Rejected Materials/HK,84 & 817	511.34	67.92	0.29	—	—
Byproducts Burnt for Cogeneration	843.64	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	3.91	—	—
Section 2 – Extractor	—	0.09	0.00	—	—
Section 3 – Delignification	—	1585.47	6.80	—	—
Section 4 – Bleachery	—	901.62	3.87	—	—
Section 5 – Pulp Machine	—	339.16	1.45	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.74	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	76.04	0.33	—	—
Section 10 – Furfural Reactor	—	66.90	0.29	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	5741.84	24.62	—	—
Cooling Water Enthalpy Increase	—	8145.69	34.93	—	—
Losses in Electricity Production	—	20.34	0.09	—	—
Sum	24771.82	23319.66	100.00	35817.17	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

[¶] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.6 — Combustion Strategy #4 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #4		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/1	4022.53	0.00	0.00	603.38‡	1.68		
Imported Electricity	—	2160.26	9.25	8331.14§	23.26		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.55	828.36‡	2.31		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.52		
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.26		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.44		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25‡	0.43		
Combustion Energy							
Byproducts (See Table 5.2)	—	9411.37	40.30	9411.37	26.27		
Bunker C Fuel Oil	—	10909.84	46.72	13192.06¶	36.83		
Sum	24771.82	23352.25	100.00	35822.56	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.52	21881.32	61.08		
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV	364.13	85.06	0.36	2733.32	7.63		
Furfural Product/DB	62.68	0.00	0.00	473.94	1.32		
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	50.71	0.14		
Concentrated Syrups/DF	411.02	146.58	0.63	10290.62	28.73		
Hot Decanter Tar/EB	51.22	14.15	0.06	392.65	1.10		
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.50	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.29	—	—		
Rejected Materials/HK,84 & 817	511.34	67.92	0.29	—	—		
Byproducts Burnt for Cogeneration	868.44	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	3.91	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.47	6.79	—	—		
Section 4 – Bleachery	—	901.62	3.86	—	—		
Section 5 – Pulp Machine	—	339.16	1.45	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.74	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	76.04	0.33	—	—		
Section 10 – Furfural Reactor	—	66.90	0.29	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	5779.24	24.75	—	—		
Cooling Water Enthalpy Increase	—	8145.69	34.88	—	—		
Losses in Electricity Production	—	20.34	0.09	—	—		
Sum	24771.82	23352.25	100.00	35822.56	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{imp,elec}$ = 25.93%. See Appendix B.

¶ – $\eta_{Bunker\ C}$ = 82.7%, Boustead & Hancock[1].

Table 5.7 — Combustion Strategy #5 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #5		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/1	4022.53	0.00	0.00	603.38‡	1.69		
Imported Electricity	—	2160.26	9.25	8331.14§	23.28		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.55	828.36‡	2.31		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.52		
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.26		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.44		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25‡	0.43		
Combustion Energy							
Byproducts (See Table 5.2)	—	9575.01	41.00	9575.01	26.76		
Bunker C Fuel Oil	—	10746.21	46.02	12994.20¶	36.31		
Sum	24771.82	23352.26	100.00	35788.34	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.52	21888.85	61.16		
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV	364.13	85.06	0.36	2734.50	7.64		
Furfural Product/DB	62.68	0.00	0.00	474.26	1.33		
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00		
Concentrated Syrups/DF	411.02	146.58	0.63	10297.82	28.77		
Hot Decanter Tar/EB	51.22	14.15	0.06	392.91	1.10		
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.50	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.29	—	—		
Rejected Materials/HK,84 & 817	511.34	67.92	0.29	—	—		
Byproducts Burnt for Cogeneration	875.15	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	3.91	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.47	6.79	—	—		
Section 4 – Bleachery	—	901.62	3.86	—	—		
Section 5 – Pulp Machine	—	339.16	1.45	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.74	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	76.04	0.33	—	—		
Section 10 – Furfural Reactor	—	66.90	0.29	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	5779.25	24.75	—	—		
Cooling Water Enthalpy Increase	—	8145.69	34.88	—	—		
Losses in Electricity Production	—	20.34	0.09	—	—		
Sum	24771.82	23352.26	100.00	35788.34	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.8 — Combustion Strategy #6 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #6					
Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38‡	1.68
Imported Electricity	—	2160.26	9.17	8331.14§	23.23
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.52	828.36‡	2.31
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.51
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.25
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.44
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25‡	0.43
Combustion Energy					
Byproducts (See Table 5.2)	—	10341.43	43.90	10341.43	28.83
Bunker C Fuel Oil	—	10181.98	43.23	12311.93¶	34.32
Sum	24771.82	23554.45	100.00	35872.49	100.00
Useful Effluents/Stream					
Wood Pulp†/HU	1800.00	355.11	1.51	22086.41	61.57
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00
Dry Lignin/BV	364.13	85.06	0.36	2765.47	7.71
Furfural Product/DB	62.68	0.00	0.00	482.45	1.35
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	51.62	0.14
Concentrated Syrups/DF	411.02	146.58	0.62	10486.54	29.23
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.34	—	—
Purge Streams/H,I & 47cond	219.36	300.88	1.28	—	—
Rejected Materials/HK,84 & 817	511.35	67.92	0.29	—	—
Byproducts Burnt for Cogeneration	919.65	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	3.87	—	—
Section 2 – Extractor	—	0.09	0.00	—	—
Section 3 – Delignification	—	1585.47	6.73	—	—
Section 4 – Bleachery	—	901.62	3.83	—	—
Section 5 – Pulp Machine	—	339.16	1.44	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.74	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	76.04	0.32	—	—
Section 10 – Furfural Reactor	—	66.90	0.28	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	5995.59	25.46	—	—
Cooling Water Enthalpy Increase	—	8145.69	34.58	—	—
Losses in Electricity Production	—	20.34	0.09	—	—
Sum	24771.82	23554.45	100.00	35872.49	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.9 — Combustion Strategy #7 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #7	Mass	Energy (Basis = 0°C)	Cumulative Energy		
Balance Items (Basis = 1 ADMT of Pulp [†])	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38 [‡]	1.68
Imported Electricity	—	2160.26	9.17	8331.14 [§]	23.25
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.52	828.36 [‡]	2.31
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04 [‡]	4.52
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04 [‡]	3.26
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92 [‡]	1.44
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25 [‡]	0.43
Combustion Energy					
Byproducts (See Table 5.2)	—	10505.06	44.60	10505.06	29.31
Bunker C Fuel Oil	—	10018.34	42.53	12114.08 [¶]	33.80
Sum	24771.82	23554.44	100.00	35838.27	100.00
Useful Effluents/Stream					
Wood Pulp [†] /HU	1800.00	355.11	1.51	22094.49	61.65
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00
Dry Lignin/BV	364.13	85.06	0.36	2766.74	7.72
Furfural Product/DB	62.68	0.00	0.00	482.78	1.35
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00
Concentrated Syrups/DF	411.02	146.58	0.62	10494.26	29.28
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.34	—	—
Purge Streams/H,I & 47 ^{cond}	219.36	300.88	1.28	—	—
Rejected Materials/HK,84 & 817	511.36	67.92	0.29	—	—
Byproducts Burnt for Cogeneration	926.35	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	3.87	—	—
Section 2 – Extractor	—	0.09	0.00	—	—
Section 3 – Delignification	—	1585.47	6.73	—	—
Section 4 – Bleachery	—	901.62	3.83	—	—
Section 5 – Pulp Machine	—	339.16	1.44	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.74	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	76.04	0.32	—	—
Section 10 – Furfural Reactor	—	66.90	0.28	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	5995.58	25.46	—	—
Cooling Water Enthalpy Increase	—	8145.69	34.58	—	—
Losses in Electricity Production	—	20.34	0.09	—	—
Sum	24771.82	23554.44	100.00	35838.27	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

[¶] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.10 — Combustion Strategy #8 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #8		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/1	4022.53	0.00	0.00	603.38‡	1.70		
Imported Electricity	—	2160.26	9.17	8331.14§	23.46		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.52	828.36‡	2.33		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.56		
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.29		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.45		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25‡	0.43		
Combustion Energy							
Byproducts (See Table 5.2)	—	12032.67	51.08	12032.67	33.88		
Bunker C Fuel Oil	—	8490.74	36.05	10266.90¶	28.90		
Sum	24771.82	23554.45	100.00	35518.70	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.51	22171.77	62.42		
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV	364.13	85.06	0.36	2778.85	7.82		
Furfural Product/DB	0.00	0.00	0.00	0.00	0.00		
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00		
Concentrated Syrups/DF	411.02	146.58	0.62	10568.08	29.76		
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00		
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20476.92	4553.96	19.34	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.28	—	—		
Rejected Materials/HK,84 & 817	511.36	67.92	0.29	—	—		
Byproducts Burnt for Cogeneration	989.03	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	3.87	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.47	6.73	—	—		
Section 4 – Bleachery	—	901.62	3.83	—	—		
Section 5 – Pulp Machine	—	339.16	1.44	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.74	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	76.04	0.32	—	—		
Section 10 – Furfural Reactor	—	66.90	0.28	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	5995.59	25.45	—	—		
Cooling Water Enthalpy Increase	—	8145.69	34.59	—	—		
Losses in Electricity Production	—	20.34	0.09	—	—		
Sum	24771.82	23554.45	100.00	35518.70	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{imp,elec} = 25.93\%$. See Appendix B.¶ – $\eta_{Bunker\ C} = 82.7\%$, Boustead & Hancock[1].

Table 5.11 — Combustion Strategy #9 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #9		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/l	4022.53	0.00	0.00	603.38‡	1.75		
Imported Electricity	—	2036.89	8.26	7855.36§	22.70		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.36	828.36‡	2.39		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.68		
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.37		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.49		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.09	153.25‡	0.44		
Combustion Energy							
Byproducts (See Table 5.2)	—	21266.32	86.22	21266.32	61.46		
Bunker C Fuel Oil	—	491.46	1.99	594.26¶	1.72		
Sum	24771.82	24665.45	100.00	34603.93	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.44	22949.35	66.32		
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV	0.00	0.00	0.00	0.00	0.00		
Furfural Product/DB	0.00	0.00	0.00	0.00	0.00		
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00		
Concentrated Syrups/DF	411.02	146.58	0.59	11654.58	33.68		
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00		
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20216.83	4520.06	18.33	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.22	—	—		
Rejected Materials/HK,84 & 817	511.36	67.92	0.27	—	—		
Byproducts Burnt for Cogeneration	1613.25	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	3.70	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.47	6.43	—	—		
Section 4 – Bleachery	—	901.62	3.66	—	—		
Section 5 – Pulp Machine	—	339.16	1.38	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.00	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	449.83	1.82	—	—		
Section 10 – Furfural Reactor	—	66.90	0.27	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	8029.48	32.55	—	—		
Cooling Water Enthalpy Increase	—	6969.69	28.26	—	—		
Losses in Electricity Production	—	19.36	0.08	—	—		
Sum	24771.82	24665.45	100.00	34603.93	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.12 — Combustion Strategy #10 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #10		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/1	4022.53	0.00	0.00	603.38‡	1.73		
Imported Electricity	—	2036.89	8.26	7855.36§	22.49		
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.36	828.36‡	2.37		
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.64		
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.34		
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.48		
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.09	153.25‡	0.44		
Combustion Energy							
Byproducts (See Table 5.2)	—	19738.71	80.03	19738.71	56.52		
Bunker C Fuel Oil	—	2019.07	8.18	2441.44¶	6.99		
Sum	24771.82	24665.45	100.00	34923.50	100.00		
Useful Effluents/Stream							
Wood Pulp†/HU	1800.00	355.11	1.44	22841.50	65.40		
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV	0.00	0.00	0.00	0.00	0.00		
Furfural Product/DB	62.68	0.00	0.00	530.40	1.52		
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00		
Concentrated Syrups/DF	411.02	146.58	0.59	11551.60	33.08		
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00		
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/BW,DD,DI,FG,FY & 5	20216.83	4520.06	18.33	—	—		
Purge Streams/H,I & 47cond	219.36	300.88	1.22	—	—		
Rejected Materials/HK,84 & 817	511.36	67.92	0.28	—	—		
Byproducts Burnt for Cogeneration	1550.57	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	911.80	3.70	—	—		
Section 2 – Extractor	—	0.09	0.00	—	—		
Section 3 – Delignification	—	1585.47	6.43	—	—		
Section 4 – Bleachery	—	901.62	3.66	—	—		
Section 5 – Pulp Machine	—	339.16	1.38	—	—		
Section 6 – Lignin Recovery	—	0.00	0.00	—	—		
Section 7 – Lignin Drier	—	0.00	0.00	—	—		
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—		
Section 9 – MVR Evaporator	—	449.83	1.82	—	—		
Section 10 – Furfural Reactor	—	66.90	0.27	—	—		
Section 11 – Furfural Refining	—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator	—	0.50	0.00	—	—		
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—		
Section 14 – Cogeneration	—	8029.48	32.55	—	—		
Cooling Water Enthalpy Increase	—	6969.69	28.26	—	—		
Losses in Electricity Production	—	19.36	0.08	—	—		
Sum	24771.82	24665.45	100.00	34923.50	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.13 — Combustion Strategy #11 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #11		Mass	Energy (Basis = 0°C)	Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38‡	1.67
Imported Electricity	—	2086.33	8.67	8045.99§	22.28
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.44	828.36‡	2.30
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.49
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.23
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.43
ClO2 Generator Chemicals/801 & 807	275.60	23.06	0.10	153.25‡	0.42
Combustion Energy					
Byproducts (See Table 5.2)	—	11222.69	46.63	11222.69	31.08
Bunker C Fuel Oil	—	9886.22	41.08	11954.31¶	33.10
Sum	24771.82	24066.02	100.00	36110.98	100.00
Useful Effluents/Stream					
Wood Pulp†/HU	1800.00	355.11	1.48	31018.46	85.90
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00
Dry Lignin/BV	364.13	85.06	0.35	4157.76	11.51
Furfural Product/DB	62.68	0.00	0.00	934.76	2.59
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00
Concentrated Syrups/DF	0.00	0.00	0.00	0.00	0.00
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	19596.81	4364.62	18.14	—	—
Purge Streams/H,I & 47cond	219.36	300.88	1.25	—	—
Rejected Materials/HK,84 & 817	511.35	67.92	0.28	—	—
Byproducts Burnt for Cogeneration	2217.49	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	3.79	—	—
Section 2 – Extractor	—	1583.24	6.58	—	—
Section 3 – Delignification	—	1585.47	6.59	—	—
Section 4 – Bleachery	—	901.62	3.75	—	—
Section 5 – Pulp Machine	—	339.16	1.41	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.74	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	76.04	0.31	—	—
Section 10 – Furfural Reactor	—	66.90	0.28	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.00	0.00	—	—
Section 13 – ClO2 Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	5449.64	22.64	—	—
Cooling Water Enthalpy Increase	—	7955.35	33.06	—	—
Losses in Electricity Production	—	21.47	0.09	—	—
Sum	24771.82	24066.02	100.00	36110.98	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.14 — Combustion Strategy #12 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #12		Mass			Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)		kg	MJ	%	MJ	%		
Influents/Stream								
Logs/l		4022.53	0.00	0.00	603.38‡	1.69		
Imported Electricity		—	2086.33	8.67	8045.99§	22.48		
Fresh Water/AN,FA,GH,HT,816 & 901		19798.35	828.36	3.44	828.36‡	2.31		
Make-up Alcohol/DJ		96.87	4.54	0.02	1619.04‡	4.52		
Delignification Chemicals/EU & EV		411.35	14.82	0.06	1167.04‡	3.26		
Bleaching Chemicals/FQ,GE & GT		167.12	0.00	0.00	516.92‡	1.44		
ClO ₂ Generator Chemicals/801 & 807		275.60	23.06	0.10	153.24‡	0.43		
Combustion Energy								
Byproducts (See Table 5.2)		—	12750.29	52.98	12750.29	35.62		
Bunker C Fuel Oil		—	8358.61	34.73	10107.16¶	28.24		
Sum		24771.82	24066.01	100.00	35791.42	100.00		
Useful Effluents/Stream								
Wood Pulp†/HU		1800.00	355.11	1.48	31550.56	88.15		
Hog Fuel/6		0.00	0.00	0.00	0.00	0.00		
Dry Lignin/BV		364.13	85.06	0.35	4240.86	11.85		
Furfural Product/DB		0.00	0.00	0.00	0.00	0.00		
Heavy Residue (Furfural)/DC		0.00	0.00	0.00	0.00	0.00		
Concentrated Syrups/DF		0.00	0.00	0.00	0.00	0.00		
Hot Decanter Tar/EB		0.00	0.00	0.00	0.00	0.00		
Brownstock Rejects/ER		0.00	0.00	0.00	0.00	0.00		
Losses								
Sewer Water/BW,DD,DI,FG,FY & 5		19596.81	4364.62	18.14	—	—		
Purge Streams/H,I & 47cond		219.36	300.88	1.25	—	—		
Rejected Materials/HK,84 & 817		511.36	67.92	0.28	—	—		
Byproducts Burnt for Cogeneration		2280.16	—	—	—	—		
Heat Rejected to the Environment :								
Section 1 – Woodroom		—	911.80	3.79	—	—		
Section 2 – Extractor		—	1583.24	6.58	—	—		
Section 3 – Delignification		—	1585.47	6.59	—	—		
Section 4 – Bleachery		—	901.62	3.75	—	—		
Section 5 – Pulp Machine		—	339.16	1.41	—	—		
Section 6 – Lignin Recovery		—	0.00	0.00	—	—		
Section 7 – Lignin Drier		—	0.74	0.00	—	—		
Section 8 – Alcohol Recovery		—	0.01	0.00	—	—		
Section 9 – MVR Evaporator		—	76.04	0.31	—	—		
Section 10 – Furfural Reactor		—	66.90	0.28	—	—		
Section 11 – Furfural Refining		—	0.59	0.00	—	—		
Section 12 – Finisher Evaporator		—	0.00	0.00	—	—		
Section 13 – ClO ₂ Generator		—	0.40	0.00	—	—		
Section 14 – Cogeneration		—	5449.64	22.64	—	—		
Cooling Water Enthalpy Increase		—	7955.34	33.06	—	—		
Losses in Electricity Production		—	21.47	0.09	—	—		
Sum		24771.82	24066.01	100.00	35791.42	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.¶ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.15 — Combustion Strategy #13 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #13					
Balance Items (Basis = 1 ADMT of Pulp[†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38 [‡]	1.71
Imported Electricity	—	1962.96	7.80	7570.21 [§]	21.51
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.29	828.36 [‡]	2.35
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04 [‡]	4.60
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04 [‡]	3.32
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92 [‡]	1.47
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.09	153.24 [‡]	0.44
Combustion Energy					
Byproducts (See Table 5.2)	—	20456.33	81.25	20456.33	58.12
Bunker C Fuel Oil	—	1886.94	7.49	2281.68 [¶]	6.48
Sum	24771.82	25177.01	100.00	35196.20	100.00
Useful Effluents/Stream					
Wood Pulp [†] /HU	1800.00	355.11	1.41	34105.52	96.90
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00
Dry Lignin/BV	0.00	0.00	0.00	0.00	0.00
Furfural Product/DB	62.68	0.00	0.00	1090.68	3.10
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00
Concentrated Syrups/DF	0.00	0.00	0.00	0.00	0.00
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00
Losses					
Sewer Water/BW,DD,DI,FG,FY & 5	19336.72	4330.72	17.20	—	—
Purge Streams/H,I & 47cond	219.36	300.88	1.19	—	—
Rejected Materials/HK,84 & 817	511.36	67.92	0.27	—	—
Byproducts Burnt for Cogeneration	2841.70	—	—	—	—
Heat Rejected to the Environment :					
Section 1 – Woodroom	—	911.80	3.62	—	—
Section 2 – Extractor	—	1583.24	6.29	—	—
Section 3 – Delignification	—	1585.47	6.30	—	—
Section 4 – Bleachery	—	901.62	3.58	—	—
Section 5 – Pulp Machine	—	339.16	1.35	—	—
Section 6 – Lignin Recovery	—	0.00	0.00	—	—
Section 7 – Lignin Drier	—	0.00	0.00	—	—
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—
Section 9 – MVR Evaporator	—	449.83	1.79	—	—
Section 10 – Furfural Reactor	—	66.90	0.27	—	—
Section 11 – Furfural Refining	—	0.59	0.00	—	—
Section 12 – Finisher Evaporator	—	0.00	0.00	—	—
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—
Section 14 – Cogeneration	—	7483.54	29.72	—	—
Cooling Water Enthalpy Increase	—	6779.34	26.93	—	—
Losses in Electricity Production	—	20.48	0.08	—	—
Sum	24771.82	25177.01	100.00	35196.20	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{imp,elec} = 25.93\%$. See Appendix B.

[¶] – $\eta_{Bunker C} = 82.7\%$, Boustead & Hancock[1].

Table 5.16 — Combustion Strategy #14 • Mass, Energy and Cumulative Energy Balances for the ALCELL® Process

Combustion Strategy #14		Mass			Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)		kg	MJ	%	MJ	%		
Influents/Stream								
Logs/1	4022.53	0.00	0.00	603.38‡	1.73			
Imported Electricity	—	1962.96	7.80	7570.21§	21.71			
Fresh Water/AN,FA,GH,HT,816 & 901	19798.35	828.36	3.29	828.36‡	2.37			
Make-up Alcohol/DJ	96.87	4.54	0.02	1619.04‡	4.64			
Delignification Chemicals/EU & EV	411.35	14.82	0.06	1167.04‡	3.35			
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	1.48			
ClO ₂ Generator Chemicals/801 & 807	275.60	23.06	0.09	153.24‡	0.44			
Combustion Energy								
Byproducts (See Table 5.2)	—	21983.94	87.32	21983.94	63.03			
Bunker C Fuel Oil	—	359.34	1.42	434.51¶	1.25			
Sum	24771.82	25177.02	100.00	34876.64	100.00			
Useful Effluents/Stream								
Wood Pulp†/HU	1800.00	355.11	1.41	34876.64	100.00			
Hog Fuel/6	0.00	0.00	0.00	0.00	0.00			
Dry Lignin/BV	0.00	0.00	0.00	0.00	0.00			
Furfural Product/DB	0.00	0.00	0.00	0.00	0.00			
Heavy Residue (Furfural)/DC	0.00	0.00	0.00	0.00	0.00			
Concentrated Syrups/DF	0.00	0.00	0.00	0.00	0.00			
Hot Decanter Tar/EB	0.00	0.00	0.00	0.00	0.00			
Brownstock Rejects/ER	0.00	0.00	0.00	0.00	0.00			
Losses								
Sewer Water/BW,DD,DI,FG,FY & 5	19336.72	4330.72	17.20	—	—			
Purge Streams/H,I & 47cond	219.36	300.88	1.19	—	—			
Rejected Materials/HK,84 & 817	511.36	67.92	0.27	—	—			
Byproducts Burnt for Cogeneration	2904.38	—	—	—	—			
Heat Rejected to the Environment :								
Section 1 – Woodroom	—	911.80	3.62	—	—			
Section 2 – Extractor	—	1583.24	6.29	—	—			
Section 3 – Delignification	—	1585.47	6.30	—	—			
Section 4 – Bleachery	—	901.62	3.58	—	—			
Section 5 – Pulp Machine	—	339.16	1.35	—	—			
Section 6 – Lignin Recovery	—	0.00	0.00	—	—			
Section 7 – Lignin Drier	—	0.00	0.00	—	—			
Section 8 – Alcohol Recovery	—	0.01	0.00	—	—			
Section 9 – MVR Evaporator	—	449.83	1.79	—	—			
Section 10 – Furfural Reactor	—	66.90	0.27	—	—			
Section 11 – Furfural Refining	—	0.59	0.00	—	—			
Section 12 – Finisher Evaporator	—	0.00	0.00	—	—			
Section 13 – ClO ₂ Generator	—	0.40	0.00	—	—			
Section 14 – Cogeneration	—	7483.54	29.72	—	—			
Cooling Water Enthalpy Increase	—	6779.35	26.93	—	—			
Losses in Electricity Production	—	20.48	0.08	—	—			
Sum	24771.82	25177.02	100.00	34876.64	100.00			

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{imp,elec} = 25.93\%$. See Appendix B.¶ – $\eta_{Bunker C} = 82.7\%$, Boustead & Hancock[1].

The cumulative energy consumption of the products of the ALCELL® process are of particular interest. Table 5.17 provides the specific cumulative energy consumption of these products.

Table 5.17 — Specific CEnC of the Products of the ALCELL® Process

Combustion Strategy	Specific Cumulative Energy Consumption (MJ/kg†)							
	Pressed Pulp	Furfural Product	Dry Lignin	Wood Syrups	Furfural Residue	Tar Layer	BSW Rejects	Hog Fuel
1	11.858	7.207	7.275	23.789	7.207	7.308	2.637	0.485
2	11.876	7.228	7.289	23.864	7.228	7.329	✓	0.485
3	12.138	7.540	7.492	24.960	7.540	7.645	2.702	✓
4	12.156	7.562	7.506	25.037	7.562	7.667	✓	✓
5	12.160	7.567	7.510	25.054	✓	7.672	✓	✓
6	12.270	7.698	7.595	25.514	7.698	✓	✓	✓
7	12.275	7.703	7.598	25.532	✓	✓	✓	✓
8	12.318	✓	7.632	25.712	✓	✓	✓	✓
9	12.750	✓	✓	28.355	✓	✓	✓	✓
10	12.690	8.463	✓	28.105	✓	✓	✓	✓
11	17.232	14.914	11.418	✓	✓	✓	✓	✓
12	17.528	✓	11.647	✓	✓	✓	✓	✓
13	18.948	17.402	✓	✓	✓	✓	✓	✓
14	19.376	✓	✓	✓	✓	✓	✓	✓

† – Refers to the total mass flow of the stream being considered.

✓ – Indicates combustion of byproduct.

The efficiencies of steam and electricity generation are based on the cumulative energy consumption concept, as described in Chapter 2. Therefore, these efficiencies are affected by burning different combinations of the byproducts of the ALCELL® process. The efficiencies of steam and electricity generation are shown in Table 5.18 for each of the combustion scenarios.

Table 5.18 — Energy Efficiency of Generation of Electricity and Steam

Combustion Strategy †	Generation Efficiency (%)	
	Electricity (η_{elec})	Steam (η_{steam})
1	33.60	64.39
2	33.58	64.20
3	33.28	61.48
4	33.26	61.30
5	33.26	61.26
6	33.14	60.19
7	33.13	60.15
8	33.08	59.74
9	32.66	55.90
10	32.72	56.40
11	29.11	35.55
12	28.86	34.65
13	27.74	30.88
14	27.41	29.90

† – See Table 5.2 for Combustion Strategies.

The method of calculating these efficiencies for “Combustion Strategy #7” is shown in Appendix A, Equations A.60 to A.66.

5.3 Cumulative Energy Consumption of the Kraft Process

Unlike the ALCELL® process, the Kraft process has only one byproduct that is available as a fuel for the cogeneration process. This byproduct is the woodroom rejects (also known as “Hog Fuel”). Three combustion strategies for this byproduct were considered and they are as follows:

Strategy A None of the woodroom rejects are burnt for steam generation.

Strategy B Only the required amount of woodroom rejects are burnt to satisfy the steam shortfall and to eliminate the need for Bunker C fuel oil.

Strategy C All of the woodroom rejects are burnt. Excess steam is expanded through a turbine to produce electricity. Additional electricity is supplied from the grid or exported.

Tables 5.19 to 5.21 present summarized mass, energy, and cumulative energy consumption balances for the three byproduct combustion strategies that were considered for this process.

Table 5.19 — Combustion Strategy A • Mass, Energy and Cumulative Energy Balances for the Kraft Process

Strategy A		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp [†])	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/101	3769.57	0.00	0.00	565.44 [‡]	2.54		
Imported Electricity	—	1427.11	8.77	5503.71 [§]	24.69		
Fresh Water [¶]	7656.28	34.52	0.21	34.52 [‡]	0.15		
Make-up Saltcake/401	32.58	0.00	0.00	152.81 [‡]	0.68		
Make-up Lime/507	14.06	0.00	0.00	139.85 [‡]	0.63		
Lime Kiln Fuel Oil/520	34.13	1467.40	9.01	1774.37 [□]	7.96		
Delignification Chemicals/603	11.14	0.00	0.00	103.89 [‡]	0.47		
Bleaching Chemicals/701	137.95	0.00	0.00	397.50 [‡]	1.78		
ClO ₂ Generator Chemicals/801 & 807	148.32	12.41	0.08	82.48 [‡]	0.37		
Combustion Air/407 & 521	7682.89	0.00	0.00	0.00	0.00		
Combustion Energy (Boilers Only)							
Hog Fuel	—	0.00	0.00	0.00	0.00		
Black Liquor Solids	—	12391.01	76.10	12391.01	55.58		
Bunker C Fuel Oil	—	949.63	5.83	1148.27 [□]	5.15		
Sum	19486.92	16282.08	100.00	22293.85	100.00		
Useful Effluents/Stream							
Wood Pulp [†] /900	1800.00	355.11	2.18	21869.42	98.01		
Hog Fuel/104	802.16	0.00	0.00	424.43	1.99		
Losses							
Sewer Water/105 & 715	6401.93	1185.74	7.28	—	—		
Blowdown from Recovery Boiler/410	351.34	484.94	2.98	—	—		
Stack Gases/415 & 524	9219.01	1890.90	11.61	—	—		
Purge Streams/ 201 & 509	594.45	558.22	3.43	—	—		
Rejected Materials/505,508,817 & 903	318.03	59.89	0.37	—	—		
Hog Fuel Burnt in the Hog Boiler	0.00	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	889.45	5.46	—	—		
Section 2 – Digester	—	844.14	5.18	—	—		
Section 3 – Evaporators	—	36.28	0.22	—	—		
Section 4 – Recovery Boiler	—	1499.29	9.21	—	—		
Section 5 – Recausticizing	—	1784.12	10.96	—	—		
Section 6 – Delignification	—	1361.10	8.36	—	—		
Section 7 – Bleachery	—	1048.24	6.44	—	—		
Section 8 – ClO ₂ Generator	—	12.56	0.08	—	—		
Section 9 – Pulp Machine	—	403.29	2.48	—	—		
Section 10 – Cogeneration	—	184.70	1.13	—	—		
Cooling Water Enthalpy Increase	—	3665.97	22.52	—	—		
Losses in Electricity Production	—	18.14	0.11	—	—		
Sum	19486.92	16282.08	100.00	22293.85	100.00		

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

[¶] – Fresh Water Streams Include - 504,513,518,523,605,723,816,902 & 1001

[□] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.20 — Combustion Strategy B • Mass, Energy and Cumulative Energy Balances for the Kraft Process

Strategy B		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp [†])	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/101	3769.57	0.00	0.00	565.44 [‡]	2.53		
Imported Electricity	—	1427.11	8.61	5503.70 [§]	24.58		
Fresh Water [¶]	7656.28	34.52	0.21	34.52 [‡]	0.15		
Make-up Saltcake/401	32.58	0.00	0.00	152.81 [‡]	0.68		
Make-up Lime/507	14.06	0.00	0.00	139.85 [‡]	0.62		
Lime Kiln Fuel Oil/520	34.13	1467.40	8.85	1774.37 [□]	7.93		
Delignification Chemicals/603	11.14	0.00	0.00	103.89 [‡]	0.46		
Bleaching Chemicals/701	137.95	0.00	0.00	397.50 [‡]	1.78		
ClO ₂ Generator Chemicals/801 & 807	148.32	12.41	0.08	82.48 [‡]	0.37		
Combustion Air/407 & 521	7682.89	0.00	0.00	0.00	0.00		
Combustion Energy (Boilers Only)							
Hog Fuel	—	1241.82	7.49	1241.82	5.55		
Black Liquor Solids	—	12391.01	74.76	12391.01	55.35		
Bunker C Fuel Oil	—	0.00	0.00	0.00 [□]	0.00		
Sum	19486.92	16574.27	100.00	22387.39	100.00		
Useful Effluents/Stream							
Wood Pulp [†] /900	1800.00	355.11	2.14	22022.28	98.37		
Hog Fuel/104	688.89	0.00	0.00	365.11	1.63		
Losses							
Sewer Water/105 & 715	6401.93	1185.74	7.15	—	—		
Blowdown from Recovery Boiler/410	351.34	484.94	2.93	—	—		
Stack Gases/415 & 524	9219.01	1890.90	11.41	—	—		
Purge Streams/ 201 & 509	594.45	558.22	3.37	—	—		
Rejected Materials/505,508,817 & 903	318.03	59.89	0.36	—	—		
Hog Fuel Burnt in the Hog Boiler	113.27	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	889.45	5.37	—	—		
Section 2 – Digester	—	844.14	5.09	—	—		
Section 3 – Evaporators	—	36.28	0.22	—	—		
Section 4 – Recovery Boiler	—	1499.29	9.05	—	—		
Section 5 – Recausticizing	—	1784.12	10.76	—	—		
Section 6 – Delignification	—	1361.10	8.21	—	—		
Section 7 – Bleachery	—	1048.24	6.325	—	—		
Section 8 – ClO ₂ Generator	—	12.56	0.08	—	—		
Section 9 – Pulp Machine	—	403.29	2.43	—	—		
Section 10 – Cogeneration	—	476.90	2.88	—	—		
Cooling Water Enthalpy Increase	—	3665.96	22.12	—	—		
Losses in Electricity Production	—	18.14	0.11	—	—		
Sum	19486.92	16574.27	100.00	22387.39	100.00		

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{\text{imp,elec}} = 25.93\%$. See Appendix B.

[¶] – Fresh Water Streams Include - 504,513,518,523,605,723,816,902 & 1001

[□] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock[1].

Table 5.21 — Combustion Strategy C • Mass, Energy and Cumulative Energy Balances for the Kraft Process

Strategy C		Mass		Energy (Basis = 0°C)		Cumulative Energy	
Balance Items (Basis = 1 ADMT of Pulp†)	kg	MJ	%	MJ	%		
Influents/Stream							
Logs/101	3769.57	0.00	0.00	565.44‡	2.16		
Imported Electricity	—	445.91	1.93	1719.67§	6.58		
Fresh Water¶	7656.28	34.52	0.15	34.52‡	0.13		
Make-up Saltcake/401	32.58	0.00	0.00	152.81‡	0.58		
Make-up Lime/507	14.06	0.00	0.00	139.85‡	0.54		
Lime Kiln Fuel Oil/520	34.13	1467.40	6.34	1774.37□	6.78		
Delignification Chemicals/603	11.14	0.00	0.00	103.89‡	0.40		
Bleaching Chemicals/701	137.95	0.00	0.00	397.50‡	1.52		
ClO ₂ Generator Chemicals/801 & 807	148.32	12.41	0.05	82.48‡	0.32		
Combustion Air/407 & 521	7682.89	0.00	0.00	0.00	0.00		
Combustion Energy (Boilers Only)							
Hog Fuel	—	8794.13	37.99	8794.13	33.62		
Black Liquor Solids	—	12391.01	53.54	12391.01	47.37		
Bunker C Fuel Oil	—	0.00	0.00	0.00□	0.00		
Sum	19486.92	23145.38	100.00	26155.67	100.00		
Useful Effluents/Stream							
Wood Pulp†/900	1800.00	355.11	1.53	26155.67	100.00		
Hog Fuel/104	0.00	0.00	0.00	0.00	0.00		
Losses							
Sewer Water/105 & 715	6401.93	1185.74	5.12	—	—		
Blowdown from Recovery Boiler/410	351.34	484.94	2.10	—	—		
Stack Gases/415 & 524	9219.01	1890.90	8.17	—	—		
Purge Streams/ 201 & 509	594.45	558.22	2.41	—	—		
Rejected Materials/505,508,817 & 903	318.03	59.89	0.26	—	—		
Hog Fuel Burnt in the Hog Boiler	802.16	—	—	—	—		
Heat Rejected to the Environment :							
Section 1 – Woodroom	—	889.45	3.84	—	—		
Section 2 – Digester	—	844.14	3.65	—	—		
Section 3 – Evaporators	—	36.28	0.16	—	—		
Section 4 – Recovery Boiler	—	1499.29	6.48	—	—		
Section 5 – Recausticizing	—	1784.12	7.71	—	—		
Section 6 – Delignification	—	1361.10	5.88	—	—		
Section 7 – Bleachery	—	1048.24	4.53	—	—		
Section 8 – ClO ₂ Generator	—	12.56	0.05	—	—		
Section 9 – Pulp Machine	—	403.29	1.74	—	—		
Section 10 – Cogeneration	—	3106.95	13.42	—	—		
Cooling Water Enthalpy Increase	—	7592.08	32.81	—	—		
Losses in Electricity Production	—	33.08	0.14	—	—		
Sum	19486.92	23145.38	100.00	26155.67	100.00		

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

§ – $\eta_{imp,elec} = 25.93\%$. See Appendix B.

¶ – Fresh Water Streams Include - 504,513,518,523,605,723,816,902 & 1001

□ – $\eta_{Bunker C} = 82.7\%$, Boustead & Hancock[1].

The specific cumulative energy consumption values for the wood pulp and hog fuel are presented in Table 5.22 for each of the combustion strategies.

Table 5.22 — Specific CEnC for the Products of the Kraft Process

	Specific CEnC (MJ/kg [†])		
	Wood Pulp	Hog Fuel	Hog Fuel Burnt (%)
Strategy A	12.150	0.529	0.00
Strategy B	12.235	0.530	14.12
Strategy C	14.531	—	100.00

[†] – Refers to the total mass flow of the stream being considered.

Electricity and steam generation efficiencies are affected by the amount of hog fuel burnt as shown in Table 5.23.

Table 5.23 — Energy Efficiency of Generation of Electricity and Steam

Combustion Strategy	Generation Efficiency (%)		Hog Fuel Burnt (%)
	Electricity (η_{elec})	Steam (η_{steam})	
A	28.19	31.47	0.00
B	28.07	31.14	14.12
C	24.63	24.38	100.00

The method of calculating these efficiencies for “Combustion Strategy C” is shown in Appendix A, Equations A.105 to A.112.

CHAPTER 6

DISCUSSION

6.1 Introduction

The principle objective of this thesis has been to present the method of the Cumulative Energy Consumption analysis to industrial processes. As shown in Appendix A, the Cumulative Energy balance equations are easily constructed once the material and energy balances around the sub-sections of the process under consideration have been completed.

The Cumulative Energy Consumption analysis has been applied to the ALCELL® and Kraft wood pulping processes so that a comparison between the two processes could be made. This comparison may affect the decisions that will be made by ALCELL® Technologies Limited¹ pertaining to the construction and/or the design of the proposed commercial ALCELL® mill.

The computer models that have been developed for the ALCELL® and Kraft processes are based on data that may be classified in two different categories. The first category pertains to the data that were used to simulate the mass and energy flows entering and leaving the sub-sections of the ALCELL® process. These data come from a design that has been developed by ALCELL® Technologies Limited for the proposed commercial ALCELL® mill. These data have a degree of uncertainty since they are based on a pilot-scale size ALCELL®

¹ ALCELL® Technologies Limited is a REPAP Enterprises Company.

mill and not on another commercial size mill. This uncertainty will be reflected in the results of calculations for the ALCELL® process.

The data that have been used to construct the computer model of the Kraft process can be assigned to the second data category. Calculations for the Kraft process are based on design data for the proposed Athabasca mill in Alberta. Although these data are also based upon a plant design, they have a lesser degree of uncertainty than that associated with the ALCELL® mill design data. The lesser degree of uncertainty for the Kraft mill design data comes from the fact that they are based on experience with, and operational data from, other Kraft mills that have been operating for many years. Hence the results of calculations for the Kraft process are believed to be more precise.

6.2 Comparison of the Most Probable Operating Strategies of the ALCELL® and Kraft Processes

The most probable operating strategy for a commercial ALCELL® mill would involve the combustion of the following byproducts:

- ① Woodroom "Chip Screen" Rejects (Stream 6)
- ② Brownstock Screen Rejects (Stream ER)
- ③ Furfural Residue (heavy oil) (Stream DC)
- ④ Hot Decanter Tar Layer (Stream EB)

These byproducts are the most likely candidates to be used as fuel for the cogeneration process because they have little if any development potential. Research by ALCELL® Technologies Limited has shown that the other byproducts (i.e., lignin, furfural and wood syrups) of the ALCELL® process are useful and salable, therefore these byproducts will not be used as fuel in the

cogeneration process. This combustion strategy is presented in Tables 5.9, 5.18 & 5.19 as “Combustion Strategy #7”.

The most probable combustion strategy for the Kraft process would involve the combustion of all of the “Hog Fuel” so that the Bunker C fuel oil requirement is reduced to zero and so that surplus high pressure steam is produced to generate additional electricity in order to reduce the required amount of imported electricity. This combustion strategy is presented in Tables 5.21, 5.22 & 5.23 as “Combustion Strategy C”.

6.2.1 Comparison of the Cumulative Energy Inputs for the ALCELL® and Kraft Processes

The total amount of Cumulative Energy entering the ALCELL® and Kraft processes per air dry metric tonne (ADMT) of pulp, for the most probable operating strategies, is equal to 35.8 GJ and 26.2 GJ respectively. The large difference in the total Cumulative Energy Consumption of these two processes is depicted graphically in Figures 6.1 and 6.2 for a variety of input streams and combustion energy sources. A large portion of the difference in the total Cumulative Energy Consumption of the two processes is due to the large difference in the amount of Cumulative Energy entering each process as imported electricity. Admittedly, the ALCELL® process requires a larger amount of electrical energy than the Kraft process. However, due to the large uncertainty associated with the electrical energy demands of the ALCELL® process, the difference in the Cumulative Energy value of the imported electricity between the two processes may be reduced once a commercial size ALCELL® mill is constructed and actual electrical energy demands are determined.

Other noticeable differences exist between the two processes for the following inputs:

- ① **Delignification Chemicals** – A relatively large difference between the two processes exists for this input stream because the Kraft process is able to use white liquor as its source of sodium hydroxide in its Oxygen delignification section while the ALCELL® process must use fresh sodium hydroxide that has a large specific Cumulative Energy Consumption associated with it. (See Appendix B, Sections B.1.4 & B.2.4).
- ② **Make-up Chemicals** – The make-up chemicals for the ALCELL® process pertain only to the additional alcohol that is required by the process. For the Kraft process the make-up chemicals refer to the additional saltcake and lime that are required for the chemical recovery process.

Input Stream

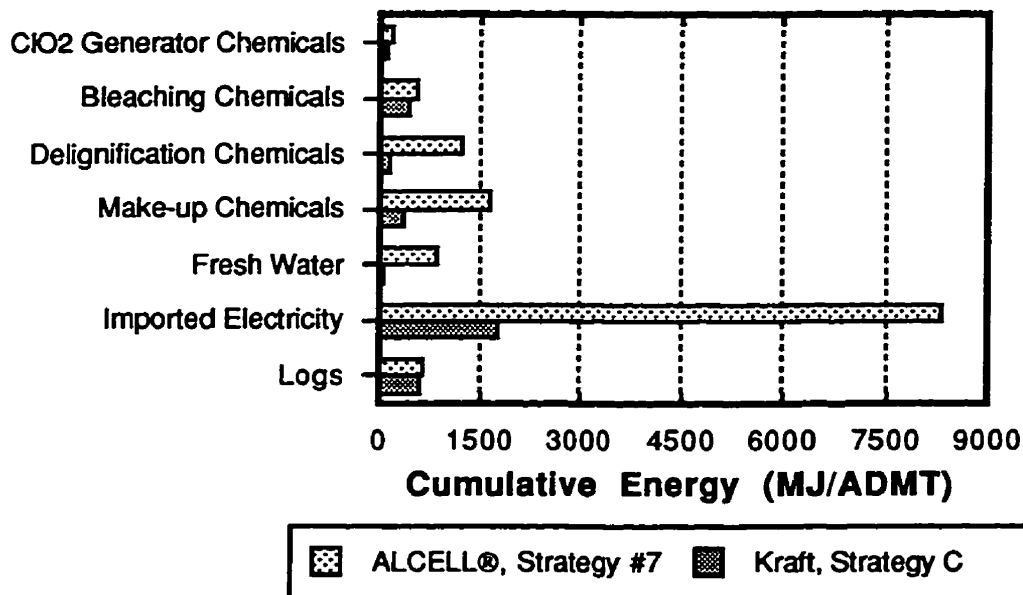


Figure 6.1 — Comparison of the Raw Materials Input as Cumulative Energy for the ALCELL® and Kraft Processes

Figure 6.2 shows a graphical representation of the amount of Cumulative Energy entering the processes due to the combustion of byproducts, Bunker C fuel oil and black liquor solids. This comparison reveals that the difference between the two processes is not in the total combustion energy requirement but in the sources of the combustion energy.

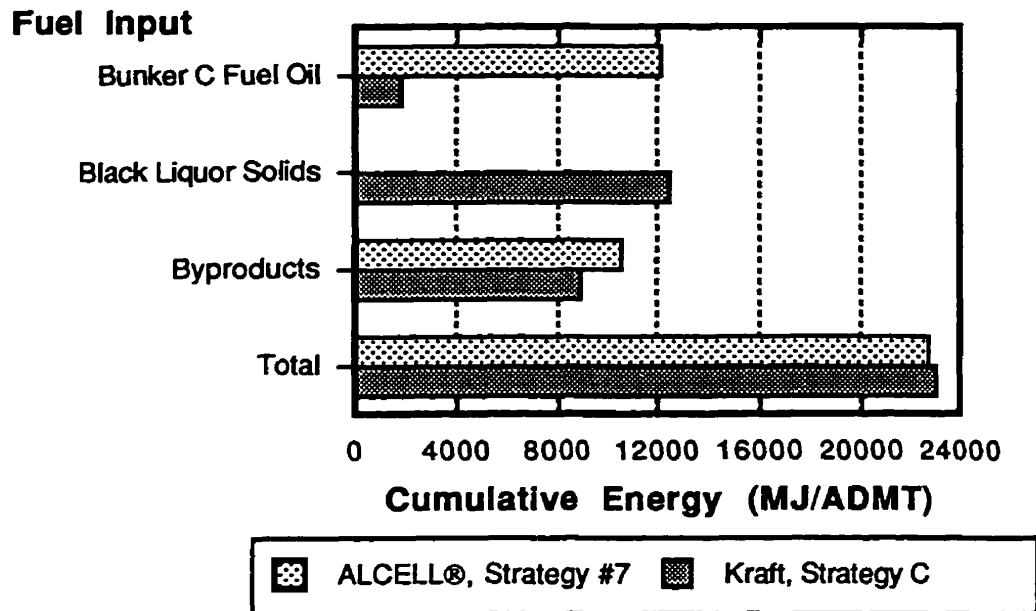


Figure 6.2 — Comparison of the Combustion Energy Input as Cumulative Energy for the ALCELL® and Kraft Processes

6.2.2 Comparison of the Cumulative Energy Outputs for the ALCELL® and Kraft Processes

The Cumulative Energy entering the process is distributed amongst the useful products in proportion to their masses. The resulting distribution of Cumulative Energy is shown in Figure 6.3.

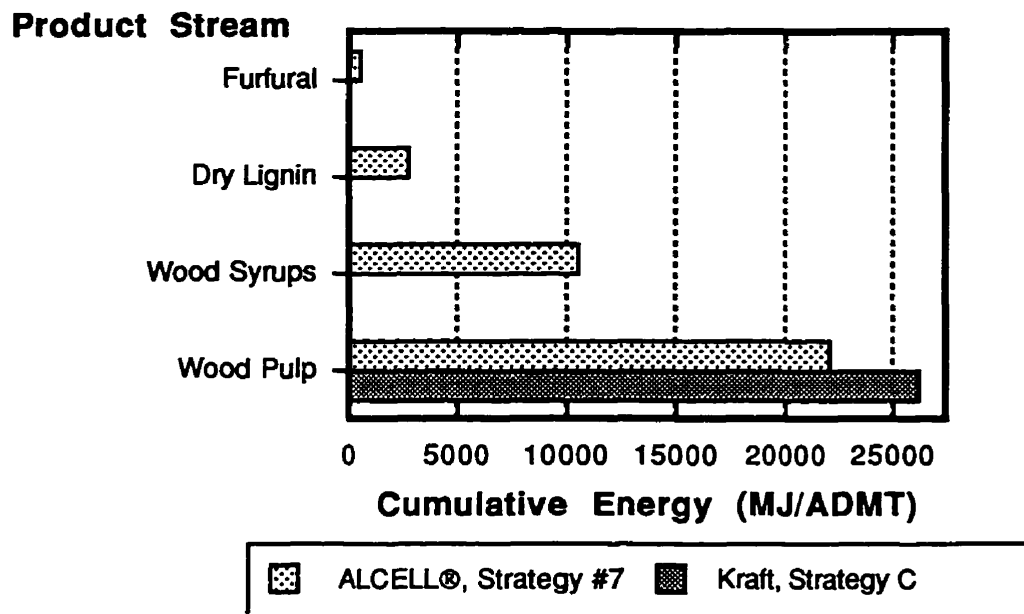


Figure 6.3 — Comparison of the Cumulative Energy of the Products of the ALCELL® and Kraft Processes

The comparison of these operating strategies reveals that the ALCELL® process has a specific CEnC for the wood pulp, $c_{pulp} = 12.3$ MJ/kg whereas for the Kraft process the $c_{pulp} = 14.5$ MJ/kg. In these terms the ALCELL® process is superior. However, in order to produce the ALCELL® pulp at the above specified specific CEnC, the process must also produce furfural, lignin and wood syrups as useful products. This allows each of these products to be assigned an appropriate Cumulative Energy value.

6.3 Byproduct Combustion Effects on the ALCELL® and Kraft Processes

The main advantage associated with the combustion of byproducts from the ALCELL® and Kraft processes is the reduction in the required amount of Bunker C fuel oil and electrical energy. The reduction in the required amount of Bunker C fuel oil is due to the utilization of the combustion energy of the byproducts, instead of Bunker C, for steam generation. The electrical energy requirement is reduced due to byproduct combustion for two possible reasons.

- ① If the Bunker C fuel oil demand is reduced to zero, then the cogeneration system is producing the required amount of process-steam and possibly a surplus amount. While all steam produced by the cogeneration system is used to produce electricity by expansion through a turbine, the surplus steam allows for the production of an additional amount of electricity, thus reducing the imported electrical energy demand of the process.
- ② If the wet lignin cake and/or the wood syrups are used as fuel in the ALCELL® process, the electricity consumption of the Lignin Dryer (Section 7) and the Finisher Evaporator (Section 12) are set to zero.

These effects are demonstrated by comparing “Combustion Strategies” #7 with #11 for the ALCELL® process and “Combustion Strategies” A with C for the Kraft process. “Combustion Strategy #7” of the ALCELL® process is described in Section 6.2. “Combustion Strategy #11” differs from “#7” by using the wood syrups as a fuel in the cogeneration system. “Combustion Strategy A” of the Kraft process does not burn any of the “Hog Fuel” and “Combustion Strategy C” burns all of it.

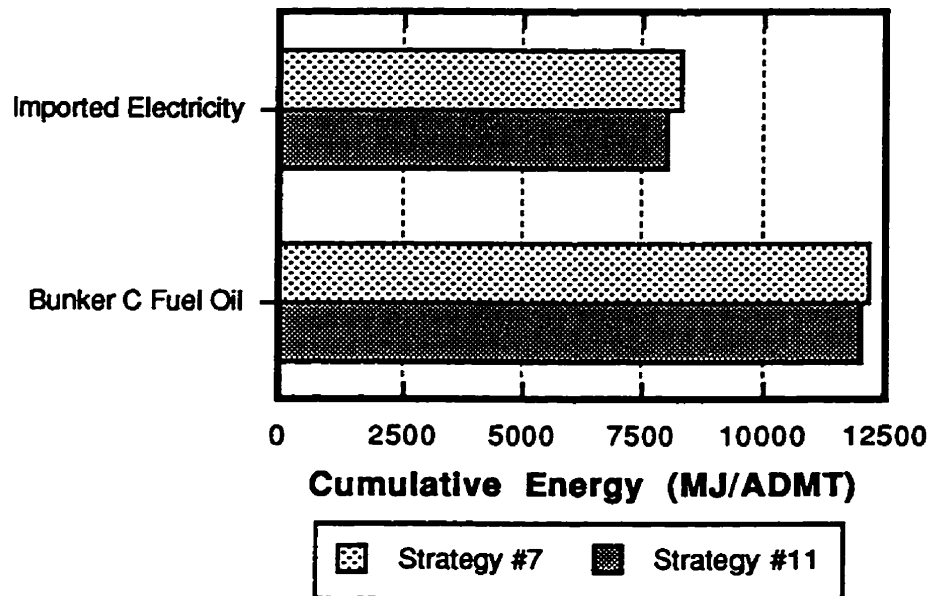


Figure 6.4 — Comparison of Imported Electricity and Bunker C Fuel Consumption for Combustion Strategies 7 and 11 of the ALCELL® Process

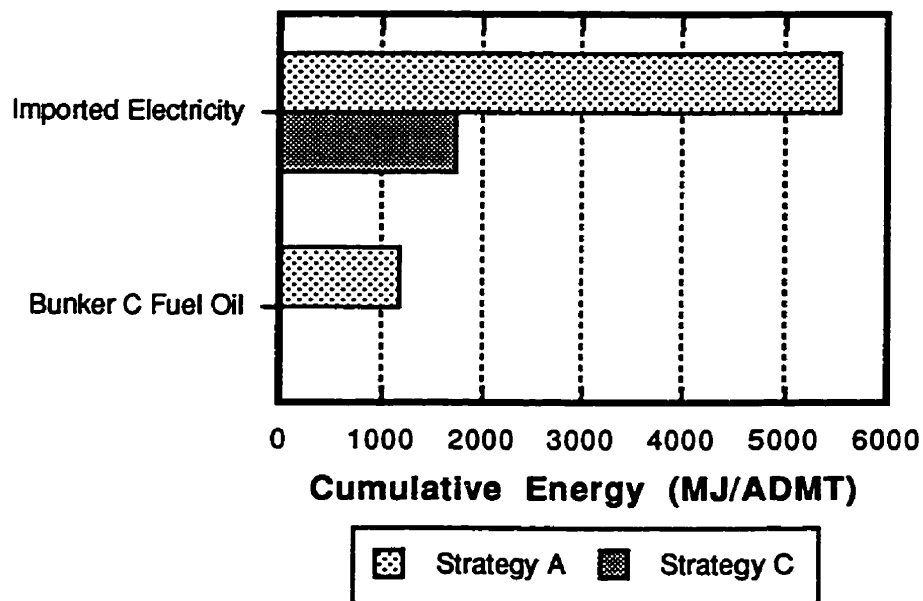


Figure 6.5 — Comparison of Imported Electricity and Bunker C Fuel Consumption for Combustion Strategies “A” and “C” of the Kraft Process

The combustion of the “Hog Fuel” for “Combustion Strategy C” of the Kraft process has a very noticeable effect on the import requirements of electricity and Bunker C fuel oil.

6.4 Energetic Efficiency of Generation of Steam and Electricity for the ALCELL® and Kraft Processes

Steam and Electricity generation efficiencies for the ALCELL® and Kraft processes are presented in Tables 5.18 & 5.23 respectively.

The energetic efficiencies for the generation of electricity and steam are affected by the byproducts that are used as fuel in the cogeneration process. To illustrate the effect that these byproducts have on the steam and electricity generation efficiencies² “Combustion Strategy #7” and “Combustion Strategy #11”, both of the ALCELL® process, are compared. The generation efficiencies of electricity and steam are listed in Table 6.1.

Table 6.1 — Energy Efficiency of Generation of Electricity and Steam for the ALCELL® Process

Combustion Strategy	Generation Efficiency (%)	
	Electricity (η_{elec})	Steam (η_{steam})
7	33.13	60.15
11	29.11	35.55

The generation efficiencies are highly dependent upon the amount of Cumulative Energy that enters the cogeneration process with the Bunker C fuel oil and with the byproducts that have been designated for combustion. A comparison between the fuel requirements of “Combustion Strategies” #7 and #11 is shown in Table 6.2. This table shows that more Cumulative Energy enters the cogeneration process with the fuel for “Combustion Strategy #11” than it does for “Combustion Strategy #7”. There are two reasons for the difference in the Cumulative Energy entering the cogeneration process:

² Refer to Appendix A Equations A.60 to A.66 and A.105 to A.112 for the method of calculating these efficiencies.

- ① The combustion efficiency of some of the byproducts is low compared to the combustion efficiency of the Bunker C fuel that they are replacing. Therefore, more Cumulative Energy enters the cogeneration process for the same amount of steam and electricity production.
- ② In general, the Energetic Production Efficiency of the byproducts is lower than that of the Bunker C fuel. Therefore, more Cumulative Energy enters the cogeneration process for the same amount of Combustion Energy of Bunker C fuel.

A noticeable exception to reason ② is the Energetic Production Efficiency of the "Woodroom Rejects" (See Tables 6.2 & 6.4). Although its Energetic Production Efficiency is much higher than that of the Bunker C fuel, its Combustion Efficiency is much lower. Therefore a combination of reasons ① and ② causes more Cumulative Energy to enter the cogeneration process with the "Woodroom Rejects" than does with the Bunker C fuel for the same effect (i.e., produce the same amount of steam and electricity).

Table 6.2 — Comparison of the Fuel Requirement of the Cogeneration System for the ALCELL® Process

		Thermal ‡ Energy (MJ)	Cumulative Energy (MJ)	Energetic § Production Efficiency (%)	Combustion Efficiency ¶ (%)
Combustion Strategy #7					
①	Bunker C Fuel Oil	10018.34	12114.08	82.7	85.0
②	Woodroom Rejects	9248.79	9660.15	95.7	65.0
③	Decanter Tar Layer	944.20	1330.00	71.0	65.0
④	Brownstock Rejects	167.39	230.35	72.7	65.0
⑤	Furfural Residue	163.64	215.30	76.0	85.0
Total		20542.36	23549.88		
Combustion Strategy #11					
①	Bunker C Fuel Oil	9886.22	11954.32	82.7	85.0
②	Woodroom Rejects	9248.79	9681.22	95.5	65.0
③	Decanter Tar Layer	944.20	1372.08	68.8	65.0
④	Wood Syrups	1215.67	11643.96	10.4	65.0
⑤	Brownstock Rejects	167.39	259.00	64.6	65.0
⑥	Furfural Residue	163.64	220.39	74.2	85.0
Total		21625.91	35130.97		

‡ – Thermal Energy is equal to the sum of the Physical and Chemical Energies.

§ – Ratio of Thermal Energy to Cumulative Energy.

¶ – Boiler Efficiency.

Table 6.3 — Energy Efficiency of Generation of Electricity and Steam for the Kraft Process

Combustion Strategy	Generation Efficiency (%)	
	Electricity (η_{elec})	Steam (η_{steam})
A	28.19	31.47
B	28.07	31.14
C	24.63	24.38

The steam generation efficiency for the Kraft process is lower than that of the ALCELL® process because the steam that is produced in the recovery boiler has a large amount of Cumulative Energy associated with it. This is caused by the normal apportioning of Cumulative Energy to the useful products of the recovery boiler in proportion to their masses (See Equation A.88). As a result the energy efficiency of the steam leaving the recovery boiler is as follows:

$$\begin{aligned}
 \text{For Strategy C: } C_{\text{steam}} &= 39323.19 \text{ MJ} \\
 E_{\text{steam}} &= 10828.90 \text{ MJ} \\
 \eta_{\text{steam}} &= \frac{E_{\text{steam}}}{C_{\text{steam}}} \times 100\% = 27.54\%
 \end{aligned}$$

This steam then enters the cogeneration system where additional fuel, in the form of “Hog Fuel”, and some electricity are also inserted. Cumulative Energy balance equations around the cogeneration system (See Equations A.105 to A.112) result in the steam generation efficiency shown for “Combustion Strategy C” in Table 6.3.

Although this result appears to be detrimental to the Kraft process, in actuality it is not because it does not affect the amount of Cumulative Energy entering the process. Since the most probable operating strategy of the Kraft process involves the production of only one product, the steam generation efficiency will not affect the Cumulative Energy value of the wood pulp.

Table 6.4 — Comparison of the Fuel Requirement of the Cogeneration System for the Kraft Process

		Fuel	Thermal ‡ Energy (MJ)	Cumulative Energy (MJ)	Energetic § Production Efficiency (%)	Combustion Efficiency ¶ (%)
Combustion Strategy A						
①		Bunker C Fuel Oil	949.63	1148.28	82.7	85.0
		Total	949.63	1148.28		
Combustion Strategy B						
①		Woodroom Rejects	1241.82	1301.85	95.4	65.0
		Total	1241.82	1301.85		

‡ – Thermal Energy is equal to the sum of the Physical and Chemical Energies.

§ – Ratio of Thermal Energy to Cumulative Energy.

¶ – Boiler Efficiency.

Table 6.4 depicts a comparison between Combustion Strategies “A” and “B” of the Kraft process. Both Combustion Strategies produce the same amount of steam and electricity in the cogeneration system. However, the type of fuel differs for the two strategies and this effects the generation efficiencies of steam and electricity for the same reasons that are given for the ALCELL® process.

6.5 Distribution of Cumulative Energy Amongst the Products of the ALCELL® and Kraft Processes

The cumulative energy entering the ALCELL® and Kraft processes is distributed amongst the useful products as described in Chapter 2. The cumulative energy of these useful products for Combustion Strategies “#7” and “#11” of the ALCELL® process are shown in Figure 6.6. A similar graph for Combustion Strategies “A”, “B” and “C” of the Kraft process are shown in Figure 6.7.

For the combustion strategies that have been considered for the ALCELL® and Kraft processes, there are only two factors that influence the Cumulative Energy values of the products of the processes. They are as follows:

- ① The total Cumulative Energy entering the process.
- ② The number of products amongst which the Cumulative Energy entering the process is distributed.

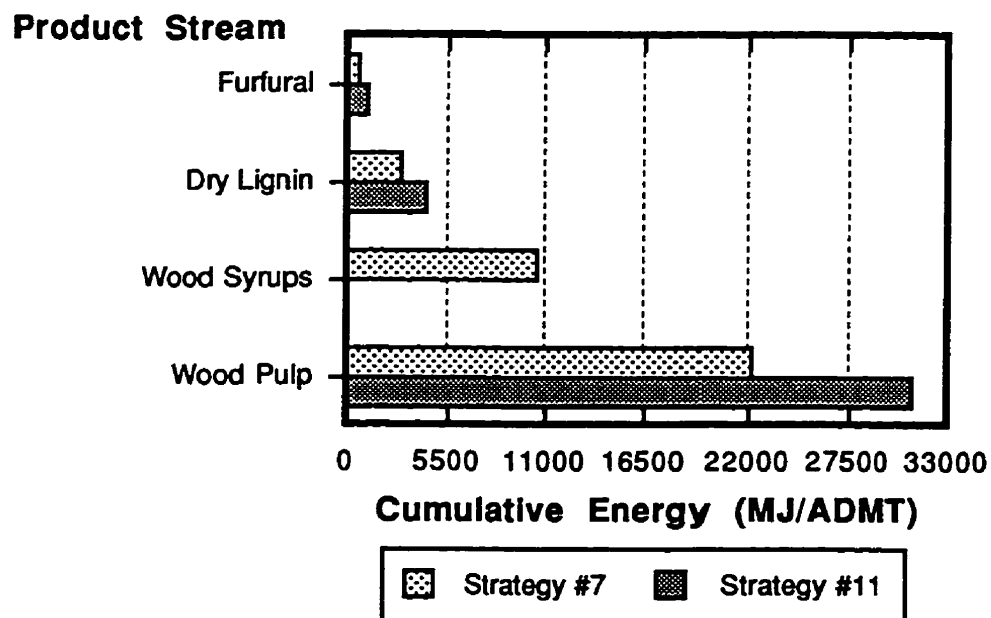


Figure 6.6 — Comparison of Cumulative Energy Values of the Products of the ALCELL® Process for Combustion Strategies “7” and “11”

The comparison of the ALCELL® process “Combustion Strategies” in Figure 6.6 graphically displays the effect that burning the wood syrups has on the remaining useful products. The Cumulative Energy value of all of the remaining products increases because;

- ① The wood syrups stream is a more “expensive” fuel, in terms of its Energetic Production Efficiency, than the fuel it is replacing in the cogeneration system, namely Bunker C fuel oil. (See Table 6.2).
- ② There are fewer useful products amongst which the Cumulative Energy entering the process can be distributed.

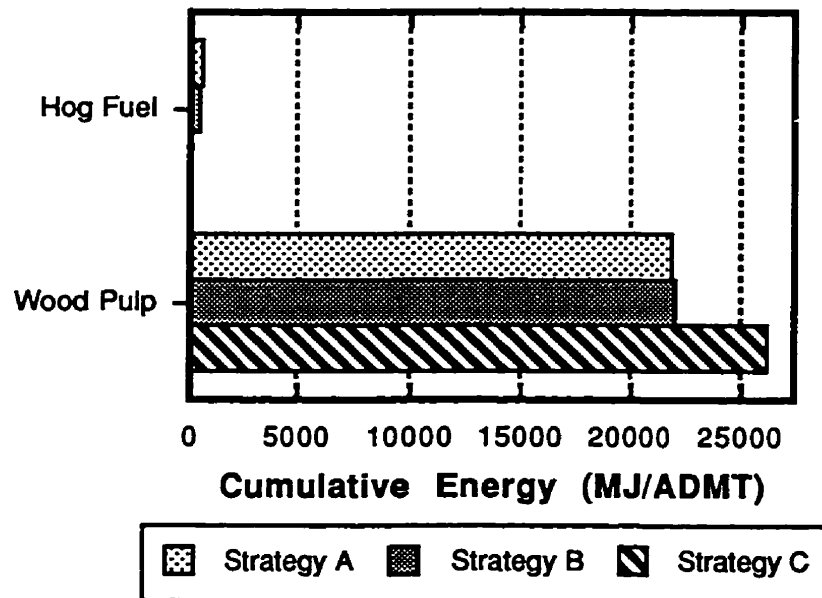


Figure 6.7 — Comparison of Cumulative Energy Values of the Products of the Kraft Process for Combustion Strategies “A”, “B” and “C”

Observations, similar to those of the ALCELL® process, can be made for the use of “Hog Fuel” in the cogeneration system of the Kraft process.

6.6 Alternative Treatment of the ALCELL® Process

A method of demonstrating the usefulness of the Cumulative Energy Consumption analysis may be performed by assuming that the ALCELL® process is comprised of only one large section (referred to as the “Lumped” ALCELL® process in Figure 6.8). The result of this assumption would be that the useful product streams obtain Cumulative Energy values based solely upon their masses. Figure 6.8 graphically represents the differences that arise due to an alternative treatment of the same process.

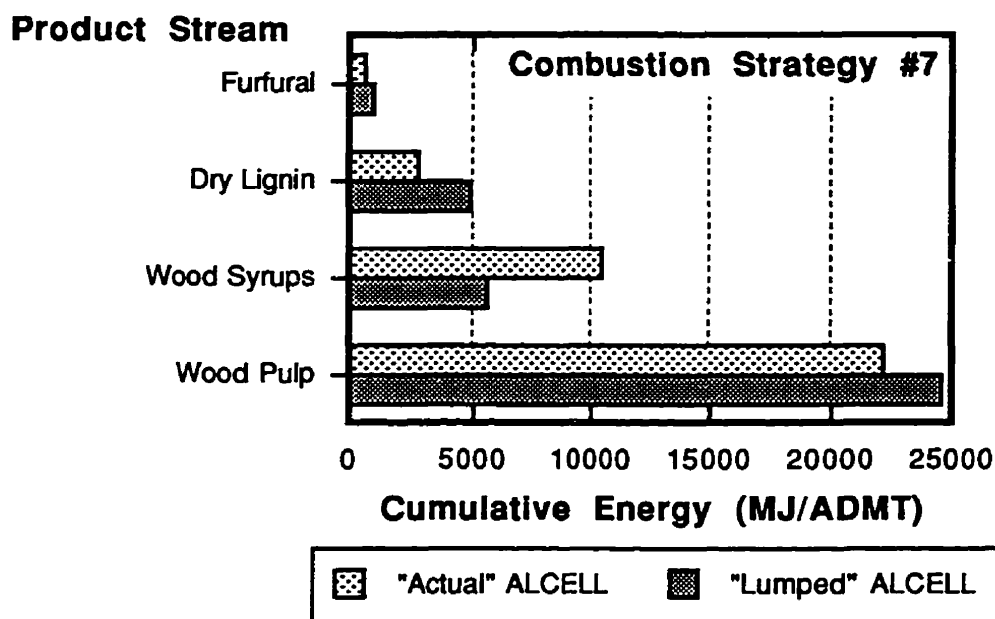


Figure 6.8 — Comparison of the Cumulative Energy of the Products of the “Actual” and “Lumped” ALCELL® Processes

The effects of “lumping” a process into large sections, or even assuming that the entire process is comprised of only one section, are noticeable in Figure 6.8. These effects may be listed as follows:

- ① The processing/refining requirements of certain product streams may be underestimated by assuming a “lumped” model. (e.g., “lumping”

the ALCELL® process into one section caused the Cumulative Energy value of the wood syrups to decrease to a value that is approximately equal to one half of its “unlumped” Cumulative Energy value.)

- ② The opposite effect of that mentioned in ① is also observed for the other three products that are produced with “Combustion Strategy #7.

CHAPTER 7

CONCLUSIONS

7.1 Conclusions

Conclusions pertaining to the Cumulative Energy Consumption analysis are listed as follows:

- ① The analysis can be used to determine the Cumulative Energy value of a product in terms of the amount of energy required to produce that product.
- ② The analysis distributes the energy required by a process among its useful products in proportion to their masses. Therefore a process may be evaluated on the basis of more than one product.
- ③ The analysis can be used to compare the energy requirements of widely varying processes.
- ④ The analysis can be used to compare different processes that produce a common product.
- ⑤ The most probable byproduct combustion strategies give specific Cumulative Energy Consumption values to the wood pulp of 12.3 MJ/kg for the ALCELL® process and 14.5 MJ/kg for the Kraft process.

- ⑥ The Cumulative Energy Consumption efficiency of generation of steam and electricity decrease when a fuel with a specified “combustion efficiency”¹ replaces another fuel with higher “combustion efficiency”.
- ⑦ The Cumulative Energy Consumption efficiency of generation of steam and electricity decrease when a fuel with a specified “Energy Production Efficiency”² replaces another fuel with higher “Energy Production Efficiency”.
- ⑧ Steam and electricity generation efficiency changes affect the Cumulative Energy Consumption values of the products of the process.

¹ Boiler Efficiency.

² Energy Production Efficiency is defined as the ratio of the “energy made available from combustion” to the sum of the “energy made available from combustion” and the “energy required to produce the fuel”.

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APPENDIX A

SAMPLE CALCULATIONS

A.1 Sample Calculation for the most Probable Byproduct Combustion Strategy of the ALCELL® Process

The most probable operating strategy for the ALCELL® process would involve the combustion of some of the byproducts of the process. The combustion of these byproducts is done so that the fuel oil (e.g. Bunker C) requirement, of the Cogeneration System (Section 14), can be reduced or even eliminated.

The byproduct combustion strategy that is most likely to be followed by a commercial ALCELL® plant is presented as “Combustion Strategy #7” and it would involve the combustion of the following byproducts:

- ① Woodroom Rejects (Stream 6)
- ② Brownstock Screen Rejects (Stream ER)
- ③ Hot Decanter Tar Layer (Stream EB)
- ④ Heavy Furfural Residue (Stream DC)

The sample calculations presented here follow the plant sections that were described in Chapter 3 of this thesis. The operating parameters for this set of results may be found in Table 5.1. In the following tables, streams are identified according to Figure 3.1 and Table 3.1.

A.1.1 Section 1 — The Woodroom

A schematic diagram of the woodroom used for the ALCELL® process is shown in Figure 3.2. This section contains two sub-sections, the debarking drums and the chipper. The debarking drums and chipper are referred to as sub-sections 1A & 1B respectively.

Table A.1.1 — Mass, Energy and Cumulative Energy Balances for the Woodroom of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Logs/1	4022.53	0.00	0.00	603.38 [‡]	22.85
Low Pressure Injection Steam/2	0.00	0.00	0.00	0.00 [¶]	0.00
Recirculated Wash Water/3	3370.00	987.01	73.94	987.01	37.39
Electricity	—	347.80	26.06	1049.74 [§]	39.76
Sum	7392.53	1334.81	100.00	2640.13	100.00
Useful Effluents/Stream					
Wood Chips/C	3178.89	0.00 [□]	0.00	2228.77	84.42
Hog Fuel/6	843.64	0.00	0.00	411.36	15.58
Losses/Stream					
Heat Rejected to the Environment	—	911.81	68.31	0.00	0.00
Sewer Water/5	3370.00	423.00	31.69	0.00	0.00
Sum	7392.53	1334.81	100.00	2640.13	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

□ – Wood Chips are stored as a “Chip Pile” where they cool down to the datum temperature.

‡ – Refer to Appendix B for Sample Calculation.

¶ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Sub-Section 1A — Debarking Drum

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_{1A} &= M_{\text{Debarked Logs}} + M_{\text{Bark}} \\
 &= 3311.35 + 711.18 \\
 &= 4022.53 \text{ kg}
 \end{aligned}
 \tag{A.1}$$

Cumulative Energy entering Sub-Section 1A $\Rightarrow$

$$\begin{aligned}\sum C_{1A} &= C_{Logs} + C_{Steam} + C_{Recirc. Water} + C_{Elec 1A} \\ &= 603.38 + 0.00 + 547.69 + 650.37 \\ &= 1801.44 \text{ MJ}\end{aligned}\quad (A.2)$$

Cumulative Energy of the Debarked Logs $\Rightarrow$

$$\begin{aligned}C_{Debarked Logs} &= \frac{M_{Debarked Logs}}{\sum M_{1A}} \times \sum C_{1A} \\ &= \left(\frac{3311.35}{4022.53} \right) \times 1801.44 \\ &= 1482.94 \text{ MJ}\end{aligned}\quad (A.3)$$

Cumulative Energy of the Bark $\Rightarrow$

$$\begin{aligned}C_{Bark} &= \frac{M_{Bark}}{\sum M_{1A}} \times \sum C_{1A} \\ &= \left(\frac{711.18}{4022.53} \right) \times 1801.44 \\ &= 318.49 \text{ MJ}\end{aligned}\quad (A.4)$$

Sub-Section 1B — Chipper

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_{1B} &= M_{Wood Chips} + M_{Fines} \\ &= 3178.89 + 132.45 \\ &= 3311.34 \text{ kg}\end{aligned}\quad (A.5)$$

Cumulative Energy entering Sub-Section 1B $\Rightarrow$

$$\begin{aligned}\sum C_{1B} &= C_{Debarked Logs} + C_{Recirc. Water} + C_{Elec 1B} \\ &= 1482.94 + 439.32 + 399.37 \\ &= 2321.63 \text{ MJ}\end{aligned}\quad (A.6)$$

Cumulative Energy of the Wood Chips $\Rightarrow$

$$\begin{aligned}
 C_{Wood\ Chips} &= \frac{M_{Wood\ Chips}}{\sum M_{1B}} \times \sum C_{1B} \\
 &= \left(\frac{3178.89}{3311.34} \right) \times 2321.63 \\
 &= 2228.77 \text{ MJ}
 \end{aligned} \tag{A.7}$$

Cumulative Energy of the Fines $\Rightarrow$

$$\begin{aligned}
 C_{Fines} &= \frac{M_{Fines}}{\sum M_{1B}} \times \sum C_{1B} \\
 &= \left(\frac{132.45}{3311.34} \right) \times 2321.63 \\
 &= 92.87 \text{ MJ}
 \end{aligned} \tag{A.8}$$

The Cumulative Energy of the woodroom's rejects is equal to the sum of the Cumulative Energy of the fines and the bark.

$$\begin{aligned}
 C_{Woodroom\ Rejects} &= C_{Bark} + C_{Fines} \\
 &= 318.49 + 92.87 \\
 &= 411.36 \text{ MJ}
 \end{aligned} \tag{A.9}$$

A.1.2 Section 2 — Extraction and Flash Evaporation

A schematic diagram of the Extraction & Flash Evaporation section is shown in Figure 3.3.

Table A.1.2 — Mass, Energy and Cumulative Energy Balances for the Extraction and Flash Evaporation Section of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Wood Chips/C	3178.89	0.00 [□]	0.00	2228.77	7.28
Fresh Liquor/DK	5607.25	1506.65	10.89	8755.81	28.61
Wash Water/AN	7791.42	2656.74	19.21	2656.74	8.68
Low Pressure Injection Steam/D	356.27	975.18	7.05	1621.27 [†]	5.30
Medium Pressure Injection Steam/F	201.50	555.23	4.02	923.08 [†]	3.02
High Pressure Indirect Heat Steam/W	—	7477.17	54.06	12430.98 [†]	40.61
Electricity	—	659.59	4.77	1990.81 [§]	6.50
Sum	17135.33	13830.56	100.00	30607.46	100.00
Useful Effluents/Stream					
Flashed Weak Black Liquor/BF	6228.01	1767.09	12.78	9798.35	32.01
Wet Pulp/AO	7420.98	1966.61	14.22	11675.22	38.14
High Pressure Flash Vapor/BB	1602.35	2448.66	17.70	2520.93	8.24
Medium Pressure Flash Vapor/BC	1130.58	1746.61	12.63	1778.72	5.81
Low Pressure Flash Vapor/BD	575.73	866.71	6.27	905.78	2.96
High Pressure Steam Condensate	—	2362.95	17.08	3928.46 [†]	12.84
Losses					
Heat Rejected to the Environment	—	0.09	0.00	0.00	0.00
Purge Streams/H & I	177.68	281.94	2.04	0.00	0.00
Cooling Water Enthalpy Increase	—	2389.90	17.28	0.00	0.00
Sum	17135.33	13830.56	100.00	30607.46	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

□ – Wood Chips are stored as a “Chip Pile” where they cool down to the datum temperature.

[†] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 2 — Extraction and Flash Evaporation

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_2 &= M_{\text{Wet Pulp}} + M_{\text{Weak Liquor}} + M_{\text{HP, MP \& LP Flash Vapors}} \\
 &= 7420.98 + 6228.01 + 1602.35 + 1130.58 + 575.73 \\
 &= 16957.65 \text{ kg}
 \end{aligned}
 \tag{A.10}$$

Cumulative Energy entering Section 2 $\Rightarrow$

$$\begin{aligned}\sum C_2 &= C_{Wood\ Chips} + C_{Fresh\ Liquor} + C_{Wash\ Water} + C_{Steam} + C_{Elec\ 2} \\ &= 2228.77 + 8755.81 + 2656.74 + 14975.33 + 1990.81 \\ &= 30607.46\ MJ\end{aligned}\quad (A.11)$$

Cumulative Energy of the Wet Pulp $\Rightarrow$

$$\begin{aligned}C_{Wet\ Pulp} &= \frac{M_{Wet\ Pulp}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{7420.98}{16957.65} \right) \times \{ 30607.46 - 3928.46 \} \\ &= 11675.22\ MJ\end{aligned}\quad (A.12)$$

Cumulative Energy of the Weak Liquor $\Rightarrow$

$$\begin{aligned}C_{Weak\ Liquor} &= \frac{M_{Weak\ Liquor}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{6228.01}{16957.65} \right) \times \{ 30607.46 - 3928.46 \} \\ &= 9798.35\ MJ\end{aligned}\quad (A.13)$$

Cumulative Energy of the High Pressure Flash Vapor $\Rightarrow$

$$\begin{aligned}C_{HP\ Flash\ Vapor} &= \frac{M_{HP\ Flash\ Vapor}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{1602.35}{16957.65} \right) \times \{ 30607.46 - 3928.46 \} \\ &= 2520.93\ MJ\end{aligned}\quad (A.14)$$

Cumulative Energy of the Medium Pressure Flash Vapor $\Rightarrow$

$$\begin{aligned}C_{MP\ Flash\ Vapor} &= \frac{M_{MP\ Flash\ Vapor}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{1130.58}{16957.65} \right) \times \{ 30607.46 - 3928.46 \} \\ &= 1778.72\ MJ\end{aligned}\quad (A.15)$$

Cumulative Energy of the Low Pressure Flash Vapor $\Rightarrow$

$$\begin{aligned}C_{LP\ Flash\ Vapor} &= \frac{M_{LP\ Flash\ Vapor}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{575.73}{16957.65} \right) \times \{ 30607.46 - 3928.46 \} \\ &= 905.78\ MJ\end{aligned}\quad (A.16)$$

A.1.3 Section 3 — Screening & Oxygen Delignification

A schematic diagram of the Screening & Oxygen Delignification section is shown in Figure 3.4.

Table A.1.3 — Mass, Energy and Cumulative Energy Balances for the Screening & Oxygen Delignification Section of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Wet Pulp/AO	7420.98	1966.61	24.17	11675.22	55.35
Delignification Chemicals/EU&EV	411.34	14.82	0.18	1167.04 [‡]	5.54
Wash Water/FA	8950.00	3632.19	53.78	3632.19	21.19
Medium Pressure Injection Steam/EW	348.00	958.90	11.19	1594.20 [¶]	7.35
High Pressure Injection Steam/EX	34.50	104.44	1.22	173.63 [¶]	0.80
Recovered Heat (M12)	—	149.79	1.89	149.79	0.75
Electricity	—	649.12	7.57	1959.20 [§]	9.02
Sum	17164.82	7475.87	100.00	20351.27	100.00
Useful Effluents/Stream					
Clean Pulp/FC	7099.86	2316.43	27.89	19404.18	90.69
Screen Rejects/ER	24.80	4.81	0.06	67.77	0.32
Recovered Heat (M11)	—	588.43	11.45	588.43	4.51
Recovered Heat (M17)	—	290.89	11.36	290.89	4.48
Losses					
Heat Rejected to the Environment	—	1585.47	29.72	0.00	0.00
Sewer Water/FG	10040.16	2689.84	19.52	0.00	0.00
Sum	17164.82	7475.87	100.00	20351.27	100.00

[†] – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[¶] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 3 — Screening and Oxygen Delignification

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_3 &= M_{\text{Clean Pulp}} + M_{\text{Screen Rejects}} \\
 &= 7099.86 + 24.80 \\
 &= 7124.66 \text{ kg}
 \end{aligned}
 \tag{A.17}$$

Cumulative Energy entering Section 3 $\Rightarrow$

$$\begin{aligned}\sum C_3 &= C_{Wet\ Pulp} + C_{Chemicals} + C_{Water} + C_{Steam} + C_{M12} + C_{Elec\ 3} \\ &= 11675.22 + 1167.04 + 3632.19 + 1767.83 + 149.79 + 1959.20 \quad (A.18) \\ &= 20351.27\ MJ\end{aligned}$$

Cumulative Energy of the Clean Pulp $\Rightarrow$

$$\begin{aligned}C_{Clean\ Pulp} &= \frac{M_{Clean\ Pulp}}{\sum M_3} \times \{ \sum C_3 - C_{M11,M17} \} \\ &= \left(\frac{7099.86}{7124.66} \right) \times \{ 20351.26 - 879.32 \} \quad (A.19) \\ &= 19404.18\ MJ\end{aligned}$$

Cumulative Energy of the Screen Rejects $\Rightarrow$

$$\begin{aligned}C_{Screen\ Rejects} &= \frac{M_{Screen\ Rejects}}{\sum M_3} \times \{ \sum C_3 - C_{M11,M17} \} \\ &= \left(\frac{24.80}{7124.66} \right) \times \{ 20351.26 - 879.32 \} \quad (A.20) \\ &= 67.77\ MJ\end{aligned}$$

A.1.4 Section 4 — The Bleach Plant

A schematic diagram of the Bleach Plant is shown in Figure 3.5.

Table A.1.4 — Mass, Energy and Cumulative Energy Balances for the Bleach Plant of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Clean Pulp/FC	7099.86	2316.43	44.64	19404.17	80.26
Bleaching Chemicals/FQ,GE & GT	167.12	0.00	0.00	516.92‡	2.12
Wash Water/GH	123.95	50.30	0.97	50.30	0.15
Recirculated Wash Water/HX	6176.05	1808.84	34.85	1808.84	7.42
Chlorine Dioxide Solution/FP & GS	1595.14	0.00	0.00	517.27	2.77
Medium Pressure ClO ₂ Sparge Steam	14.82	40.84	0.79	67.90¶	0.07
Medium Pressure Injection Steam/FR...	66.20	182.41	3.51	303.26¶	1.24
Recovered Heat (M12)	—	69.98	1.35	69.98	0.30
Recovered Heat (M13)	—	403.74	7.78	403.74	1.77
Electricity	—	317.02	6.11	956.83§	3.90
Sum	15243.14	5189.56	100.00	24099.21	100.00
Useful Effluents/Stream					
Bleached Pulp/HG	8156.95	2216.07	42.40	22879.65	94.01
Recirculated Wash Water/3	3370.00	987.01	18.73	987.01	4.02
Recovered Heat (M16)	—	232.55	9.18	232.55	1.97
Losses					
Heat Rejected to the Environment	—	901.62	17.46	0.00	0.00
Sewer Water/FY	3716.19	852.31	12.23	0.00	0.00
Sum	15243.14	5189.56	100.00	24099.21	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

¶ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 4 — The Bleach Plant

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_4 &= M_{\text{Bleached Pulp}} \\
 &= 8156.95 \text{ kg}
 \end{aligned}
 \tag{A.21}$$

Cumulative Energy entering Section 4 $\Rightarrow$

$$\begin{aligned}\sum C_4 &= C_{Clean\ Pulp} + C_{Chemicals} + C_{Water} + C_{Steam} + C_{M12,M13} + C_{Elec\ 4} \\ &= 19404.17 + 1034.19 + 1859.14 + 371.16 + 473.72 + 956.83 \quad (A.22) \\ &= 24099.21\ MJ\end{aligned}$$

Cumulative Energy of the Bleached Pulp $\Rightarrow$

$$\begin{aligned}C_{Bleached\ Pulp} &= \frac{M_{Bleached\ Pulp}}{\sum M_4} \times \{ \sum C_4 - C_{M16} - C_{Recirc.\ Water} \} \\ &= \left(\frac{8156.95}{8156.95} \right) \times \{ 24099.21 - 232.55 - 987.01 \} \quad (A.23) \\ &= 22879.65\ MJ\end{aligned}$$

A.1.5 Section 5 — The Pulp Machine

A schematic diagram of the Pulp Machine is shown in Figure 3.6.

Table A.1.5 — Mass, Energy and Cumulative Energy Balances for the Pulp Machine of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Bleached Pulp/HG	8156.95	2216.07	86.73	22879.67	95.72
Shower Water/HT	0.00	0.00	0.00	0.00	0.00
Low Pressure Injection Steam/HH	0.00	0.00	0.00	0.00‡	0.00
Electricity	—	339.16	13.27	1023.66§	4.28
Sum	8156.95	2555.23	100.00	23903.33	100.00
Useful Effluents/Stream					
Pressed Pulp†/HU	1800.00	355.11	13.90	22094.49	92.43
Recirculated Wash Water/HX	6176.05	1808.84	70.79	1808.84	7.57
Losses					
Heat Rejected to the Environment	—	339.16	13.27	0.00	0.00
Screen Rejects/HK	180.90	52.12	2.04	0.00	0.00
Sum	8156.95	2555.23	100.00	23903.33	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{elec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 5 — The Pulp Machine

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_5 &= M_{\text{Pressed Pulp}} \\ &= 1800.00 \text{ kg}\end{aligned}\tag{A.24}$$

Cumulative Energy entering Section 5 $\Rightarrow$

$$\begin{aligned}\sum C_5 &= C_{\text{Bleached Pulp}} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec 5}} \\ &= 22879.67 + 0.00 + 0.00 + 1023.66 \\ &= 23903.33 \text{ MJ}\end{aligned}\tag{A.25}$$

Cumulative Energy of the Pressed Pulp $\Rightarrow$

$$\begin{aligned} C_{Pressed\ Pulp} &= \frac{M_{Pressed\ Pulp}}{\sum M_5} \times \{ \sum C_5 - C_{Recirc.\ Water} \} \\ &= (1800.00 / 1800.00) \times \{ 23903.33 - 1808.84 \} \\ &= 22094.49\ MJ \end{aligned} \quad (A.26)$$

A.1.6 Section 6 — Lignin Recovery

A schematic diagram of the Lignin Recovery section is shown in Figure 3.7.

Table A.1.6 — Mass, Energy and Cumulative Energy Balances for the Lignin Recovery Section of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Flashed Weak Black Liquor/BF	6228.01	1767.09	46.08	9798.35	41.22
Stillage from Alcohol Recovery/BG	7869.61	1219.43	31.80	12288.53	51.70
Recirculated Wash Water/BR	3000.00	434.46	11.33	434.46	1.83
Electricity	—	413.50	10.79	1248.03§	5.25
Sum	17097.62	3834.48	100.00	23769.37	100.00
Useful Effluents/Stream					
Dilute Alcohol/BL	16473.40	1386.77	36.17	20592.80	86.64
Wet Lignin/BT	624.22	51.45	1.34	780.31	3.28
Recovered Heat (M21)	—	2396.26	62.49	2396.26	10.08
Losses					
Heat Rejected to the Environment	—	0.00	0.00	0.00	0.00
Sum	17097.62	3834.48	100.00	23769.37	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

§ – $\eta_{\text{olelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 6 — Lignin Recovery

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_6 &= M_{\text{Wet Lignin}} + M_{\text{Dilute Alcohol}} \\
 &= 624.22 + 16473.40 \\
 &= 17097.62 \text{ kg}
 \end{aligned}
 \tag{A.27}$$

Cumulative Energy entering Section 6 $\Rightarrow$

$$\begin{aligned}
 \sum C_6 &= C_{\text{Weak Liquor}} + C_{\text{Stillage}} + C_{\text{Recirc. Water}} + C_{\text{Elec 6}} \\
 &= 9798.35 + 12288.53 + 434.46 + 1248.03 \\
 &= 23769.37 \text{ MJ}
 \end{aligned}
 \tag{A.28}$$

Cumulative Energy of the Dilute Alcohol $\Rightarrow$

$$\begin{aligned}
 C_{Dilute\ Alcohol} &= \frac{M_{Dilute\ Alcohol}}{\sum M_6} \times \{ \sum C_6 - C_{M21} \} \\
 &= \left(\frac{16473.40}{17097.62} \right) \times \{ 23769.37 - 2396.26 \} \\
 &= 20592.80\ MJ
 \end{aligned} \tag{A.29}$$

Cumulative Energy of the Wet Lignin $\Rightarrow$

$$\begin{aligned}
 C_{Wet\ Lignin} &= \frac{M_{Wet\ Lignin}}{\sum M_6} \times \{ \sum C_6 - C_{M21} \} \\
 &= \left(\frac{624.22}{17097.62} \right) \times \{ 23769.37 - 2396.26 \} \\
 &= 780.31\ MJ
 \end{aligned} \tag{A.30}$$

A.1.7 Section 7 — Lignin Dryer

A schematic diagram of the Lignin Dryer is shown in Figure 3.8.

Table A.1.7 — Mass, Energy and Cumulative Energy Balances for the Lignin Dryer of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Wet Lignin/BT	624.22	51.45	3.47	780.31	24.58
Medium Pressure Indirect Heat Steam	—	395.10	26.56	656.86 [‡]	20.70
High Pressure Indirect Heating Steam	—	478.82	32.19	796.04 [‡]	25.07
Recovered Heat (M4)	—	373.80	25.13	373.80	11.77
Electricity	—	188.10	12.65	567.73 [§]	17.88
Sum	624.22	1487.27	100.00	3174.74	100.00
Useful Effluents					
Dry Lignin/BV	364.13	85.06	5.72	2766.74	87.15
Medium Pressure Condensate	—	94.10	6.33	156.44 [‡]	4.93
High Pressure Condensate	—	151.32	10.17	251.56 [‡]	7.92
Losses					
Heat Rejected to the Environment	—	0.74	0.05	0.00	0.00
Sewered Condensate/BW	260.09	33.90	2.28	0.00	0.00
Cooling Water Enthalpy Increase	—	1122.15	75.45	0.00	0.00
Sum	624.22	1487.27	100.00	3174.74	100.00

[†] – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

[‡] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 7 — Lignin Dryer

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_7 &= M_{\text{Dry Lignin}} \\ &= 364.13 \text{ kg}\end{aligned}\tag{A.31}$$

Cumulative Energy entering Section 7 $\Rightarrow$

$$\begin{aligned}\sum C_7 &= C_{\text{Wet Lignin}} + C_{\text{Steam}} + C_{\text{M4}} + C_{\text{Elec 7}} \\ &= 780.31 + 1452.90 + 373.80 + 567.73 \\ &= 3174.74 \text{ MJ}\end{aligned}\tag{A.32}$$

Cumulative Energy of the Dry Lignin $\Rightarrow$

$$\begin{aligned} C_{Dry\ Lignin} &= \frac{M_{Dry\ Lignin}}{\sum M_7} \times \{ \sum C_7 - C_{Cond} \} \\ &= \left(\frac{364.13}{364.13} \right) \times \{ 3174.74 - 408.00 \} \\ &= 2766.74\ MJ \end{aligned} \quad (A.33)$$

A.1.8 Section 8 — Alcohol Recovery

A schematic diagram of the Alcohol Recovery section is shown in Figure 3.9.

Table A.1.8 — Mass, Energy and Cumulative Energy Balances for the Alcohol Recovery Section of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Dilute Alcohol/BL	16473.40	1386.77	13.31	20592.80	59.36
Recirculated Alcohol/CT	1.58	0.33	0.00	12.21	0.04
Make-up Alcohol/DJ	96.87	4.54	0.04	1619.04 [‡]	4.67
High Pressure Flash Vapor/BB	1602.35	2448.66	23.51	2520.93	7.27
Medium Pressure Flash Condensate/BC	1130.58	163.46	1.57	195.56	0.56
Low Pressure Flash Vapor/BD	575.73	866.71	8.32	905.78	2.61
Medium Pressure Indirect Heat Steam	—	3633.97	34.89	6041.57 [¶]	17.42
Low Pressure Indirect Heat Steam/46	—	0.00	0.00	0.00 [¶]	0.00
High Pressure Ejector Steam/45	—	90.51	0.87	150.48 [¶]	0.43
Recovered Heat (M6)	—	1410.00	13.54	1410.00	4.06
Electricity	—	411.37	3.95	1241.63 [§]	3.58
Sum	19880.51	10416.32	100.00	34690.00	100.00
Useful Effluents/Stream					
Fresh Liquor/DK	5607.24	1506.65	14.46	8755.81	25.24
Stillage to Lignin Recovery Section/BG	7869.60	1219.43	11.71	12288.53	35.42
Decanted Furfural/CH	24.01	-0.21	0.00	37.49	0.11
MVR Evaporator Feed/CK	6379.66	2278.58	21.87	9961.94	28.72
Recovered Heat (M2)	—	480.00	4.61	480.00	1.38
Recovered Heat (M14)	—	1591.30	15.28	1591.30	4.59
Medium Pressure Condensate	—	865.47	8.31	1438.87 [¶]	4.15
Low Pressure Condensate/46B	—	0.00	0.00	0.00 [¶]	0.00
Vacuum Ejector Exhaust/45B	—	81.84	0.79	136.06 [¶]	0.39
Losses					
Heat Rejected to the Environment	—	0.01	0.00	0.00	0.00
Cooling Water Enthalpy Increase	—	2393.25	22.97	0.00	0.00
Sum	19880.51	10416.32	100.00	34690.00	100.00

[†] – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[¶] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 8 — Alcohol Recovery

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_8 &= M_{\text{Fresh Liquor}} + M_{\text{Stillage}} + M_{\text{Decanted Furfural}} + M_{\text{Evap Feed}} \\ &= 5607.24 + 7869.60 + 24.01 + 6379.66 \\ &= 19880.51 \text{ kg}\end{aligned}\quad (\text{A.34})$$

Cumulative Energy entering Section 8 $\Rightarrow$

$$\begin{aligned}\sum C_8 &= C_{\text{HP \& LP Flash Vapors}} + C_{\text{MP Flash Cond.}} + C_{\text{Alcohol}} + C_{M6} + C_{\text{Steam}} + C_{\text{Elec 8}} \\ &= 3426.71 + 195.56 + 22224.05 + 1410.00 + 6192.05 + 1241.63 \\ &= 34690.00 \text{ MJ}\end{aligned}\quad (\text{A.35})$$

Cumulative Energy of the Fresh Liquor $\Rightarrow$

$$\begin{aligned}C_{\text{Fresh Liquor}} &= \frac{M_{\text{Fresh Liquor}}}{\sum M_8} \times \{ \sum C_8 - C_{M2, M14} - C_{\text{Cond}} - C_{\text{Exhaust}} \} \\ &= \left(\frac{5607.24}{19880.51} \right) \times \{ 34690.00 - 2071.30 - 1438.87 - 136.06 \} \\ &= 8755.81 \text{ MJ}\end{aligned}\quad (\text{A.36})$$

Cumulative Energy of the Stillage $\Rightarrow$

$$\begin{aligned}C_{\text{Stillage}} &= \frac{M_{\text{Stillage}}}{\sum M_8} \times \{ \sum C_8 - C_{M2, M14} - C_{\text{Cond}} - C_{\text{Exhaust}} \} \\ &= \left(\frac{7869.60}{19880.51} \right) \times \{ 34690.00 - 2071.30 - 1438.87 - 136.06 \} \\ &= 12288.53 \text{ MJ}\end{aligned}\quad (\text{A.37})$$

Cumulative Energy of the Decanted Furfural $\Rightarrow$

$$\begin{aligned}C_{\text{Decanted Furfural}} &= \frac{M_{\text{Decanted Furfural}}}{\sum M_8} \times \{ \sum C_8 - C_{M2, M14} - C_{\text{Cond}} - C_{\text{Exhaust}} \} \\ &= \left(\frac{24.01}{19880.51} \right) \times \{ 34690.00 - 2071.30 - 1438.87 - 136.06 \} \\ &= 37.49 \text{ MJ}\end{aligned}\quad (\text{A.38})$$

Cumulative Energy of the Mechanical Vapor Recompression (MVR) Evaporator Feed $\Rightarrow$

$$\begin{aligned} C_{Evap\ Feed} &= \frac{M_{Evap\ Feed}}{\sum M_B} \times \left\{ \sum C_B - C_{M2,M14} - C_{Cond} - C_{Exhaust} \right\} \\ &= \left(\frac{6379.66}{19880.51} \right) \times \{ 34690.00 - 2071.30 - 1438.87 - 136.06 \} \quad (A.39) \\ &= 9961.94 \text{ MJ} \end{aligned}$$

A.1.9 Section 9 — Mechanical Vapor Recompression Evaporator

A schematic diagram of the MVR Evaporator is shown in Figure 3.10.

Table A.1.9 — Mass, Energy and Cumulative Energy Balances for the Mechanical Vapor Recompression Evaporator of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
MVR Evaporator Feed/CK	6379.66	2278.58	18.93	9961.94	37.85
Turbine Compressor Inlet Steam/CM	—	9498.77	78.91	15791.93 [‡]	60.01
High Pressure Ejector Steam/48	—	50.95	0.42	84.70 [‡]	0.32
Medium Pressure Purge Steam/47	—	114.09	0.95	189.68 [‡]	0.72
Electricity	—	95.61	0.79	288.57 [§]	1.10
Sum	6379.66	12038.00	100.00	26316.82	100.00
Useful Effluents/Stream					
Aqueous Layer/EA	1118.09	442.85	3.68	8731.32	33.18
Tar Layer/EB	51.22	14.15	0.12	399.95	1.52
Recirculated Wash Water/BR	3000.00	434.46	3.61	434.46	1.65
Turbine Compressor Exhaust Steam	—	9108.46	75.66	15143.04 [‡]	57.54
Vacuum Ejector Exhaust/48B	—	46.07	0.38	76.58 [‡]	0.29
Recovered Heat (M4)	—	373.80	3.10	373.80	1.42
Recovered Heat (M12)	—	219.77	1.83	219.77	0.84
Recovered Heat (M13)	—	403.74	3.35	403.74	1.53
Recovered Heat (M20)	—	534.16	4.44	534.16	2.03
Losses					
Heat Rejected to the Environment	—	76.04	0.63	0.00	0.00
Sewer Water/DI	2210.35	365.56	3.04	0.00	0.00
Purge Condensate	—	18.94	0.16	0.00	0.00
Sum	6379.66	12038.00	100.00	26316.82	100.00

[†] – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

[‡] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{elec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 9 — MVR Evaporator

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_g &= M_{\text{Aqueous Layer}} + M_{\text{Tar Layer}} \\
 &= 1118.09 + 51.22 \\
 &= 1169.31 \text{ kg}
 \end{aligned}
 \tag{A.40}$$

Cumulative Energy entering Section 9 $\Rightarrow$

$$\begin{aligned}\sum C_9 &= C_{\text{Evap. Feed}} + C_{\text{Steam}} + C_{\text{Elec } 9} \\ &= 9961.94 + 16066.31 + 288.57 \\ &= 26316.82 \text{ MJ}\end{aligned}\quad (\text{A.41})$$

Cumulative Energy of the Aqueous Layer $\Rightarrow$

$$\begin{aligned}C_{\text{Aqueous Layer}} &= \frac{M_{\text{Aqueous Layer}}}{\sum M_9} \times \left\{ \sum C_9 - C_{M4, M12, M13, M20} - C_{\text{Recirc. Water}} - C_{\text{Exhaust}} \right\} \\ &= \left(\frac{1118.09}{1169.31} \right) \times \{ 26316.82 - 1531.47 - 434.46 - 15219.63 \} \\ &= 8731.32 \text{ MJ}\end{aligned}\quad (\text{A.42})$$

Cumulative Energy of the Tar Layer $\Rightarrow$

$$\begin{aligned}C_{\text{Tar Layer}} &= \frac{M_{\text{Tar Layer}}}{\sum M_9} \times \left\{ \sum C_9 - C_{M4, M12, M13, M20} - C_{\text{Recirc. Water}} - C_{\text{Exhaust}} \right\} \\ &= \left(\frac{51.22}{1169.31} \right) \times \{ 26316.82 - 1531.47 - 434.46 - 15219.63 \} \\ &= 399.95 \text{ MJ}\end{aligned}\quad (\text{A.43})$$

A.1.10 Section 10 — Furfural Reactor

A schematic diagram of the Furfural Reactor is shown in Figure 3.11.

Table A.1.10 — Mass, Energy and Cumulative Energy Balances for the Furfural Reactor of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Aqueous Layer/EA	1118.09	442.85	38.94	8731.32	88.32
Reactor Injection Steam/CO	220.00	694.52	61.06	1154.66 [‡]	11.68
Electricity	—	0.00	0.00	0.00 [§]	0.00
Sum	1338.09	1137.37	100.00	9885.98	100.00
Useful Effluents/Stream					
Reacted Furfural/CP	1338.09	1070.47	94.12	9885.98	100.00
Losses					
Heat Rejected to the Environment	—	66.90	5.88	0.00	0.00
Sum	1338.09	1137.37	100.00	9885.98	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{elec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 10 — Furfural Reactor

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_{10} &= M_{\text{Reacted Furfural}} \\ &= 1338.09 \text{ kg}\end{aligned}\quad (\text{A.44})$$

Cumulative Energy entering Section 10 $\Rightarrow$

$$\begin{aligned}\sum C_{10} &= C_{\text{Aqueous Layer}} + C_{\text{Steam}} + C_{\text{Elec } 10} \\ &= 8731.32 + 1154.66 + 0.00 \\ &= 9885.98 \text{ MJ}\end{aligned}\quad (\text{A.45})$$

Cumulative Energy of the Reacted Furfural $\Rightarrow$

$$\begin{aligned}C_{\text{Reacted Furfural}} &= \frac{M_{\text{Reacted Furfural}}}{\sum M_{10}} \times \sum C_{10} \\ &= \left(\frac{1338.09}{1338.09} \right) \times 9885.98 \\ &= 9885.98 \text{ MJ}\end{aligned}\quad (\text{A.46})$$

A.1.11 Section 11 — Furfural Recovery

A schematic diagram of the Furfural Recovery section is shown in Figure 3.12.

Table A.1.11 — Mass, Energy and Cumulative Energy Balances for the Furfural Recovery Section of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Reacted Furfural/CP	1338.09	1070.47	70.55	9885.98	92.67
Decanted Furfural/CH	24.01	-0.21	0.00	37.49	0.35
Medium Pressure Indirect Heat Steam	—	445.37	29.35	740.44 [‡]	6.94
Electricity	—	1.51	0.10	4.56 [§]	0.04
Sum	1362.10	1517.14	100.00	10668.47	100.00
Useful Effluents/Stream					
Recirculated Alcohol/CT	1.58	0.33	0.02	12.21	0.11
Finisher Evaporator Feed/CW	1291.13	498.04	32.83	9945.47	93.22
Furfural Product/DB	62.68	0.00	0.00	482.78	4.53
Heavy Residue (Furfural)/DC	6.71	0.00	0.00	51.66	0.49
Medium Pressure Condensate	—	106.07	6.99	176.35 [‡]	1.65
Losses					
Heat Rejected to the Environment	—	0.59	0.04	0.00	0.00
Cooling Water Enthalpy Increase	—	912.11	60.12	0.00	0.00
Sum	1362.10	1517.14	100.00	10668.47	100.00

[†] – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

[‡] – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

[§] – $\eta_{\text{elec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 11 — Furfural Refining

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_{11} &= M_{\text{Recirc. Alcohol}} + M_{\text{Evap. Feed}} + M_{\text{Furfural Product}} + M_{\text{Residue}} \\
 &= 1.58 + 1291.13 + 62.68 + 6.71 \\
 &= 1362.10 \text{ kg}
 \end{aligned}
 \tag{A.47}$$

Cumulative Energy entering Section 11 $\Rightarrow$

$$\begin{aligned}
 \sum C_{11} &= C_{\text{Decanted Furfural}} + C_{\text{Reacted Furfural}} + C_{\text{Steam}} + C_{\text{Elec 11}} \\
 &= 37.49 + 9885.98 + 740.44 + 4.56 \\
 &= 10668.47 \text{ MJ}
 \end{aligned}
 \tag{A.48}$$

Cumulative Energy of the Recirculated Alcohol $\Rightarrow$

$$\begin{aligned}
 C_{Recirc. Alcohol} &= \frac{M_{Recirc. Alcohol}}{\sum M_{11}} \times \{ \sum C_{11} - C_{Cond} \} \\
 &= \left(\frac{1.58}{1362.10} \right) \times \{ 10668.47 - 176.34 \} \\
 &= 12.21 \text{ MJ}
 \end{aligned} \tag{A.49}$$

Cumulative Energy of the Finisher Evaporator Feed $\Rightarrow$

$$\begin{aligned}
 C_{Evap. Feed} &= \frac{M_{Evap. Feed}}{\sum M_{11}} \times \{ \sum C_{11} - C_{Cond} \} \\
 &= \left(\frac{1291.13}{1362.10} \right) \times \{ 10668.47 - 176.34 \} \\
 &= 9945.47 \text{ MJ}
 \end{aligned} \tag{A.50}$$

Cumulative Energy of the Furfural Product $\Rightarrow$

$$\begin{aligned}
 C_{Furfural Product} &= \frac{M_{Furfural Product}}{\sum M_{11}} \times \{ \sum C_{11} - C_{Cond} \} \\
 &= \left(\frac{62.68}{1362.10} \right) \times \{ 10668.47 - 176.34 \} \\
 &= 482.78 \text{ MJ}
 \end{aligned} \tag{A.51}$$

Cumulative Energy of the Heavy Residue $\Rightarrow$

$$\begin{aligned}
 C_{Residue} &= \frac{M_{Residue}}{\sum M_{11}} \times \{ \sum C_{11} - C_{Cond} \} \\
 &= \left(\frac{6.71}{1362.10} \right) \times \{ 10668.47 - 176.34 \} \\
 &= 51.66 \text{ MJ}
 \end{aligned} \tag{A.52}$$

A.1.12 Section 12 — Finisher Evaporator

A schematic diagram of the Finisher Evaporator is shown in Figure 3.13.

Table A.1.12 — Mass, Energy and Cumulative Energy Balances for the Finisher Evaporator of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Finisher Evaporator Feed/CW	1291.13	498.04	15.80	9945.47	75.15
Medium Pressure Flash Vapor/BC	1130.58	1746.61	55.39	1778.72	13.44
Medium Pressure Indirect Heat Steam	—	908.46	28.81	1510.34 [‡]	11.41
Electricity	—	0.00	0.00	0.00 [§]	0.00
Sum	2421.71	3153.11	100.00	13234.53	100.00
Useful Effluents/Stream					
Concentrated Syrups/DF	411.02	146.58	4.65	10494.26	79.29
Recovered Heat (M6)	—	1410.00	44.72	1410.00	10.65
Recovered Heat (M18)	—	775.00	24.58	775.00	5.86
Medium Pressure Flash Condensate/BC	1130.58	163.46	5.18	195.57	1.48
Medium Pressure Condensate	—	216.36	6.86	359.70 [‡]	2.72
Losses					
Heat Rejected to the Environment	—	0.49	0.02	0.00	0.00
Sewer Water/DD	880.11	189.34	6.00	0.00	0.00
Cooling Water Enthalpy Increase	—	251.88	7.99	0.00	0.00
Sum	2421.71	3153.11	100.00	13234.53	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 12 — Finisher Evaporator

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_{12} &= M_{\text{Wood Syrups}} \\ &= 411.02 \text{ kg}\end{aligned}\tag{A.53}$$

Cumulative Energy entering Section 12 $\Rightarrow$

$$\begin{aligned}\sum C_{12} &= C_{\text{Evap Feed}} + C_{\text{MP Flash Vapor}} + C_{\text{Steam}} + C_{\text{Elec 12}} \\ &= 9945.47 + 1778.72 + 1510.34 + 0.00 \\ &= 13234.53 \text{ MJ}\end{aligned}\tag{A.54}$$

Since the medium pressure (MP) flash vapor is used solely as a source of heat by condensing the vapor in an indirect manner. This heat will be considered as being a recovered energy stream. Therefore the Cumulative Energy of the Flash Condensate is given by:

$$\begin{aligned}
 C_{MP \text{ Flash Cond}} &= C_{MP \text{ Flash Vapor}} - (E_{MP \text{ Flash Vapor}} - E_{MP \text{ Flash Cond}}) \\
 &= 1778.72 - (1746.61 - 163.46) \\
 &= 195.57 \text{ MJ}
 \end{aligned} \tag{A.55}$$

Cumulative Energy of the Concentrated Syrups $\Rightarrow$

$$\begin{aligned}
 C_{Syrups} &= \frac{M_{Syrups}}{\sum M_{12}} \times \{ \sum C_{12} - C_{M6,M18} - C_{MP \text{ Flash Cond}} - C_{Cond} \} \\
 &= \left(\frac{411.02}{411.02} \right) \times \{ 13234.53 - 2185.00 - 195.57 - 359.70 \} \\
 &= 10494.26 \text{ MJ}
 \end{aligned} \tag{A.56}$$

A.1.13 Section 13 — The Chlorine Dioxide Generator

A schematic diagram of the Chlorine Dioxide generator is shown in Figure 3.14.

Table A.1.13 — Mass, Energy and Cumulative Energy Balances for the Chlorine Dioxide Generator of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Sulfuric Acid/801	37.76	3.16	0.92	40.77‡	6.26
Chemicals/807	237.83	19.90	5.80	112.48‡	17.28
Chilled Water/816	1650.00	69.04	20.12	69.04	10.60
Medium Pressure Indirect Heat Steam	—	208.47	60.76	346.59¶	53.23
High Pressure Ejector Steam/818	—	34.11	9.94	56.70¶	8.71
Electricity	—	8.45	2.46	25.50§	3.92
Sum	1925.59	343.13	100.00	651.08	100.00
Useful Effluents/Stream					
Chlorine Dioxide Solution/FP & GS	1595.14	0.00	0.00	517.27	79.45
Medium Pressure Condensate/804	—	49.65	14.47	82.54¶	12.68
High Pressure Ejector Exhaust/819	—	30.84	8.98	51.27¶	7.87
Losses					
Heat Rejected to the Environment	—	0.40	0.12	0.00	0.00
Saltcake/84	167.49	12.72	3.71	0.00	0.00
Chlorine Byproduct/817	162.96	3.08	0.90	0.00	0.00
Cooling Water Enthalpy Increase	—	246.44	71.82	0.00	0.00
Sum	1925.59	343.13	100.00	651.08	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

¶ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

Section 13 — Chlorine Dioxide Generator

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_{13} &= M_{\text{ClO}_2 \text{ Solution}} \\ &= 1595.14 \text{ kg}\end{aligned}\tag{A.57}$$

Cumulative Energy entering Section 13 $\Rightarrow$

$$\begin{aligned}\sum C_{13} &= C_{\text{Chemicals}} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec } 13} \\ &= 153.25 + 69.04 + 403.29 + 25.50 \\ &= 651.08 \text{ MJ}\end{aligned}\tag{A.58}$$

Cumulative Energy of the Chlorine Dioxide Solution $\Rightarrow$

$$\begin{aligned} C_{ClO_2 \text{ Solution}} &= \frac{M_{ClO_2 \text{ Solution}}}{\sum M_{13}} \times \{ \sum C_{13} - C_{Cond} - C_{Exhaust} \} \\ &= \left(\frac{1595.14}{1595.14} \right) \times \{ 651.08 - 82.54 - 51.27 \} \quad (A.59) \\ &= 517.27 \text{ MJ} \end{aligned}$$

A.1.14 Section 14 — Cogeneration System

A schematic diagram of the Cogeneration system is shown in Figure 3.15.

Table A.1.14 — Mass, Energy and Cumulative Energy Balances for the Cogeneration System of the ALCELL® Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Condensate Boiler Feed Water/902	3781.51	2253.94	9.32	3747.23 [‡]	13.01
Make-up Boiler Feed Water/901	1282.97	1308.68	5.41	1308.68	4.54
Electricity	—	64.80	0.27	195.58 [§]	0.68
Combustion Energy					
Woodroom Rejects/6	—	9248.79	38.27	9660.15	33.54
Brownstock Screen Rejects/ER	—	167.39	0.69	230.35	0.80
Heavy Residue (Furfural)/DC	—	163.64	0.68	215.30	0.75
Decanter Tar Layer/EB	—	944.20	3.91	1330.00	4.62
Bunker C Oil	—	10018.34	41.45	12114.08 [□]	42.06
Sum	5064.48	24169.78	100.00	28801.37	100.00
Useful Effluents/Stream					
Process Steam/907	5064.48	15988.12	66.15	26580.65	92.29
Electricity	—	1335.75	5.53	2220.72	7.71
Losses					
Heat Rejected to the Environment	—	6015.93	24.89	0.00	0.00
Cooling Water Enthalpy Increase	—	829.98	3.43	0.00	0.00
Sum	5064.48	24169.78	100.00	28801.37	100.00

† – Pulp is leaving the Pulp Machine & Press at a consistency of 50%.

‡ – $\eta_{\text{steam}} = 60.15\%$ (Table 5.18, Strategy 7)

§ – $\eta_{\text{ovelec}} = 33.13\%$ (Table 5.18, Strategy 7)

□ – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock [1].

Section 14 — Cogeneration

Total Energy of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum E_{14} &= E_{\text{Produced Electricity}} + E_{\text{Process Steam}} \\
 &= 1335.75 + 15988.12 \\
 &= 17323.87 \text{ MJ}
 \end{aligned}
 \tag{A.60}$$

Cumulative Energy entering Section 14 $\Rightarrow$

$$\begin{aligned}\sum C_{14} &= C_{BFW} + C_{Elec\ 14} + C_{Woodroom\ Rejects}^* + C_{Screen\ Rejects}^* + C_{Residue}^* + C_{Tar\ Layer}^* + C_{Bunker\ C} \\ &= 5055.91 + 195.58 + 9660.15 + 230.35 + 215.30 + 1330.00 + 12114.08 \\ &= 28801.37\ MJ\end{aligned}\quad (A.61)$$

The Cumulative Energy of the byproducts that are used as fuel in the cogeneration section is equal to the sum of the Cumulative Energy that is normally apportioned to this stream by mass and the streams combustion energy (i.e. heat of combustion).

$$\therefore C_{Byproduct}^* = C_{Byproduct} + M_{Byproduct} \times h_c$$

Cumulative Energy of the Produced Electricity $\Rightarrow$

$$\begin{aligned}C_{Elec}^{Prod} &= \frac{E_{Produced\ Electricity}}{\sum E_{14}} \times \sum C_{14} \\ &= \left(\frac{1335.75}{17323.87} \right) \times 28801.37 \\ &= 2220.72\ MJ\end{aligned}\quad (A.62)$$

Cumulative Energy of the Process Steam $\Rightarrow$

$$\begin{aligned}C_{Process\ Steam} &= \frac{E_{Process\ Steam}}{\sum E_{14}} \times \sum C_{14} \\ &= \left(\frac{15988.12}{17323.87} \right) \times 28801.37 \\ &= 26580.65\ MJ\end{aligned}\quad (A.63)$$

Cumulative Energy of the Imported Electricity $\Rightarrow$

$$\begin{aligned}C_{Elec}^{Imp} &= \frac{\sum_{N=1}^{14} E_{Elec\ N} - E_{Produced\ Electricity}}{\eta_{Elec}^{Imp}} \\ &= \left(\frac{[3496.03 - 1335.75]}{25.93\%} \right) \\ &= 8331.14\ MJ\end{aligned}\quad (A.64)$$

Overall Efficiency of Electricity Generation $\Rightarrow$

$$\begin{aligned}\eta_{\text{ovelec}} &= \frac{\sum_{N=1}^{14} E_{\text{Elec } N}}{C_{\text{Elec}}^{\text{Imp}} + C_{\text{Elec}}^{\text{Prod}}} \\ &= \left(\frac{3496.03}{8331.14 + 2220.72} \right) \times 100\% \\ &= 33.13\%\end{aligned} \tag{A.65}$$

Efficiency of Steam Generation $\Rightarrow$

$$\begin{aligned}\eta_{\text{Steam}} &= \frac{E_{\text{Process Steam}}}{C_{\text{Process Steam}}} \\ &= \left(\frac{15988.12}{26580.65} \right) \times 100\% \\ &= 60.15\%\end{aligned} \tag{A.66}$$

A.2 Sample Calculation for the most Probable Operating Strategy of the Kraft Process

The Kraft process produces only one byproduct that can be used as a fuel for the Cogeneration system (Section 10). For a commercial Kraft mill the normal mode of operation would be to burn all of the woodroom rejects (Stream 104). This strategy is presented as "Combustion Strategy C".

The sample calculations presented here follow the plant sections that were described in Chapter 4 of this thesis. The operating parameters for this set of results may be found in Table 5.1. In the following tables, streams are identified according to Figure 4.1 and Table 4.1.

A.2.1 Section 1 — The Woodroom

A schematic diagram of the woodroom used for the Kraft process is shown in Figure 4.2. This section contains two sub-sections, the debarking drums and the chipper. The debarking drums and chipper are referred to as sub-sections 1A & 1B respectively.

Table A.2.1 — Mass, Energy and Cumulative Energy Balances for the Woodroom of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Logs/101	3769.57	0.00	0.00	565.44‡	19.68
Recirculated Wash Water/102	3370.00	987.01	75.20	987.01	34.35
Low Pressure Injection Steam/103	0.00	0.00	0.00	0.00¶	0.00
Electricity	—	325.45	24.80	1321.25§	45.97
Sum	7139.57	1312.46	100.00	2873.70	100.00
Useful Effluents/Stream					
Wood Chips/12	2967.41	0.00	0.00	2424.74	84.38
Hog Fuel/104	802.16	0.00	0.00	448.96	15.62
Losses					
Heat Rejected to the Environment	—	889.46	67.77	0.00	0.00
Sewer Water/105	3370.00	423.00	32.23	0.00	0.00
Sum	7139.57	1312.46	100.00	2873.70	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

¶ – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

§ – $\eta_{\text{elec}} = 24.63\%$ (Table 5.23, Strategy C)

Sub-Section 1A — Debarking Drum

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_{1A} &= M_{\text{Debarked Logs}} + M_{\text{Bark}} \\
 &= 3091.05 + 678.52 \\
 &= 3769.57 \text{ kg}
 \end{aligned}
 \tag{A.67}$$

Cumulative Energy entering Sub-Section 1A $\Rightarrow$

$$\begin{aligned}\sum C_{1A} &= C_{Logs} + C_{Steam} + C_{Recirc. Water} + C_{Elec 1A} \\ &= 565.44 + 0.00 + 547.69 + 819.79 \\ &= 1932.92 \text{ MJ}\end{aligned}\quad (A.68)$$

Cumulative Energy of the Debarked Logs $\Rightarrow$

$$\begin{aligned}C_{Debarked Logs} &= \frac{M_{Debarked Logs}}{\sum M_{1A}} \times \sum C_{1A} \\ &= \left(\frac{3091.05}{3769.57} \right) \times 1932.92 \\ &= 1584.99 \text{ MJ}\end{aligned}\quad (A.69)$$

Cumulative Energy of the Bark $\Rightarrow$

$$\begin{aligned}C_{Bark} &= \frac{M_{Bark}}{\sum M_{1A}} \times \sum C_{1A} \\ &= \left(\frac{678.52}{3769.57} \right) \times 1932.92 \\ &= 347.92 \text{ MJ}\end{aligned}\quad (A.70)$$

Sub-Section 1B — Chipper

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_{1B} &= M_{Wood Chips} + M_{Fines} \\ &= 2967.41 + 123.64 \\ &= 3091.05 \text{ kg}\end{aligned}\quad (A.71)$$

Cumulative Energy entering Sub-Section 1B $\Rightarrow$

$$\begin{aligned}\sum C_{1B} &= C_{Debarked Logs} + C_{Recirc. Water} + C_{Elec 1B} \\ &= 1584.99 + 439.32 + 501.46 \\ &= 2525.77 \text{ MJ}\end{aligned}\quad (A.72)$$

Cumulative Energy of the Wood Chips $\Rightarrow$

$$\begin{aligned}
 C_{Wood\ Chips} &= \frac{M_{Wood\ Chips}}{\sum M_{1B}} \times \sum C_{1B} \\
 &= \left(\frac{2967.41}{3091.05} \right) \times 2525.77 \\
 &= 2424.74 \text{ MJ}
 \end{aligned} \tag{A.73}$$

Cumulative Energy of the Fines $\Rightarrow$

$$\begin{aligned}
 C_{Fines} &= \frac{M_{Fines}}{\sum M_{1B}} \times \sum C_{1B} \\
 &= \left(\frac{123.64}{3091.05} \right) \times 2525.77 \\
 &= 101.04 \text{ MJ}
 \end{aligned} \tag{A.74}$$

The Cumulative Energy of the woodroom's rejects is equal to the sum of the Cumulative Energy of the fines and the bark.

$$\begin{aligned}
 C_{Woodroom\ Rejects} &= C_{Bark} + C_{Fines} \\
 &= 347.92 + 101.04 \\
 &= 448.96 \text{ MJ}
 \end{aligned} \tag{A.75}$$

A.2.2 Section 2 — Pulping System

A schematic diagram of the Pulping System is shown in Figure 4.3.

Table A.2.2 — Mass, Energy and Cumulative Energy Balances for the Pulping System of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Wood Chips/12	2967.41	0.00 [□]	0.00	2424.74	9.19
White Liquor/52	3072.14	936.57	14.89	10757.85	40.76
Recirculated Wash Water/62	9354.61	2812.89	44.72	2812.89	10.66
Low Pressure Injection Steam/204	185.00	508.76	8.09	2086.71 [¶]	7.91
High Pressure Injection Steam/213	106.43	326.95	5.20	1341.02 [¶]	5.08
Low Pressure Indirect Heating Steam	—	550.01	8.74	2255.91 [¶]	8.55
High Pressure Indirect Heating Steam	—	614.38	9.77	2519.93 [¶]	9.55
Electricity	—	540.00	8.59	2192.31 [§]	8.30
Sum	15685.59	6289.56	100.00	26391.36	100.00
Useful Effluents/Stream					
Weak Black Liquor/23	8096.39	3066.23	48.75	13408.87	50.81
Screened Pulp/26	7131.78	1902.01	30.24	11811.33	44.75
Low Pressure Condensate	—	126.85	2.02	520.29 [¶]	1.97
High Pressure Condensate	—	158.69	2.52	650.87 [¶]	2.47
Losses					
Heat Rejected to the Environment	—	844.13	13.42	0.00	0.00
Steaming Vessel Purge/201	457.42	191.65	3.05	0.00	0.00
Sum	15685.59	6289.56	100.00	26391.36	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[□] – Wood Chips are stored as a “Chip Pile” where they cool down to the datum temperature.

[¶] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{elec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 2 — Pulping System

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_2 &= M_{\text{Weak Liquor}} + M_{\text{Screened Pulp}} \\
 &= 8096.39 + 7131.78 \\
 &= 15228.17 \text{ kg}
 \end{aligned}
 \tag{A.76}$$

Cumulative Energy entering Section 2 $\Rightarrow$

$$\begin{aligned}\sum C_2 &= C_{Wood\ Chips} + C_{White\ Liquor} + C_{Recirc.\ Water} + C_{Steam} + C_{Elec\ 2} \\ &= 2424.74 + 10757.85 + 2812.89 + 8203.57 + 2192.31 \\ &= 26391.36\ MJ\end{aligned}\quad (A.77)$$

Cumulative Energy of the Weak Black Liquor $\Rightarrow$

$$\begin{aligned}C_{Weak\ Liquor} &= \frac{M_{Weak\ Liquor}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{8096.39}{15228.17} \right) \times \{ 26391.36 - 1171.16 \} \\ &= 13408.87\ MJ\end{aligned}\quad (A.78)$$

Cumulative Energy of the Screened Pulp $\Rightarrow$

$$\begin{aligned}C_{Screened\ Pulp} &= \frac{M_{Screened\ Pulp}}{\sum M_2} \times \{ \sum C_2 - C_{Cond} \} \\ &= \left(\frac{7131.78}{15228.17} \right) \times \{ 26391.36 - 1171.16 \} \\ &= 11811.33\ MJ\end{aligned}\quad (A.79)$$

A.2.3 Section 3 — Black Liquor Evaporators

A schematic diagram of the Black Liquor Evaporators is shown in Figure 4.4.

Table A.2.3 — Mass, Energy and Cumulative Energy Balances for the Black Liquor Evaporators of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Weak Black Liquor/23	8096.39	3066.23	40.99	13408.87	42.55
Low Pressure Indirect Heat Steam/301	—	4378.89	58.53	17960.29‡	56.99
Electricity	—	36.00	0.48	146.16§	0.46
Sum	8096.39	7481.12	100.00	31515.32	100.00
Useful Effluents/Stream					
Strong Black Liquor/34	1727.23	338.01	4.52	24211.75	76.83
Contaminated Condensate/36	6369.16	1732.16	23.15	1732.16	5.50
Low Pressure Condensate/302	—	1009.93	13.50	4142.31‡	13.14
Cooling Water Enthalpy Increase	—	4364.75	58.34	1429.10	4.53
Losses					
Heat Rejected to the Environment	—	36.27	0.49	0.00	0.00
Sum	8096.39	7481.12	100.00	31515.32	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

§ – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 3 — Black Liquor Evaporators

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_3 &= M_{\text{Strong Liquor}} \\ &= 1727.23 \text{ kg}\end{aligned}\tag{A.80}$$

Cumulative Energy entering Section 3 $\Rightarrow$

$$\begin{aligned}\sum C_3 &= C_{\text{Weak Liquor}} + C_{\text{Steam}} + C_{\text{Elec } 3} \\ &= 13408.87 + 17960.29 + 146.15 \\ &= 31515.32 \text{ MJ}\end{aligned}\tag{A.81}$$

Cumulative Energy of the Contaminated Condensate $\Rightarrow$

$$\begin{aligned} C_{\text{Contaminated Condensate}} &= E_{\text{Contaminated Condensate}} \\ &= 1732.16 \text{ MJ} \end{aligned} \quad (\text{A.82})$$

Cumulative Energy of the Return Cooling Water that is used elsewhere in the process $\Rightarrow$

$$\begin{aligned} C_{\text{Recirc. Water}} &= E_{\text{Recirc. Water}} \\ &= 1429.10 \text{ MJ} \end{aligned} \quad (\text{A.83})$$

Cumulative Energy of the Strong Black Liquor $\Rightarrow$

$$\begin{aligned} C_{\text{Strong Liquor}} &= \frac{M_{\text{Strong Liquor}}}{\sum M_3} \times \{ \sum C_3 - C_{\text{Cond}} - C_{\text{Recirc. Water}} \} \\ &= \left(\frac{1727.23}{1727.23} \right) \times \{ 31515.32 - 4142.31 - 3161.26 \} \quad (\text{A.84}) \\ &= 24211.75 \text{ MJ} \end{aligned}$$

A.2.4 Section 4 — The Recovery Boiler

A schematic diagram of the Kraft Recovery Boiler is shown in Figure 4.5.

Table A.2.4 — Mass, Energy and Cumulative Energy Balances for the Recovery Boiler of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Fresh Saltcake/401	32.58	0.00	0.00	152.81 [‡]	0.32
Saltcake from ClO ₂ Generator/84	96.58	7.34	0.05	55.19	0.11
Combustion Air/407	7114.47	0.00	0.00	0.00	0.00
Boiler Feed Water/412	3513.36	1351.83	8.58	4408.92	9.18
Electricity	—	36.00	0.23	146.15 [§]	0.30
Low Pressure Indirect Heat Steam/408	—	1400.95	8.89	5746.10 [¶]	11.96
High Pressure Injection Steam/402	73.84	226.83	1.44	930.35 [¶]	1.94
Strong Black Liquor/34	1727.23	338.01	2.15	24211.75	50.40
Combustion Energy Strong Black Liquor	—	12391.01	78.66	12391.01	25.79
Sum	12558.06	15751.97	100.00	48042.28	100.00
Useful Effluents/Stream					
Smelt/45	594.55	802.64	5.09	7393.84	15.39
Main Steam/413	3162.02	10828.90	68.75	39323.19	81.85
Low Pressure Condensate/409	—	323.11	2.05	1325.25 [¶]	2.76
Losses					
Heat Rejected to the Environment	—	1499.29	9.52	0.00	0.00
Blowdown/410	351.34	484.94	3.08	0.00	0.00
Flue Gas/415	8450.15	1813.09	11.51	0.00	0.00
Sum	12558.06	15751.97	100.00	48042.28	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[¶] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{lowelec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 4 — Recovery Boiler

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_4 &= M_{\text{Smelt}} + M_{\text{Main Steam}} \\
 &= 594.55 + 3162.02 \\
 &= 3756.57 \text{ kg}
 \end{aligned}
 \tag{A.85}$$

Cumulative Energy entering Section 4 $\Rightarrow$

$$\begin{aligned}\sum C_4 &= C_{Strong\ Liquor}^* + C_{Saltcake} + C_{Combustion\ Air} + C_{BFW} + C_{Steam} + C_{Elec\ 4} \\ &= 36602.76 + 208.00 + 0.00 + 4408.92 + 6676.45 + 146.15 \\ &= 48042.28\ MJ\end{aligned}\quad (A.86)$$

Cumulative Energy of the Smelt $\Rightarrow$

$$\begin{aligned}C_{Smelt} &= \frac{M_{Smelt}}{\sum M_4} \times \{ \sum C_4 - C_{Cond} \} \\ &= \left(\frac{594.55}{3756.57} \right) \times \{ 48042.28 - 1325.25 \} \\ &= 7393.84\ MJ\end{aligned}\quad (A.87)$$

Cumulative Energy of the Main Steam $\Rightarrow$

$$\begin{aligned}C_{Main\ Steam} &= \frac{M_{Main\ Steam}}{\sum M_4} \times \{ \sum C_4 - C_{Cond} \} \\ &= \left(\frac{3162.02}{3756.57} \right) \times \{ 48042.28 - 1325.25 \} \\ &= 39323.19\ MJ\end{aligned}\quad (A.88)$$

A.2.5 Section 5 — The Causticizing Cycle

A schematic diagram of the Causticizing Cycle is shown in Figure 4.6.

Table A.2.5 — Mass, Energy and Cumulative Energy Balances for the Causticizing Cycle of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Smelt/45	594.55	802.64	24.93	7393.84	65.18
Shower Water/504, 513, 518 & 523	2962.79	867.75	26.94	1700.01	14.99
Make-up Lime/507	14.06	0.00	0.00	139.85 [‡]	1.23
Calciner Fuel Oil/520	34.13	1467.40	45.56	1774.37 [□]	15.64
Combustion Air/521	568.42	0.00	0.00	0.00	0.00
Electricity	—	82.80	2.57	336.15 [§]	2.96
Sum	4173.95	3220.59	100.00	11344.22	100.00
Useful Effluents/Stream					
White Liquor/52 & 56	3239.59	987.62	30.67	11344.22	100.00
Losses					
Heat Rejected to the Environment	—	1784.12	55.40	0.00	0.00
Evaporated Water off Slaker/509	137.02	366.57	11.38	0.00	0.00
Dregs/505	8.00	0.48	0.01	0.00	0.00
Grits/508	24.15	3.98	0.12	0.00	0.00
Flue Gas/524	765.19	77.82	2.42	0.00	0.00
Sum	4173.95	3220.59	100.00	11344.22	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[§] – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

[□] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock [1].

Section 5 — Causticizing Cycle

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_5 &= M_{\text{White Liquor}} \\ &= 3239.59 \text{ kg}\end{aligned}\tag{A.89}$$

Cumulative Energy entering Section 5 $\Rightarrow$

$$\begin{aligned}\sum C_5 &= C_{\text{Smelt}} + C_{\text{Water}} + C_{\text{Make-up Lime}} + C_{\text{Fuel Oil}} + C_{\text{Combustion Air}} + C_{\text{Elec 5}} \\ &= 7393.84 + 1700.01 + 139.85 + 1774.37 + 0.00 + 336.15 \\ &= 11344.22 \text{ MJ}\end{aligned}\tag{A.90}$$

Cumulative Energy of the White Liquor $\Rightarrow$

$$\begin{aligned} C_{\text{White Liquor}} &= \frac{M_{\text{White Liquor}}}{\sum M_5} \times \sum C_5 \\ &= \left(\frac{3239.59}{3239.59} \right) \times 11344.22 \\ &= 11344.22 \text{ MJ} \end{aligned} \quad (\text{A.91})$$

A.2.6 Section 6 — Oxygen Delignification

A schematic diagram of the Oxygen Delignification section is shown in Figure 4.7.

Table A.2.6 — Mass, Energy and Cumulative Energy Balances for the Oxygen Delignification Section of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp†)	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Screened Pulp/26	7131.78	1902.01	29.74	11811.33	49.95
Contaminated Condensate/36	6369.16	1732.16	27.09	1732.16	7.33
White Liquor/56	167.45	51.05	0.80	586.37	2.48
Wash Water/605	2580.84	539.91	8.44	539.91	2.28
Delignification Chemicals/603	11.14	0.00	0.00	103.89‡	0.44
Low Pressure Injection Steam	349.23	960.44	15.02	3939.30†	16.66
High Pressure Injection Steam	34.50	105.98	1.66	434.69†	1.84
Low Pressure Indirect Heat Steam/610	—	453.89	7.10	1861.66†	7.87
Electricity	—	649.12	10.15	2635.29§	11.15
Sum	16644.10	6394.56	100.00	23644.60	100.00
Useful Effluents/Stream					
Clean Pulp/67	7289.49	2115.88	33.09	20402.34	86.29
Recirculated Wash Water/62	9354.61	2812.89	43.99	2812.89	11.90
Low Pressure Condensate	—	104.68	1.64	429.37†	1.81
Losses					
Heat Rejected to the Environment	—	1361.11	21.28	0.00	0.00
Sum	16644.10	6394.56	100.00	23644.60	100.00

† – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

‡ – Refer to Appendix B for Sample Calculation.

† – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

§ – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 6 — Oxygen Delignification

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_6 &= M_{\text{Clean Pulp}} \\ &= 7289.49 \text{ kg}\end{aligned}\tag{A.92}$$

Cumulative Energy entering Section 6 $\Rightarrow$

$$\begin{aligned}\sum C_6 &= C_{\text{Screened Pulp}} + C_{\text{Condensate}} + C_{\text{Chemicals}} + C_{\text{White Liquor}} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec 6}} \\ &= 11811.33 + 1732.16 + 103.89 + 586.37 + 539.91 + 6235.65 + 2635.30 \\ &= 23644.60 \text{ MJ}\end{aligned}$$

(A.93)

Cumulative Energy of the Clean Pulp $\Rightarrow$

$$\begin{aligned}C_{\text{Clean Pulp}} &= \frac{M_{\text{Clean Pulp}}}{\sum M_6} \times \{ \sum C_6 - C_{\text{Cond}} - C_{\text{Recirc. Water}} \} \\ &= \left(\frac{7289.49}{7289.49} \right) \times \{ 23644.60 - 429.37 - 2812.89 \} \\ &= 20402.34 \text{ MJ}\end{aligned} \quad (\text{A.94})$$

A.2.7 Section 7 — The Bleach Plant

A schematic diagram of the Bleach Plant is shown in Figure 4.8.

Table A.2.7 — Mass, Energy and Cumulative Energy Balances for the Bleach Plant of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Clean Pulp/67	7289.49	2115.88	40.30	20402.34	72.20
ClO ₂ Solution/87	772.61	32.33	0.61	441.56	1.56
Recirculated Wash Water/97	6194.29	1814.18	34.56	1814.18	6.42
Wash Water/723	102.23	21.39	0.41	21.39	0.08
Bleaching Chemicals/701	137.95	0.00	0.00	397.50 [‡]	1.41
Low Pressure Injection Steam	18.88	51.92	0.99	212.95 [¶]	0.75
High Pressure Injection Steam/724	66.20	182.05	3.47	746.71 [¶]	2.64
Low Pressure Indirect Heating Steam	—	715.02	13.62	2932.68 [¶]	10.38
Electricity	—	317.02	6.04	1287.02 [§]	4.56
Sum	14581.65	5249.79	100.00	28256.33	100.00
Useful Effluents/Stream					
Bleached Pulp/79	8179.72	2286.88	43.56	26592.94	94.11
Recirculated Water/102	3370.00	987.01	18.80	987.01	3.49
Low Pressure Condensate	—	164.90	3.14	676.38 [¶]	2.40
Losses					
Heat Rejected to the Environment	—	1048.26	19.97	0.00	0.00
Sewer Water/715	3031.93	762.74	14.53	0.00	0.00
Sum	14581.65	5249.79	100.00	28256.33	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[¶] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 7 — Bleach Plant

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_7 &= M_{\text{Bleached Pulp}} \\ &= 8179.72 \text{ kg}\end{aligned}\quad (\text{A.95})$$

Cumulative Energy entering Section 7 $\Rightarrow$

$$\begin{aligned}\sum C_7 &= C_{\text{Clean Pulp}} + C_{\text{Chemicals}} + C_{\text{ClO}_2} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec } 7} \\ &= 20402.34 + 397.50 + 441.56 + 1835.57 + 3892.34 + 1287.03 \quad (\text{A.96}) \\ &= 28256.33 \text{ MJ}\end{aligned}$$

Cumulative Energy of the Bleached Pulp $\Rightarrow$

$$\begin{aligned} C_{\text{Bleached Pulp}} &= \frac{M_{\text{Bleached Pulp}}}{\sum M_7} \times \{ \sum C_7 - C_{\text{Cond}} - C_{\text{Recirc. Water}} \} \\ &= \left(\frac{8179.72}{8179.72} \right) \times \{ 28256.33 - 676.38 - 987.01 \} \quad (\text{A.97}) \\ &= 26592.94 \text{ MJ} \end{aligned}$$

A.2.8 Section 8 — The Chlorine Dioxide Generator

A schematic diagram of the Chlorine Dioxide generator is shown in Figure 4.9.

Table A.2.8 — Mass, Energy and Cumulative Energy Balances for the Chlorine Dioxide Generator of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Sulfuric Acid/801	20.32	1.70	0.93	21.94 [‡]	3.27
Chemicals/807	128.00	10.71	5.89	60.53 [‡]	9.03
Chilled Water/816	825.00	34.52	18.97	34.52	5.15
Low Pressure Indirect Heating Steam	—	111.97	61.54	459.27 [¶]	68.48
High Pressure Ejector Steam/818	—	18.51	10.17	75.93 [¶]	11.32
Electricity	—	4.55	2.50	18.45 [§]	2.75
Sum	973.32	181.96	100.00	670.64	100.00
Useful Effluents/Stream					
Chlorine Dioxide Solution/87	772.61	32.33	17.77	441.56	65.84
Low Pressure Condensate/804	—	25.83	14.20	105.92 [¶]	15.79
High Pressure Ejector Exhaust/819	—	16.57	9.11	67.97 [¶]	10.14
Saltcake/84	96.58	7.34	4.03	55.19	8.23
Losses					
Heat Rejected to the Environment	—	12.56	6.90	0.00	0.00
Chlorine Byproduct/817	104.13	1.99	1.09	0.00	0.00
Cooling Water Enthalpy Increase	—	85.34	46.90	0.00	0.00
Sum	973.32	181.96	100.00	670.64	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – Refer to Appendix B for Sample Calculation.

[¶] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 8 — Chlorine Dioxide Generator

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum M_B &= M_{\text{ClO}_2 \text{ Solution}} + M_{\text{Saltcake}} \\
 &= 772.61 + 96.58 \\
 &= 869.19 \text{ kg}
 \end{aligned}
 \tag{A.98}$$

Cumulative Energy entering Section 8 $\Rightarrow$

$$\begin{aligned}\sum C_8 &= C_{\text{Chemicals}} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec } 8} \\ &= 82.47 + 34.52 + 535.20 + 18.45 \\ &= 670.64 \text{ MJ}\end{aligned}\quad (\text{A.99})$$

Cumulative Energy of the Chlorine Dioxide Solution $\Rightarrow$

$$\begin{aligned}C_{\text{ClO}_2 \text{ Solution}} &= \frac{M_{\text{ClO}_2 \text{ Solution}}}{\sum M_8} \times \{ \sum C_8 - C_{\text{Cond}} \} \\ &= \left(\frac{772.61}{869.19} \right) \times \{ 670.64 - 173.89 \} \\ &= 441.56 \text{ MJ}\end{aligned}\quad (\text{A.100})$$

Cumulative Energy of the Saltcake $\Rightarrow$

$$\begin{aligned}C_{\text{Saltcake}} &= \frac{M_{\text{Saltcake}}}{\sum M_8} \times \{ \sum C_8 - C_{\text{Cond}} \} \\ &= \left(\frac{96.58}{869.19} \right) \times \{ 670.64 - 173.89 \} \\ &= 55.19 \text{ MJ}\end{aligned}\quad (\text{A.101})$$

A.2.9 Section 9 — The Pulp Machine

A schematic diagram of the Pulp Machine is shown in Figure 4.10.

Table A.2.9 — Mass, Energy and Cumulative Energy Balances for the Pulp Machine of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Bleached Pulp/79	8179.72	2286.88	87.08	26592.94	95.08
Shower Water/102	0.00	0.00	0.00	0.00	0.00
Low Pressure Injection Steam/901	0.00	0.00	0.00	0.00 [‡]	0.00
Electricity	—	339.16	12.92	1376.91 [§]	4.92
Sum	8179.72	2626.04	100.00	27969.85	100.00
Useful Effluents/Stream					
Pressed Pulp/900	1800.00	355.11	13.52	26155.67	93.51
Recirculated Wash Water/97	6194.29	1814.18	69.08	1814.18	6.49
Losses					
Heat Rejected to the Environment	—	403.31	15.36	0.00	0.00
Screen Rejects/903	185.43	53.44	2.04	0.00	0.00
Sum	8179.72	2626.04	100.00	27969.85	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[‡] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{elec}} = 24.63\%$ (Table 5.23, Strategy C)

Section 9 — The Pulp Machine

Total Mass of the useful products $\Rightarrow$

$$\begin{aligned}\sum M_9 &= M_{\text{Pressed Pulp}} \\ &= 1800.00 \text{ kg}\end{aligned}\tag{A.102}$$

Cumulative Energy entering Section 9 $\Rightarrow$

$$\begin{aligned}\sum C_9 &= C_{\text{Bleached Pulp}} + C_{\text{Water}} + C_{\text{Steam}} + C_{\text{Elec 9}} \\ &= 26592.94 + 0.00 + 0.00 + 1376.91 \\ &= 27969.85 \text{ MJ}\end{aligned}\tag{A.103}$$

Cumulative Energy of the Pressed Pulp $\Rightarrow$

$$\begin{aligned} C_{Pressed\ Pulp} &= \frac{M_{Pressed\ Pulp}}{\sum M_g} \times \{ \sum C_g - C_{Recirc.\ Water} \} \\ &= \left(\frac{1800.00}{1800.00} \right) \times \{ 27969.85 - 1814.18 \} \quad (A.104) \\ &= 26155.67\ MJ \end{aligned}$$

A.2.10 Section 10 — Cogeneration System

A schematic diagram of the Cogeneration system is shown in Figure 4.11.

Table A.2.10 — Mass, Energy and Cumulative Energy Balances for the Cogeneration System of the Kraft Process

Balance Items (Basis = 1 ADMT of Pulp [†])	Mass	Energy (Basis = 0°C)		Cumulative Energy	
	kg	MJ	%	MJ	%
Influents/Stream					
Condensate Boiler Feed Water/1000	2495.87	1584.81	6.80	6500.11 [†]	11.35
Make-up Boiler Feed Water/1001	1283.01	268.40	1.16	268.40	0.44
Steam from Recovery Boiler/413	3162.02	10828.90	50.06	39323.19	69.59
Electricity	—	288.00	1.33	1169.23 [§]	2.19
Combustion Energy					
Woodroom Rejects/104	—	8794.13	40.65	9243.09	16.43
Bunker C Oil	—	0.00	0.00	0.00 [□]	0.00
Sum	6940.90	21764.24	100.00	56504.02	100.00
Useful Effluents/Stream					
Process Steam/420	3427.54	10529.15	44.93	43185.81	75.02
Electricity	—	2172.17	10.36	8909.29	17.29
Recovery Boiler Feed Water/412	3513.36	1351.83	6.25	4408.92	7.69
Losses					
Heat Rejected to the Environment	—	3140.02	14.59	0.00	0.00
Cooling Water Enthalpy Increase	—	4571.07	23.87	0.00	0.00
Sum	6940.90	21764.24	100.00	56504.02	100.00

[†] – Pulp is leaving the Pulp Machine Press at a consistency of 50%.

[†] – $\eta_{\text{steam}} = 24.38\%$ (Table 5.23, Strategy C)

[§] – $\eta_{\text{ovelec}} = 24.63\%$ (Table 5.23, Strategy C)

[□] – $\eta_{\text{Bunker C}} = 82.7\%$, Boustead & Hancock [1].

Section 10 — Cogeneration

Total Energy of the useful products $\Rightarrow$

$$\begin{aligned}
 \sum E_{10} &= E_{\text{Produced Electricity}} + E_{\text{Process Steam}} \\
 &= 2172.17 + 10529.15 \\
 &= 12701.32 \text{ MJ}
 \end{aligned}
 \tag{A.105}$$

Cumulative Energy entering Section 10 $\Rightarrow$

$$\begin{aligned}
 \sum C_{10} &= C_{\text{Woodroom Rejects}} + C_{\text{Bunker C}} + C_{\text{BFW}} + C_{\text{Steam}} + C_{\text{Elec 10}} \\
 &= 9243.09 + 0.00 + 6768.51 + 39323.19 + 1169.23 \\
 &= 56504.02 \text{ MJ}
 \end{aligned}
 \tag{A.106}$$

The Cumulative Energy of the byproducts that are used as fuel in the cogeneration section is equal to the sum of the cumulative energy that is normally apportioned to this stream by mass and the streams combustion energy (i.e. heat of combustion).

$$\therefore C_{Byproduct}^* = C_{Byproduct} + M_{Byproduct} \times h_c$$

The Cumulative Energy of the Feed Water for the Recovery Boiler is given by the following equation (Please see Figure 4.11 for clarification) $\Rightarrow$

$$\begin{aligned} C_{BFW}^{Recovery} &= \frac{M_{BFW}^{Recovery}}{M_{BFW}^{Recovery} + M_{BFW}^{Hog} + M_{BFW}^{Power}} \times \{C_{BFW}^{Cond} + C_{BFW}^{Make-up}\} \\ &= \left(\frac{3513.36}{3513.36 + 1880.38 + 0.00} \right) \times \{6500.11 + 268.40\} \quad (A.107) \\ &= 4408.92 \text{ MJ} \end{aligned}$$

Cumulative Energy of the Produced Electricity $\Rightarrow$

$$\begin{aligned} C_{Elec}^{Prod} &= \frac{E_{Produced Electricity}}{\sum E_{10}} \times \{ \sum C_{10} - C_{BFW}^{Recovery} \} \\ &= \left(\frac{2172.17}{12701.32} \right) \times \{56504.02 - 4408.92\} \quad (A.108) \\ &= 8909.29 \text{ MJ} \end{aligned}$$

Cumulative Energy of the Process Steam $\Rightarrow$

$$\begin{aligned} C_{Process Steam} &= \frac{E_{Process Steam}}{\sum E_{10}} \times \{ \sum C_{10} - C_{BFW}^{Recovery} \} \\ &= \left(\frac{10529.15}{12701.32} \right) \times \{56504.02 - 4408.92\} \quad (A.109) \\ &= 43185.81 \text{ MJ} \end{aligned}$$

Cumulative Energy of the Imported Electricity $\Rightarrow$

$$\begin{aligned} C_{Elec}^{Imp} &= \frac{\sum_{N=1}^{10} E_{Elec N} - E_{Produced Electricity}}{\eta_{Elec}^{Imp}} \\ &= \left(\frac{[2618.10 - 2172.17]}{25.93\%} \right) \quad (A.110) \\ &= 1719.67 \text{ MJ} \end{aligned}$$

Overall Efficiency of Electricity Generation $\Rightarrow$

$$\begin{aligned}\eta_{ovelec} &= \frac{\sum_{N=1}^{10} E_{Elec\ N}}{C_{Elec}^{Imp} + C_{Elec}^{Prod}} \\ &= \left(\frac{2618.10}{1719.67 + 8909.29} \right) \times 100\% \\ &= 24.63\%\end{aligned}\tag{A.111}$$

Efficiency of Steam Generation $\Rightarrow$

$$\begin{aligned}\eta_{Steam} &= \frac{E_{Process\ Steam}}{C_{Process\ Steam}} \\ &= \left(\frac{10529.15}{43185.81} \right) \times 100\% \\ &= 24.38\%\end{aligned}\tag{A.112}$$

APPENDIX B

CUMULATIVE ENERGY CONSUMPTION of RAW MATERIALS

B.1 Cumulative Energy of the Raw Materials required by the ALCELL® Process

B.1.1 Cumulative Energy of the Logs

Assume that the Cumulative Energy associated with the logs arises solely from the transportation of the logs.

REQUIRED PARAMETERS:

Mass of Logs $\Rightarrow$ 4022.53 kg/ADMT
 Round Trip Distance $\Rightarrow$ 200 km
 Transport Payload $\Rightarrow$ 17500 kg
 Transport Fuel Consumption $\Rightarrow$ 30 ℓ /100 km
 Diesel Fuel Energetic Production Efficiency $\Rightarrow$ 83.5% [1]
 Diesel Fuel Calorific Value $\Rightarrow$ 44.84 MJ/kg [1]
 Density of Diesel Fuel $\Rightarrow$ 0.8 kg/ ℓ [10]

The Specific CEnC of the Logs may be calculated as follows:

$$c = \frac{44.84 \text{ MJ/kg} \times 0.8 \text{ kg}/\ell \times 30 \ell/100 \text{ km} \times 200 \text{ km}}{83.5\% \times 17500 \text{ kg}} \\ = 0.15 \text{ MJ/kg}$$

The Cumulative Energy associated with the logs for the ALCELL® process is as follows:

$$C_{\text{Logs}} = 0.15 \text{ MJ/kg} \times 4022.53 \text{ kg} \\ = 603.38 \text{ MJ}$$

B.1.2 Generation Efficiency and the Cumulative Energy of the Imported Electricity

Assume that the imported electricity comes from a power generation facility that uses Bunker C oil as its fuel.

REQUIRED PARAMETERS:

Thermal Efficiency of Electricity Production $\Rightarrow 32 \%$ [13]
 Bunker C Fuel Energetic Production Efficiency $\Rightarrow 82.7 \%$ [1]
 Losses due to Electricity Transmission $\Rightarrow 2 \%$

The generation efficiency, based on the cumulative energy concept, of the imported electricity may be calculated as follows:

$$\begin{aligned}\eta_{Elec}^{imp} &= (32 \% \times 82.7 \%) \times (100 \% - 2 \%) \\ &= 25.93 \%\end{aligned}$$

Therefore, the Cumulative Energy of the imported electricity (for “Combustion Strategy #7”) for the ALCELL® process may be determined by the following:

$$\begin{aligned}C_{Elec}^{imp} &= E_{Elec}^{imp} / \eta_{Elec}^{imp} \\ &= 2160.26 / 25.93 \% \\ &= 8331.14 \text{ MJ}\end{aligned}$$

B.1.3 Cumulative Energy of the Fresh Water

Assume that no water treatment is necessary and that the energy requirement of pumping the water is negligible.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 10\text{ }^{\circ}\text{C}$

Reference Temperature $\Rightarrow 0\text{ }^{\circ}\text{C}$

Mass Flow $\Rightarrow 19798.35\text{ kg/ADMT}$

Specific Heat of Water $\Rightarrow 4.184\text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the fresh water entering the ALCELL® process may be calculated as follows:

$$\begin{aligned}C_{\text{Fresh Water}} &= E_{\text{Fresh Water}} \\&= M \times C_p \times \Delta T \\&= 19798.35\text{ kg} \times 4.184\text{ kJ/kg}\cdot^{\circ}\text{C} \times (10^{\circ}\text{C} - 0^{\circ}\text{C}) \\&= 828.36\text{ MJ}\end{aligned}$$

B.1.4 Cumulative Energy of the Delignification Chemicals

Assume that the solutions are dilute enough that their specific heat capacity may be estimated as being equal to that of water.

REQUIRED PARAMETERS:

Temperature of Oxygen and Magnesium Sulfate $\Rightarrow 66^{\circ}\text{C}$
 Temperature of Sodium Hydroxide $\Rightarrow 0^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0^{\circ}\text{C}$
 Mass of Oxygen $\Rightarrow 8.94 \text{ kg/ADMT}$
 Specific CEnC of Oxygen $\Rightarrow 9.33 \text{ MJ/kg [1]}$
 Mass of Sodium Hydroxide $\Rightarrow 35.77 \text{ kg/ADMT}$
 Specific CEnC of Pure Sodium Hydroxide $\Rightarrow 29.88 \text{ MJ/kg [1]}$
 Mass of Magnesium Sulfate $\Rightarrow 4.47 \text{ kg/ADMT}$
 Specific CEnC of Magnesium Sulfate $\Rightarrow 0.00 \text{ MJ/kg}^1$
 Mass of Water with Oxygen & Magnesium Sulfate $\Rightarrow 40.24 \text{ kg/ADMT}$
 Mass of Water with Sodium Hydroxide $\Rightarrow 321.92 \text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the delignification chemicals for the ALCELL® process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{O}_2 \& \text{MgSO}_4 \text{ Solution}} \cdot C_{p(\text{Water})} \times \Delta T + M_{\text{NaOH Solution}} \cdot C_{p(\text{Water})} \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \cdot c) \\
 &= \left(\frac{53.65 \times 4.184 \times (66 - 0) + 0.00}{1000} \right) + \{8.94 \cdot 9.33 + 0.00 + 35.77 \cdot 29.88\} \\
 &= 1167.04 \text{ MJ}
 \end{aligned}$$

¹ The Specific CEnC of Magnesium Sulfate was not found in [1], Boustead & Hancock.

B.1.5 Cumulative Energy of the Bleaching Chemicals

Assume that the solutions are dilute enough that their specific heat capacity may be estimated as being equal to that of water.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 0^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0^{\circ}\text{C}$
 Mass of Oxygen $\Rightarrow 4.00 \text{ kg/ADMT}$
 Specific CEnC of Oxygen $\Rightarrow 9.33 \text{ MJ/kg [1]}$
 Mass of Sodium Hydroxide $\Rightarrow 15.61 \text{ kg/ADMT}$
 Specific CEnC of Pure Sodium Hydroxide $\Rightarrow 29.88 \text{ MJ/kg [1]}$
 Mass of Sulfuric Acid $\Rightarrow 5.00 \text{ kg/ADMT}$
 Specific CEnC of Sulfuric Acid $\Rightarrow 2.62 \text{ MJ/kg [1]}$
 Mass of Sulfur Dioxide $\Rightarrow 2.00 \text{ kg/ADMT}$
 Specific CEnC of Sulfur Dioxide $\Rightarrow 0.00 \text{ MJ/kg}^2$
 Mass of Water with Solution $\Rightarrow 140.51 \text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the bleaching chemicals for the ALCELL® process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{Solution}} \cdot C_{p(\text{Water})} \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \cdot c) \\
 &= \left(\frac{0.00}{1000} \right) + \{4.00 \cdot 9.33 + 15.61 \cdot 29.88 + 5.00 \cdot 2.62 + 0.00\} \\
 &= 516.92 \text{ MJ}
 \end{aligned}$$

² The Specific CEnC of Sulfur Dioxide was not found in [1], Boustead & Hancock.

B.1.6 Cumulative Energy of the Chemicals for the Chlorine Dioxide Generator

Assume that the solutions are dilute enough that their specific heat capacity may be estimated as being equal to that of water.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 20^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0^{\circ}\text{C}$
 Mass of Sulfuric Acid $\Rightarrow 14.36 \text{ kg/ADMT}$
 Specific CEnC of Sulfuric Acid $\Rightarrow 2.62 \text{ MJ/kg}$ [1]
 Mass of Sodium Chlorate $\Rightarrow 23.54 \text{ kg/ADMT}$
 Specific CEnC of Sodium Chlorate $\Rightarrow 0.00 \text{ MJ/kg}$ ³
 Mass of Methanol $\Rightarrow 2.15 \text{ kg/ADMT}$
 Specific CEnC of Methanol $\Rightarrow 42.99 \text{ MJ/kg}$ [1]
 Mass of Water with Solution $\Rightarrow 235.55 \text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the chlorine dioxide generator chemicals for the ALCELL® process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{Solution}} \cdot C_{p(\text{Water})} \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \cdot c) \\
 &= \left(\frac{275.60 \cdot 4.184 \times (20 - 0)}{1000} \right) + \{14.36 \cdot 2.62 + 0.00 + 2.15 \cdot 42.99\} \\
 &= 153.25 \text{ MJ}
 \end{aligned}$$

³ The Specific CEnC of Sodium Chlorate was not found in [1], Boustead & Hancock.

B.1.7 Cumulative Energy of the Bunker C Fuel Oil**REQUIRED PARAMETERS (Strategy 7):**

Process Energy Requirement from Bunker C $\Rightarrow$ 10018.34 MJ/ADMT
Bunker C Energetic Production Efficiency $\Rightarrow$ 82.7% [1]

The Cumulative Energy entering the ALCELL® process with the Bunker C fuel oil is given by:

$$\begin{aligned} C_{\text{Bunker C}} &= \frac{E_{\text{Bunker C}}}{\eta_{\text{Bunker C}}} \\ &= 10018.34 / (82.7\% / 100) \\ &= 12114.08 \text{ MJ} \end{aligned}$$

B.1.8 Cumulative Energy of the Make-up Alcohol Solution

Assume that ethanol is available at a concentration of 95% and that the water added to the solution does not require any treatment.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 20\text{ }^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0\text{ }^{\circ}\text{C}$
 Make-up Ethanol Solution Mass Flow $\Rightarrow 96.87\text{ kg/ADMT}$
 Pure Ethanol Mass Flow $\Rightarrow 82.37\text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184\text{ kJ/kg}\cdot^{\circ}\text{C}$
 Specific Heat of Ethanol $\Rightarrow 2.49\text{ kJ/kg}\cdot^{\circ}\text{C}$ [10]
 Specific CEnC of 95% Ethanol Production $\Rightarrow 18.62\text{ MJ/kg}$ [1]

Polynomial equations for the heat of mixing (H_{mix}) of ethanol and water were constructed by curve fitting data that were extracted from a graph in "Chemical and Process Thermodynamics" by B.G. Kyle [8]. Equations were constructed for the following temperatures: 25°C , 50°C , 58°C , 70°C , 90°C and 110°C . The heat of mixing of the make-up alcohol solution is estimated by the heat of mixing equation whose temperature is closest to the stream temperature. Therefore, the heat of mixing of the make-up alcohol solution is estimated by the equation that represents the heat of mixing at 25°C .

$$H_{mix_{25^{\circ}\text{C}}} = -3.630 - 10596 \cdot X + 49882 \cdot X^2 - 94876 \cdot X^3 \\ + 81719 \cdot X^4 - 26136 \cdot X^5$$

where $X = \text{mole fraction ethanol}$

$$\left(H_{mix} = \frac{\text{kJ}}{\text{kmol of solution}} \right)$$

For this solution: $H_{mix_{25^{\circ}\text{C}}} = -0.77\text{ MJ}$

The Cumulative Energy of the Make-up Alcohol entering the ALCELL® process may be calculated as follows:

$$\begin{aligned}
 C_{\text{Make-up}} &= \left(\frac{[M_{\text{Water}} \cdot C_{p(\text{Water})} + M_{\text{Alcohol}} \cdot C_{p(\text{Alcohol})}] \times \Delta T}{1000} + H_{\text{mix}} \right) + (M_{95\% \text{ Alcohol}} \cdot C_{95\% \text{ Alcohol}}) \\
 &= \left(\frac{[14.50 \cdot 4.184 + 82.37 \cdot 2.49] \times (20 - 0)}{1000} + (-0.77) \right) + \left(\frac{82.37}{0.95} \times 18.62 \right) \\
 &= 1619.04 \text{ MJ}
 \end{aligned}$$

B.2 Cumulative Energy of the Raw Materials required by the Kraft Process

B.2.1 Cumulative Energy of the Logs

Assume that the Cumulative Energy associated with the logs arises solely from the transportation of the logs.

REQUIRED PARAMETERS:

Mass of Logs $\Rightarrow$ 3769.57 kg/ADMT
 Round Trip Distance $\Rightarrow$ 200 km
 Transport Payload $\Rightarrow$ 17500 kg
 Transport Fuel Consumption $\Rightarrow$ 30 ℓ /100 km
 Diesel Fuel Energetic Production Efficiency $\Rightarrow$ 83.5% [1]
 Diesel Fuel Calorific Value $\Rightarrow$ 44.84 MJ/kg [1]
 Density of Diesel Fuel $\Rightarrow$ 0.8 kg/ ℓ [10]

The Specific CEnC of the Logs may be calculated as follows:

$$c = \frac{44.84 \text{ MJ/kg} \times 0.8 \text{ kg}/\ell \times 30 \ell/100 \text{ km} \times 200 \text{ km}}{83.5\% \times 17500 \text{ kg}}$$

$$= 0.15 \text{ MJ/kg}$$

The Cumulative Energy associated with the logs for the Kraft process is as follows:

$$C_{\text{Logs}} = 0.15 \text{ MJ/kg} \times 3769.57 \text{ kg}$$

$$= 565.44 \text{ MJ}$$

B.2.2 Generation Efficiency and the Cumulative Energy of the Imported Electricity

Assume that the imported electricity comes from a power generation facility that uses Bunker C oil as its fuel.

REQUIRED PARAMETERS:

Thermal Efficiency of Electricity Production $\Rightarrow 32\%$ [13]
 Bunker C Fuel Energetic Production Efficiency $\Rightarrow 82.7\%$ [1]
 Losses due to Electricity Transmission $\Rightarrow 2\%$

The generation efficiency, based on the cumulative energy concept, of the imported electricity may be calculated as follows:

$$\begin{aligned}\eta_{Elec}^{imp} &= (32\% \times 82.7\%) \times (100\% - 2\%) \\ &= 25.93\%\end{aligned}$$

Therefore, the Cumulative Energy of the imported electricity (for “Combustion Strategy C”) for the Kraft process may be determined by the following:

$$\begin{aligned}C_{Elec}^{imp} &= E_{Elec}^{imp} / \eta_{Elec}^{imp} \\ &= 445.91 / 25.93\% \\ &= 1719.67 \text{ MJ}\end{aligned}$$

B.2.3 Cumulative Energy of the Fresh Water

Assume that no water treatment is necessary and that the energy requirement of pumping the water is negligible.

REQUIRED PARAMETERS:

Reference Temperature $\Rightarrow 0^{\circ}\text{C}$

Mass Flow entering the process $0^{\circ}\text{C} \Rightarrow 6831.28 \text{ kg/ADMT}$

Mass Flow entering the process $10^{\circ}\text{C} \Rightarrow 825.00 \text{ kg/ADMT}$

Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the fresh water entering the Kraft process may be calculated as follows:

$$\begin{aligned}C_{\text{Fresh Water}} &= E_{\text{Fresh Water}} \\&= M \times C_p \times \Delta T \\&= 825.00 \text{ kg} \times 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C} \times (10^{\circ}\text{C} - 0^{\circ}\text{C}) \\&= 34.52 \text{ MJ}\end{aligned}$$

B.2.4 Cumulative Energy of the Delignification Chemicals

REQUIRED PARAMETERS:

Temperature $\Rightarrow 0^{\circ}\text{C}$

Reference Temperature $\Rightarrow 0^{\circ}\text{C}$

Mass of Oxygen $\Rightarrow 11.14 \text{ kg/ADMT}$

Specific CEnC of Oxygen $\Rightarrow 9.33 \text{ MJ/kg [1]}$

Mass of Magnesium Sulfate $\Rightarrow 0.00 \text{ kg/ADMT}$

Specific CEnC of Magnesium Sulfate $\Rightarrow 0.00 \text{ MJ/kg}^4$

The Cumulative Energy of the delignification chemicals for the Kraft process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{O}_2 \& \text{MgSO}_4} \cdot C_p \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \times c) \\
 &= \left(\frac{0.00}{1000} \right) + \{11.14 \cdot 9.33 + 0.00\} \\
 &= 103.89 \text{ MJ}
 \end{aligned}$$

⁴ The Specific CEnC of Magnesium Sulfate was not found in [1], Boustead & Hancock.

B.2.5 Cumulative Energy of the Bleaching Chemicals

Assume that the solutions are dilute enough that their specific heat capacity may be estimated as being equal to that of water.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 0^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0^{\circ}\text{C}$
 Mass of Oxygen $\Rightarrow 3.30 \text{ kg/ADMT}$
 Specific CEnC of Oxygen $\Rightarrow 9.33 \text{ MJ/kg [1]}$
 Mass of Sodium Hydroxide $\Rightarrow 11.78 \text{ kg/ADMT}$
 Specific CEnC of Pure Sodium Hydroxide $\Rightarrow 29.88 \text{ MJ/kg [1]}$
 Mass of Sulfuric Acid $\Rightarrow 5.65 \text{ kg/ADMT}$
 Specific CEnC of Sulfuric Acid $\Rightarrow 2.62 \text{ MJ/kg [1]}$
 Mass of Sulfur Dioxide $\Rightarrow 2.00 \text{ kg/ADMT}$
 Specific CEnC of Sulfur Dioxide $\Rightarrow 0.00 \text{ MJ/kg}^5$
 Mass of Water with Solution $\Rightarrow 115.22 \text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the bleaching chemicals for the Kraft process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{Solution}} \cdot C_{p(\text{Water})} \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \cdot c) \\
 &= \left(\frac{0.00}{1000} \right) + \{3.30 \cdot 9.33 + 11.78 \cdot 29.88 + 5.65 \cdot 2.62 + 0.00\} \\
 &= 397.50 \text{ MJ}
 \end{aligned}$$

⁵ The Specific CEnC of Sulfur Dioxide was not found in [1], Boustead & Hancock.

B.2.6 Cumulative Energy of the Chemicals for the Chlorine Dioxide Generator

Assume that the solutions are dilute enough that their specific heat capacity may be estimated as being equal to that of water.

REQUIRED PARAMETERS:

Temperature $\Rightarrow 20^{\circ}\text{C}$
 Reference Temperature $\Rightarrow 0^{\circ}\text{C}$
 Mass of Sulfuric Acid $\Rightarrow 7.73 \text{ kg/ADMT}$
 Specific CEnC of Sulfuric Acid $\Rightarrow 2.62 \text{ MJ/kg [1]}$
 Mass of Sodium Chlorate $\Rightarrow 12.67 \text{ kg/ADMT}$
 Specific CEnC of Pure Sodium Chlorate $\Rightarrow 0.00 \text{ MJ/kg [1]}$
 Mass of Methanol $\Rightarrow 1.16 \text{ kg/ADMT}$
 Specific CEnC of Methanol $\Rightarrow 42.99 \text{ MJ/kg [1]}$
 Mass of Water with Solution $\Rightarrow 126.77 \text{ kg/ADMT}$
 Specific Heat of Water $\Rightarrow 4.184 \text{ kJ/kg}\cdot^{\circ}\text{C}$

The Cumulative Energy of the chlorine dioxide generator chemicals for the Kraft process is as follows:

$$\begin{aligned}
 C_{\text{Chemicals}} &= \left(\frac{M_{\text{Solution}} \cdot C_{p(\text{Water})} \times \Delta T}{1000} \right) + \sum_{\text{Chemicals}} (M \cdot c) \\
 &= \left(\frac{148.32 \times 4.184 \times (20 - 0)}{1000} \right) + \{7.73 \cdot 2.62 + 0.00 + 1.16 \cdot 42.99\} \\
 &= 82.48 \text{ MJ}
 \end{aligned}$$

B.2.7 Cumulative Energy of the Bunker C Fuel Oil**REQUIRED PARAMETERS (Strategy A):**

Process Energy Requirement from Bunker C $\Rightarrow 949.63$ MJ/ADMT

Bunker C Energetic Production Efficiency $\Rightarrow 82.7\%$ [1]

The Cumulative Energy entering the process with the Bunker C fuel is given by:

$$\begin{aligned} C_{\text{Bunker C}} &= \frac{E_{\text{Bunker C}}}{\eta_{\text{Bunker C}}} \\ &= \frac{949.63}{(82.7\%/100)} \\ &= 1148.28 \text{ MJ} \end{aligned}$$

B.2.8 Cumulative Energy of the Make-up Lime**REQUIRED PARAMETERS:**Temperature $\Rightarrow 0^{\circ}\text{C}$ Reference Temperature $\Rightarrow 0^{\circ}\text{C}$ Mass of Make-up Lime $\Rightarrow 14.06 \text{ kg/ADMT}$ Specific CEnC of Lime $\Rightarrow 9.95 \text{ MJ/kg [1]}$ Specific Heat of Lime $\Rightarrow 0.75 \text{ kJ/kg}\cdot^{\circ}\text{C [10]}$

The Cumulative Energy of the make-up lime for the Kraft process is as follows:

$$\begin{aligned} C_{\text{Make-up}} &= \left(\frac{M_{\text{CaO}} \cdot C_p \times \Delta T}{1000} \right) + M_{\text{CaO}} \times C_{\text{CaO}} \\ &= \left(\frac{14.06 \cdot 0.75 \times (0 - 0)}{1000} \right) + \{14.06 \cdot 9.95\} \\ &= 139.85 \text{ MJ} \end{aligned}$$

B.2.9 Cumulative Energy of the Make-up Saltcake

REQUIRED PARAMETERS:

Temperature $\Rightarrow 0^{\circ}\text{C}$

Reference Temperature $\Rightarrow 0^{\circ}\text{C}$

Mass of Make-up Saltcake $\Rightarrow 32.58 \text{ kg/ADMT}$

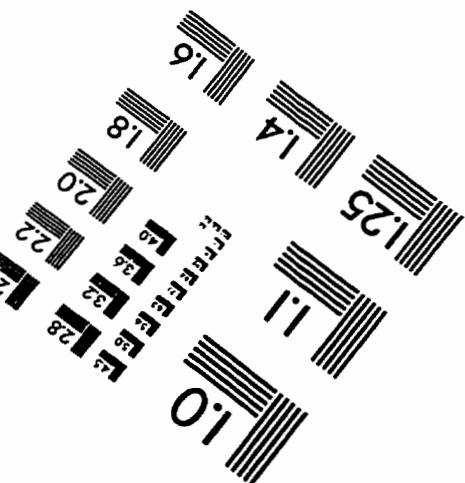
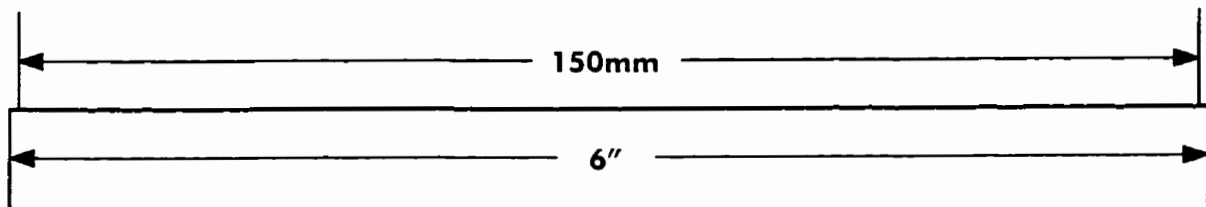
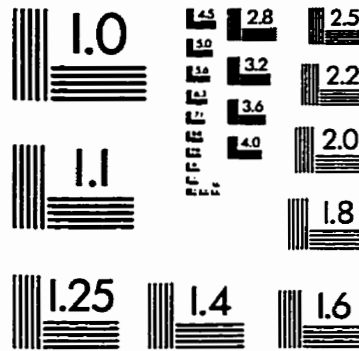
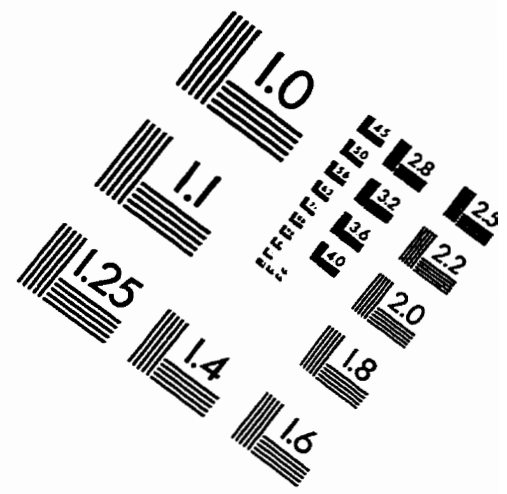
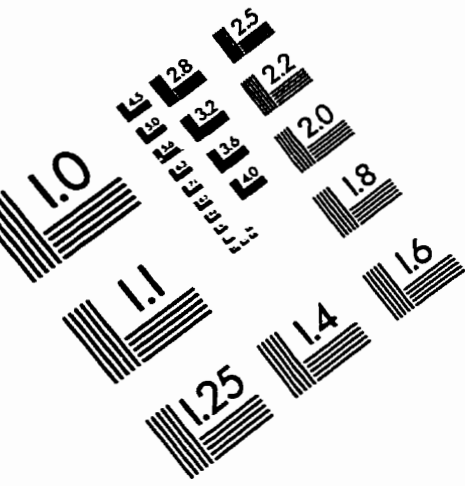
Specific CEnC of Saltcake $\Rightarrow 4.69 \text{ MJ/kg [1]}$

Specific Heat of Saltcake $\Rightarrow 0.97 \text{ kJ/kg}\cdot^{\circ}\text{C [10]}$

The Cumulative Energy of the make-up saltcake for the Kraft process is as follows:

$$\begin{aligned}
 C_{\text{Make-up}} &= \left(\frac{M_{\text{Na}_2\text{SO}_4} \cdot C_p \times \Delta T}{1000} \right) + M_{\text{Na}_2\text{SO}_4} \times C_{\text{Na}_2\text{SO}_4} \\
 &= \left(\frac{32.58 \cdot 0.97 \times (0 - 0)}{1000} \right) + \{32.58 \cdot 4.69\} \\
 &= 152.81 \text{ MJ}
 \end{aligned}$$

IMAGE EVALUATION TEST TARGET (QA-3)



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