Subcontractor Report

Lignin Process Design Confirmation and Capital Cost Evaluation

Report 42002/02:   Review of Design

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NREL

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Rev 1
March 28, 2002

REPORT 42002/02
REVIEW OF DESIGN

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LM/mlm

Rev 1
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REPORT 42002/02
REVIEW OF DESIGN

1. INTRODUCTION

The National Renewable Energy Laboratory (NREL) in Golden, Colorado is investigating potential co-products from the biomass to ethanol process. Lignin constitutes 10% to 30% of the weight of biomass. Currently lignin is physically separated from the sugar fraction and used as a boiler fuel. NREL has developed a conceptual design for a process that converts the lignin into a hydrocarbon that can be used as a high-octane automobile fuel additive. Harris Group Inc. (HGI) evaluated this design for appropriateness, completeness and operability.

In the first stage of the NREL process, base catalyzed depolymerization (BCD) breaks the lignin polymer into phenolic intermediates that can be hydroprocessed into the final product. The depolymerized lignin is a mixture of alkylated phenols, alkoxyphenols, and other hydrocarbons. In the second stage, the depolymerized lignin is subjected to a sequential two-step hydroprocessing reaction to produce a reformulated hydrocarbon gasoline product.

In the first reaction step of hydroprocessing, the depolymerized lignin is contacted with a hydroeoxygeneation catalyst to produce a hydrodeoxygenated (HDO) intermediate product. The second reaction step utilizes a hydrocracking catalyst (HCR) to convert the hydrodeoxygenerated intermediate into the reformulated gasoline additive. The final product is a mixture of naphthenic and paraffinic organics in the gasoline range.

The following is a discussion of the process flow diagrams (PFDs) and comments from Harris Group on the design review.

An additional report (Report 42002/03, Review of Capital and Operating Costs) was prepared. This report contains technical specifications for selected equipment and a discussion of capital and operating costs obtained from equipment vendors.

2. LIGNIN EXTRACTION PROCESS
PFD P500-A1000

The lignin feed stream enters the process at approximately 30% solids at atmospheric pressure. A typical analysis of this feed stream from NREL's enzymatic biomass-to-ethanol process for a corn stover feed is shown in Table 1.

Table 1: Feed Composition

Component	Weight (%)
Water	70.36
Lignin	16.03
Cellulose	3.86
Xylan	1.28
Tar	2.28
Ash	6.17
Gypsum	0.01

Before the BCD operation, the incoming lignin is isolated from the other solids in the feed by dissolving into a basic solution. The feed stream is mixed with sodium hydroxide in the solubilization tank (T-1000), where it is assumed that lignin is completely soluble in the base solution. A belt filter press (S-1010) is used to separate the solubilized lignin from the remaining solids. The solubilized lignin in the effluent stream is sent to the BCD process. The insoluble solids are sent to a co-located boiler or sold as boiler fuel.

Changes

The initial design included a screw press on the SOLIDS stream out of the BCD belt filter press, which increased the solids from 44% to 65%. There was some concern that the screw press could actually accomplish this, so it was decided to remove the screw press (plus pump P-1001) and send the solids to the biomass-to-ethanol process for additional drying. Pump P-BASEX was removed, as there was a pump (P-1310) on PFD P500-1300 that was serving the same purpose. The BCD process feed tank (T-1010) was added to collect the solubilized lignin. For clarity, BCD feed pump P-1010 was moved from PFD P500-A1100 to this PFD.

Harris Group evaluated the filter cake washing of the belt filter press (S-1010) by using a WinGEMS process model. This evaluation indicated that over 99% of the product could be recovered at a wash rate of 50 % the current rate. Details of this modeling are shown in the appendix

Concerns

The minimum concentration of NaOH required to dissolve the lignin into solution and the concentration necessary for the BCD reaction is unknown. Further investigation is recommended to determine the base requirements. Also of concern is the potential for precipitation of lignin as base reacts with carbonic acid (CO_2) evolved during BCD reaction.

3. **BASE CATALYZED DEPOLYMERIZATION (BCD)**
   PFD P500-A1100

The solubilized lignin stream passes through three heat exchangers (H-1110, H-1112 and H-1114) to raise the temperature from 64°C to 320°C before entering the BCD reactor (M-1112). The BCD reactor operates at 320°C, 121 atmospheres with 6.3% lignin in 0.24 % (wt) sodium hydroxide solution. During a 10-minute retention time, the BCD reactor breaks the lignin polymer into a mixture of alkylated phenols, alkoxyphenols and other hydrocarbons.

The BCD product stream goes to two flash tanks in series (T-1114 and T-1116). The first flash tank (T-1114) operates at 60 atmosphere and vaporizes water. This vapor is used in heat exchanger H-1112 to raise the temperature of the solubilized lignin stream to the BCD reactor. This vapor is then cooled by heat exchanger H-1118 and sent to waste water treatment. The second flash tank (T-1116) reduces the pressure to atmospheric and vaporizes much of the remaining water. This vapor is used in heat exchanger H-1110 to raise the temperature of the solubilized lignin stream to the BCD reactor. The vapor then goes to waste water treatment. The BCD product stream leaving the flash tanks is cooled by heat exchanger H-1120 from 100°C to 50°C before going to the BCD product neutralization tank (M-1120).

Changes

The area of largest concern in this process was raising the temperature of the product steam to 320°C for the reaction in the BCD reactor. The temperatures on heat exchangers H-1110 and H-1112 were adjusted to improve the heat balance. The BCD feed tank (T-1110) and pump (P-1124) are not required and were removed. Heat exchanger H-1114 was added to increase the temperature of the feed stream from 211°C to 320°C and also provide heat for start-up. Due to the high temperatures, this heat exchanger will use hot oil as the heat transfer medium.

The agitators for the BCD reactor (M-1112) and the flash tanks (T-1114 and T-1116) were not required and were eliminated. The pump (P-1110) between heat exchangers H-1110 and H-1112 was not required, as there are pumps on both sides of the heat exchangers. Heat exchanger H-1118 was added to cool the waste water before it is sent to waste water treatment. Demisters were added to both flash tanks

to prevent liquid carryover with the vapor. The operating pressure on the flash tank (T-1116) was changed from 1 to 2 atm to provide a driving force for vapor flow.

**4.   NEUTRALIZATION AND EXTRACTION
        PFD P500-A1101**

The BCD product is neutralized with sulfuric acid in tank M-1120. This forms significant quantities of sodium sulfate. The BCD product is then extracted from the aqueous solution with toluene in tank T-1130. The resultant organic and aqueous phases are separated in a decanter (M-1140). The aqueous phase is sent to a belt filter press (S-1132). The solids from the belt filter press are sent to a fluidized bed combustor and the liquid stream goes to the acid/base recovery process.

The organic phase-out of the decanter goes to an evaporator (E-1150) where a majority of the toluene is recovered and recycled back to extraction (T-1130). The BCD product leaves the evaporator 95% pure, containing only small amounts of toluene and sodium sulfate as impurities. It is then sent to storage where it will be eventually hydroprocessed into a reformulated gasoline additive.

Changes

The number of this PFD was changed from PFD P500-A1100A to PFD P500-A1101. The belt filter press (S-1132) was relocated to the aqueous stream out of the decanter (M-1140). This will facilitate separation of the oligmers. Cooling coils (H-1121, H-1122, and H-1123) were added to the lines coming into and leaving the BCD product neutralization tank (M-1120) to remove the heat. Pumps P-ACID and P-TOLU were removed, as they were duplicated on PFD P500-A1300. Toluene recycle condenser (H-1153) was added.

Harris Group evaluated the filter cake washing of the belt filter press (S1101) by using a WinGEMS process model. This evaluation indicated that over 99% of the product could be recovered at a wash rate of 50 % the current rate. Details of this modeling are shown in the appendix.

Concerns

Currently the lab process extracts the BCD from the water solution using ether in a two-stage extraction process where both the liquid BCD and the solid BCD products are extracted. The design proposes performing the process in a single extraction step using toluene as the solvent. Testing of the extraction process with toluene as opposed to ether should be investigated. Solvent extraction should be tested on the mixed neutralized material to determine if both the high (intermediate a) and low (intermediate b) viscosity BCD material are extracted or if dewatering of the high viscosity BCD solids are required prior to extraction.

NREL has stated that the solid remaining after BCD extraction is of similar chemical make-up to the BCD, indicating that this material is not simply char from the BCD reaction. This material might either be converted to BCD by recycle to the front of the process, or treated in the hydrotreater directly to RHG if the physical properties of the material are suitable. We recommend further testing of this material to determine if either the material will convert further upon recycle or if this material becomes a liquid at hydrotreating reaction temperatures where it might become feasible to feed this material to the hydrotreating/hydrocracking process to increase overall process yield. We are also concerned with the high level of Na_2SO_4 in the BCD product considering the expected low solubility of the salt in the organic phase.

5. ACID/BASE RECOVERY
PFD P500-A1200

An electrodialysis system (ED-1220) regenerates sulfuric acid and sodium hydroxide from the sodium sulfate of the decantered aqueous stream. The resultant dilute acid is recycled to neutralization of the BCD products and the dilute base stream is utilized for lignin solubilization.

Two vendors have provided quotes for an electrodialysis process to recover the acid and base from the sodium sulfate solution. The uninstalled prices ranged from $3.5 to $5 million. They did stress that from an economical sense this separation did not make sense. Harris Group will investigate the economics of not doing the separation and using fresh acid and base.

6. HYDROPROCESSING
PFDs P500-A1500 AND P500-A1501

In the second stage, the depolymerized lignin is subjected to a sequential two-step hydroprocessing reaction to produce a reformulated gasoline additive. In the first step, the BCD product is subjected to exhaustive hydrodeoxygenation (HDO) which yields hydrodeoxygenated products. Immediately following HDO, the hydrodeoxygenated product is subjected to a partial ring hydrogenation and mild hydrocracking (HCR) to produce the final reformulated hydrocarbon gasoline (RHG) product. The mixture of alkylbenzenes, branched paraffins, and alkylated naphthenes is combined into one component called HDO for the Aspen simulations.

Following hydroprocessing, the reformulated gasoline additive (RHG) stream is cooled (H-1570 and H-1580) from 380°C to 125°C and then flashed to 60 atm of pressure in the product flash tank (T-1550). The flash vapor, consisting primarily of hydrogen, is recycled to the HDO reactor. The RHG-rich flash bottoms are sent to distillation where the RHG product is pulled off the top of the distillation column and sent to storage.

Changes

The original PFD (PFD P500-A1500) was separated into two PFDs for clarity. The BCD product stream was routed to heater H-1570 and heater H-1560 was added in order to raise the temperature prior to the HDO reactor (M-1550). Pumps P-1540 and P-1570 were no longer required and were removed. Compressor C-1520 was added to increase the pressure or the recycle stream back to the HDO reactor (M-1550). The vapor cleanup system M-1570 was added in the recycle line to the HDO reactor (M-1550). Heater H-1580 was added to cool the stream into the HDO distillation column (D-1550). Pump P-1551 was added to transport water from the HDO distillation column (D-1550) to waste water treatment. The HDO condenser column T-1560 was also added.

Originally, the design incorporated a large recycle of RHG back into the reactor train. Harris Group modified the design to a once-through system typical of hydroprocessing.

Concerns

Extraction and evaporation should be investigated to determine how much toluene, water and Na_2SO_4 remain with the BCD product to be hydrotreated. Evaporation testing should also be designed to provide an estimate of the amount of BCD product (if any) that goes overhead with the solvent.

In laboratory processing, the BCD goes through a cleanup to remove salt and water prior to hydrotreating in lab testing. This level of cleanup is not designed in the proposed commercial process. Hydrotreating with a more realistic BCD will help understand the effects of Na_2SO_4 on the catalyst as a possible poison and/or hydrogen load.

Off gas (hydrogen) from these reactors should be analyzed to determine the extent of H_2S, water, and light cracking products that need to be removed/purged from the recycle hydrogen. The composition of the off gas will help determine the method and design for treating of the recycle hydrogen gas.

**APPENDIX
FILTRATION AND WASHING
MODELING ESTIMATES**

December 12, 2001

APPENDIX
FILTRATION AND WASHING
MODELING ESTIMATES

Per NREL's request HGI has performed some evaluation of the filter cake washing to provide a more realistic estimate of wash efficiency than the 100% efficient removal that NREL had estimated in the process model. This effort is summarized below.

1.   SUMMARY

Several methods were used to estimate more realistic wash efficiencies ranging from a simple reslurry to modeling a displacement wash based on Norden efficiency methods. We recommend that a N=2 efficiency wash be utilized for the cake wash for both filtration steps in the NREL Lignin conversion process and that the water used for cake washing be reduced to 50% the existing model flow. We believe that this efficiency is a realistic best case performance based on experience for a displacement wash device. This efficiency still provides for over 99% recovery of the liquid products from the solids cake. It warrants pointing out that the single most important factor in determining product recovery is the effectiveness of the filtration method at "squeezing" liquid from the cake. Changes in predicted cake dryness levels can have a significant impact on wash performance. A brief discussion of the methods used, results and recommendation are presented here.

2.   METHODS

In the current NREL model, a 100% wash efficiency is employed. To better estimate a realistic range of washing effectiveness, HGI has modeled the cake washing process using the WinGEMs process simulator. WinGEMs, a process simulator typically used in the pulp and paper industry, is programmed to handle filter cake washing calculations. Both filtration steps in the NREL lignin process were investigated. For each filtration case several options were investigated as listed below.

Cases

- Base case, filtration without washing

- Ideal wash consistent with current model

- Simple reslurry wash

- Displacement wash modeled using the Norden efficiency method with efficiencies from 2 to 4, for example

Each case was modeled both at the wash water flow in the current model and at 50% the current flow of wash water for comparison.

In the base case the slurry was filtered to a fixed dryness and the amount of product lost with the cake was calculated assuming the product was not adsorbed onto/into the solids material and only remained in the cake as a fraction of the free liquid at the same concentration as in the filtrate. This case is used as a comparison to the washing calculations to evaluate wash efficiency.

The ideal wash represents 100% removal of the liquid product from the cake consistent with the current model parameters.

In the simple reslurry method the cake is essentially mixed with the wash water and filtered again to the prescribed cake dryness. This effectively models a lower limit on the recovery of a displacement type wash. The simple reslurry is a worst-case scenario for a cake wash given a wash water rate.

A more realistic way to model a displacement wash is to use a model employing a "wash efficiency". In these calculations, a wash efficiency referred to as the Norden efficiency was used. Basically the Norden efficiency is a measure of the number of countercurrent reslurry type wash steps that the displacement wash is equivalent to. Figure 1 shows the WinGEMs model calculations demonstrating the Norden efficiency and its equivalence to a countercurrent reslurry type wash. In the upper part of the figure the slurry is filtered and washed in a countercurrent reslurry wash mode of two stages. The lower section show the application of a Norden efficiency of 2 to the cake wash process yielding equivalent results.

Unfortunately, this efficiency parameter cannot be derived for a particular application but needs to be determined experimentally for a specific piece of equipment and application. However, certain "typical" values can be applied for specific equipment based on experience. A more detailed discussion of the Norden efficiency can be found in the *Handbook for Pulp and Paper Technologists* (Smook, p. 99). This source indicates that a vacuum drum washer will have an efficiency of 2.5 to 4. Without any more information relative to the filtration equipment, we modeled efficiencies from 2 to 4 for comparison.

3.   RESULTS AND DISCUSSION

Attached are printouts from the process simulator used to simulate various wash methods and efficiency to provide support for any modification within the process model as a whole. Figures 2a and 2b represent calculations based on the first filtration step, S-1010. Figure 3a and 3b represent calculations for the second filtration step, S-1132.

The most important factor in determining the effectiveness of product recovery is the actual dryness of the filter cake. Without any indication as to the ease of filtration, we assumed a 65% cake solids in the first application investigated and a 50% cake solids in the second application. The 65% solids for the first application was used based on the current NREL processing model which uses 65%. The 50% used in the second application was chosen as a more conservative estimate than the 85% solids that is currently in the model. Our results show that even at 50% with a reduced wash, a significant percentage of the product is recovered. It is also our experience that an 85% cake solids is unlikely to be achieved commercially.

Each figure set 2a and 3a, shows the base case, the ideal wash case, the simple reslurry and wash stages with efficiencies of 2, 3, and 4. In figure sets 2b and 3b, the same filtration models are shown but at 50% the wash water rate. The results are tabulated in the Tables 1 and 2 for the two filtration processes modeled. These tables summarize the results for each case based on the current model flow rates and solids loading as well as calculations with half the wash water rate as a comparison.

The results from the S-1010 filtration modeling presented in Table 1 show that, assuming a wash efficiency of 2, 99.8% of the total product is recovered. In comparison, in the base case without washing, 96.9% of the product is recovered, and in a simple reslurry 99.3% is recovered. Cutting the wash water rate to 50% with an efficiency 2 wash still results in over 99.5% recovery of the liquid product, an 84% improvement over the case without cake washing (based on total product remaining in the cake). Similarly, Figure 2 shows the model results for the S-1132 filtration, in this case at an efficiency of 2 and a 50% wash rate result in just under 99.8% product recover.

In each of the modeled filtration processes, the recapture of the product in the liquid stream utilizing a wash efficiency of 2 results in a greater than 99% recovery of product. Given this high rate of recovery at a reduced washing rate, it seems reasonable to reduce the predicted wash rate in the current process parameters. Considering the high recovery of product, even without washing, it is worth pointing out the underlying reasons. High overall product recoveries are seen in each of this filtration processes due to the very low solids to liquid ratios, resulting in a small percentage of the total liquid remaining in the cake after filtration. In S-1010, less than 5% of the feed is suspended solids and in S-1132 the solids feed rate is less than 1% the total feed.

4.   CONCLUSIONS

Even a simple reslurry wash method results in a product recovery (based on the dissolved solid in the liquid) of over 99% in both filtration applications. This suggests that the wash water rate may be reduced without a significant loss in product recovery. Improved recoveries are observed when a displacement style wash is modeled using the Norden efficiency factor method.

We suggest that, for purposes of the model at this stage in the project development, a wash with an efficiency factor of 2 be applied and the rate of wash water be reduced to 50% the current rate. The efficiency factor of 2 appears realistic if not conservative based on literature reported values for equipment employing displacement type washing.

42002_Rpt02 Appendix

WASH WATER FLOW SET EQUAL
TO FLOW IN CURRENT MODEL

BASE CASE

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
51
SLURRY

51

SPLIT
Split3~2

16

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY
CAKE

17719 KG/HR
65% SUSP SOLIDS
6.5% DISS SOLIDS

43

FILTRATE
43

195561 KG/HR
0% SUSP SOLIDS
6.5% DISS SOLIDS

IDEAL WASH

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
2
WASH WATER

2

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
1
SLURRY

SPLIT
Split1

10

ALL OF THE SOLIDS
AND NO LIQUID
24

MIX
Mix2

6

SPLIT
Split3

5

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY
CAKE

17719 KG/HR
65% SUSP SOLIDS
0% DISS SOLIDS

16

16

MIX
Mix4

4

FILTRATE
4

218776 KG/HR
0% SUSP SOLIDS
6% DISS SOLIDS

RE-SLURRY WASH

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
26
WASH WATER

26

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
21
SLURRY

SPLIT
Split1~1

1

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY
25

MIX
Mix2~1

11

SPLIT
Split3~1

12

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY
CAKE
31

17719 KG/HR
65% SUSP SOLIDS
1.37% DISS SOLIDS

23

23

MIX
Mix4~1

13

FILTRATE
33

218776 KG/HR
0% SUSP SOLIDS
5.96% DISS SOLIDS

DISPLACEMENT WASH USING THE NORDEN EFFICIENCY METHOD

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
82
WASH WATER

EFFICIENCY FACTOR = 2

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
85
SLURRY

81

CAKE
84

17719 KG/HR
65% SUSP SOLIDS
0.35% DISS SOLIDS

83

86

86

MIX
Mix33~2

42

FILTRATE
90

218776 KG/HR
0% SUSP SOLIDS
5.98% DISS SOLIDS

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
76
WASH WATER

EFFICIENCY FACTOR = 3

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
74
SLURRY

75

CAKE
80

17719 KG/HR
65% SUSP SOLIDS
0.09% DISS SOLIDS

72

71

71

MIX
Mix33~1

34

FILTRATE
73

218776 KG/HR
0% SUSP SOLIDS
5.99% DISS SOLIDS

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
13
WASH WATER

EFFICIENCY FACTOR = 4

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
12
SLURRY

65

CAKE
15

17719 KG/HR
65% SUSP SOLIDS
0.02% DISS SOLIDS

66

70

70

MIX
Mix33

33

FILTRATE
14

218776 KG/HR
0% SUSP SOLIDS
5.99% DISS SOLIDS

TWO STAGE COUNTERCURRENT
RE-SLURRY TYPE WASH

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
◆ — 56 ————————————————

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
◆ — 52 — SPLIT Split1~3 (23) — 53 — MIX Mix2~3 (24) — 54 — SPLIT Split1~4 (25) — 62 — MIX Mix30 (30) — 63 — SPLIT Split1~5 (31) — 64 — ◆

17719 KG/HR
65% SUSP SOLIDS
0.35% DISS SOLIDS

44 → MIX Mix26 (26) — 61 — 61 — ◆

218776 KG/HR
0% SUSP SOLIDS
5.98% DISS SOLIDS

NORDEN EFFICIENCY METHOD

23215 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS
◆ 35 WASH WATER

EFFICIENCY FACTOR = 2

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS
◆ 11 SLURRY — 34 — CAKE 36 ◆

17719 KG/HR
65% SUSP SOLIDS
0.35% DISS SOLIDS

5 — MIX Mix33~3 (2) FILTRATE 10 ◆

218776 KG/HR
0% SUSP SOLIDS
5.98% DISS SOLIDS

NREL
National Renewable Energy Laboratory

S-1010
BCD FEED FILTER

Figure 1	Prepared by: SLL	11/05/01-7:42 AM
	Project No. 42002	

WASH WATER FLOW SET EQUAL TO 50% OF FLOW IN CURRENT MODEL

BASE CASE

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

111 SLURRY

111

SPLIT
Split3-3

52

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY

CAKE 113

17719 KG/HR
65% SUSP SOLIDS
6.5% DISS SOLIDS

112

FILTRATE 112

195561 KG/HR
0% SUSP SOLIDS
6.5% DISS SOLIDS

IDEAL WASH

11607.5 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

130 WASH WATER

130

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

124 SLURRY

SPLIT
Split1-2

56

ALL OF THE SOLIDS
AND NO LIQUID
126

MIX
Mix2-2

60

SPLIT
Split3-3

61

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY

CAKE 132

17719 KG/HR
65% SUSP SOLIDS
0% DISS SOLIDS

125

125

MIX
Mix4-2

62

FILTRATE 134

207169 KG/HR
0% SUSP SOLIDS
6.3% DISS SOLIDS

RE-SLURRY WASH

11607.5 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

122 WASH WATER

122

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

140 SLURRY

SPLIT
Split1-2

64

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY
123

MIX
Mix2-2

55

SPLIT
Split3-3

54

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 65% CONSISTENCY

CAKE 121

17719 KG/HR
65% SUSP SOLIDS
2.26% DISS SOLIDS

114

114

MIX
Mix4-2

53

FILTRATE 116

207169 KG/HR
0% SUSP SOLIDS
6.26% DISS SOLIDS

DISPLACEMENT WASH USING THE NORDEN EFFICIENCY METHOD

EFFICIENCY FACTOR = 2

11607.5 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

91 WASH WATER

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

46 SLURRY

50

CAKE 92

17719 KG/HR
65% SUSP SOLIDS
1.02% DISS SOLIDS

41

40

40

MIX
Mix33-4

21

FILTRATE 42

207169 KG/HR
0% SUSP SOLIDS
6.3% DISS SOLIDS

EFFICIENCY FACTOR = 3

11607.5 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

94 WASH WATER

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

100 SLURRY

93

CAKE 96

17719 KG/HR
65% SUSP SOLIDS
0.5% DISS SOLIDS

95

101

101

MIX
Mix33-4

46

FILTRATE 102

207169 KG/HR
0% SUSP SOLIDS
6.32% DISS SOLIDS

EFFICIENCY FACTOR = 4

11607.5 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

135 WASH WATER

213280 KG/HR
5.4% SUSP SOLIDS
6.5% DISS SOLIDS

106 SLURRY

110

CAKE 136

17719 KG/HR
65% SUSP SOLIDS
0.26% DISS SOLIDS

104

103

103

MIX
Mix33-4

50

FILTRATE 105

207169 KG/HR
0% SUSP SOLIDS
6.32% DISS SOLIDS

NREL
National Renewable Energy Laboratory

S-1010 BCD FEED FILTER	HARRIS GROUP INC. Suite 800 1000 Denny Way Seattle, WA 98109 (206) 494-9529 www.harrisgrp.com
Figure 2b	Prepared by: SLL	11/05/01-7:42 AM	REV. A
	Project No. 42002	

WASH WATER FLOW SET EQUAL
TO FLOW IN CURRENT MODEL

BASE CASE

128020 KG/HR
0.6% SUSP SOLIDS
0.8% DISS SOLIDS

SLURRY
51

51

SPLIT
Split3~2
16

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 50% CONSISTENCY

CAKE

1641 KG/HR
50% SUSP SOLIDS
0.788% DISS SOLIDS

43

FILTRATE
43

126379 KG/HR
0% SUSP SOLIDS
0.788% DISS SOLIDS

IDEAL WASH

1641 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

WASH WATER
2

2

128020 KG/HR
0.6% SUSP SOLIDS
6.5% DISS SOLIDS

SLURRY
1

SPLIT
Split1
10

ALL OF THE SOLIDS
AND NO LIQUID
24

MIX
Mix2
6

SPLIT
Split3
5

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 50% CONSISTENCY

CAKE

1641 KG/HR
50% SUSP SOLIDS
0% DISS SOLIDS

16

16

MIX
Mix4
4

FILTRATE

128020 KG/HR
0% SUSP SOLIDS
6.458% DISS SOLIDS

RE-SLURRY WASH

1641 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

WASH WATER
26

26

128020 KG/HR
0.6% SUSP SOLIDS
0.8% DISS SOLIDS

SLURRY
21

SPLIT
Split1~1
1

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 50% CONSISTENCY
25

MIX
Mix2~1
11

SPLIT
Split3~1
12

ALL OF THE SOLIDS
AND ENOUGH LIQUID
TO GET 50% CONSISTENCY

CAKE
31

1641 KG/HR
50% SUSP SOLIDS
0.263% DISS SOLIDS

23

23

MIX
Mix4~1
13

FILTRATE
33

128020 KG/HR
0% SUSP SOLIDS
0.781% DISS SOLIDS

DISPLACEMENT WASH USING THE NORDEN EFFICIENCY METHOD

1641 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

WASH WATER
82

EFFICIENCY FACTOR = 2

128020 KG/HR
0.6% SUSP SOLIDS
0.8% DISS SOLIDS

SLURRY
85

81

CAKE
84

1641 KG/HR
50% SUSP SOLIDS
0.113% DISS SOLIDS

83

86

86

MIX
Mix33~2
42

FILTRATE
90

128020 KG/HR
0% SUSP SOLIDS
0.782% DISS SOLIDS

1641 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

WASH WATER
76

EFFICIENCY FACTOR = 3

128020 KG/HR
0.6% SUSP SOLIDS
0.8% DISS SOLIDS

SLURRY
74

75

CAKE
80

1641 KG/HR
50% SUSP SOLIDS
0.053% DISS SOLIDS

72

71

71

MIX
Mix33~1
34

FILTRATE
73

128020 KG/HR
0% SUSP SOLIDS
0.783% DISS SOLIDS

1641 KG/HR
0% SUSP SOLIDS
0% DISS SOLIDS

WASH WATER
13

EFFICIENCY FACTOR = 4

128020 KG/HR
0.6% SUSP SOLIDS
0.8% DISS SOLIDS

SLURRY
12

65

CAKE
15

1641 KG/HR
50% SUSP SOLIDS
0.025% DISS SOLIDS

66

70

70

MIX
Mix33
33

FILTRATE
14

128020 KG/HR
0% SUSP SOLIDS
0.783% DISS SOLIDS

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		HARRIS GROUP INC.
S-1132		Suite 800
ACID/BASE RECOVERY FILTER		1000 Denny Way
		Seattle, WA 98109
Figure 3a	Prepared by: SLL	11/05/01-7:46 AM	(206) 494-9529
	Project No. 42002		www.harrisgrp.com

REV. A

WASH WATER FLOW SET EQUAL TO 50% OF FLOW IN CURRENT MODEL

BASE CASE

IDEAL WASH

RE-SLURRY WASH

DISPLACEMENT WASH USING THE NORDEN EFFICIENCY METHOD

EFFICIENCY FACTOR = 2

EFFICIENCY FACTOR = 3

EFFICIENCY FACTOR = 4
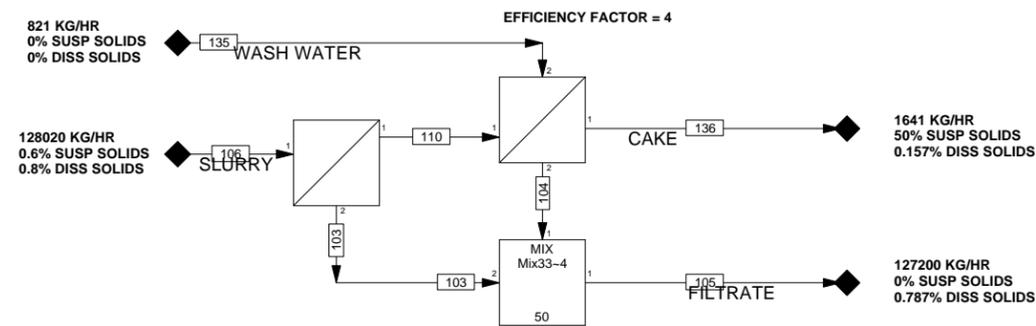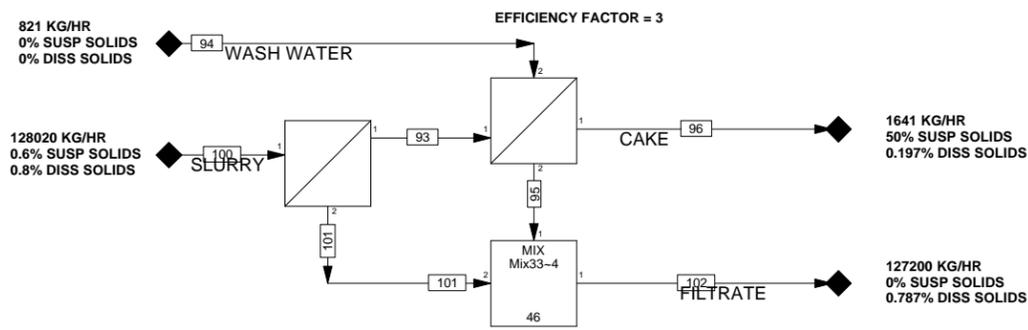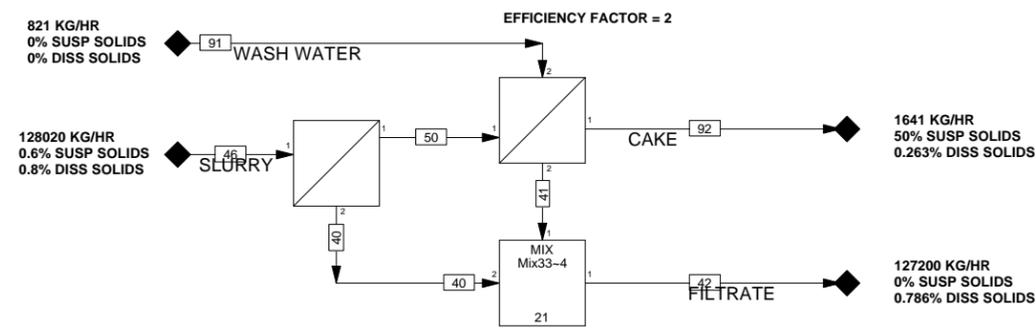
NREL		
National Renewable Energy Laboratory		
S-1132 ACID/BASE RECOVERY FILTER		HARRIS GROUP INC. Suite 800 1000 Denny Way Seattle, WA 98109 (206) 494-9529 www.harrisgrp.com
Figure 3b	Prepared by: SLL 11/05/01-7:46 AM Project No. 42002	REV. A

Table 1
S-1010 Filtration
NREL Lignin Conversion Process
8/20/2001

Feed Characteristics								
Total Flow	kg/hr	213280						
Suspended Solids	%	5.40%						
Disolved Solids (Products)	%	6.50%						
Total Product	kg/hr	13114.59						
Assumptions								
Cake dryness (as suspended solids)	%	65%						
Base Wash Rate	kg/hr	23215						
Suspended Solids removal	%	100%						

Wash Method	Wash Rate Factor	Cake Out kg/hr	Efficiency Factor	Product in Cake liquid %	Product Lost kg/hr	Percent Lost	Total Recovery	Improvement Over Baseline
No Wash (Baseline)		17719		6.50%	403.11	3.07%	96.93%	0.00%
Simple Reslurry	1	17719		1.37%	84.96	0.65%	99.35%	78.92%
Simple Reslurry	0.5	17719		2.26%	140.16	1.07%	98.93%	65.23%
Displacement Wash A	1	17719	2	0.35%	21.71	0.17%	99.83%	94.62%
Displacement Wash A	0.5	17719	2	1.02%	63.26	0.48%	99.52%	84.31%
Displacement Wash B	1	17719	3	0.09%	5.58	0.04%	99.96%	98.62%
Displacement Wash B	0.5	17719	3	0.50%	31.01	0.24%	99.76%	92.31%
Displacement Wash C	1	17719	4	0.02%	1.24	0.01%	99.99%	99.69%
Displacement Wash C	0.5	17719	4	0.26%	16.12	0.12%	99.88%	96.00%
Ideal Wash	1	17719		0%	0.00	0.00%	100.00%	100.00%

Table 2
S-1132 Filtration
NREL Lignin Conversion Process
8/20/2001

Feed Characteristics		
Total Flow	kg/hr	128020
Suspended Solids	%	0.60%
Disolved Solids (Products)	%	0.80%
Total Product	kg/hr	1018.015
Assumptions		
Cake dryness (as suspended	%	50%
Base Wash Rate	kg/hr	1641
Suspended Solids removal	%	100%

Wash Method	Wash Rate Factor	Cake Out kg/hr	Efficiency Factor	Product in Cake liquid %	Product Lost kg/hr	Percent Lost	Total Recovery	Improvement Over Baseline
No Wash (Baseline)		1641		6.50%	53.33	5.24%	94.76%	0.00%
Simple Reslurry	1	1641		0.24%	1.94	0.19%	99.81%	96.37%
Simple Reslurry	0.5	1641		0.39%	3.23	0.32%	99.68%	93.94%
Displacement Wash A	1	1641	2	0.11%	0.93	0.09%	99.91%	98.26%
Displacement Wash A	0.5	1641	2	0.26%	2.16	0.21%	99.79%	95.95%
Displacement Wash B	1	1641	3	0.05%	0.43	0.04%	99.96%	99.18%
Displacement Wash B	0.5	1641	3	0.20%	1.62	0.16%	99.84%	96.97%
Displacement Wash C	1	1641	4	0.03%	0.21	0.02%	99.98%	99.62%
Displacement Wash C	0.5	1641	4	0.16%	1.29	0.13%	99.87%	97.58%
Ideal Wash	1	1641		0%	0.00	0.00%	100.00%	100.00%

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