Production of Advanced Biofuels via Liquefaction

Hydrothermal Liquefaction Reactor Design

April 5, 2013

Dan Knorr, John Lukas, and Paul Schoen
Harris Group Inc.
Atlanta, Georgia

NREL Technical Monitor: Mary J. Biddy

The National Advanced Biofuels Consortium is a partnership of industry, national laboratory, and university members that is developing technologies to convert lignocellulosic biomass to biofuels that are compatible with the existing transportation infrastructure.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Subcontract Report
NREL/SR-5100-60462
November 2013

Contract No. DE-AC36-08GO28308

Production of Advanced Biofuels via Liquefaction

Hydrothermal Liquefaction Reactor Design

April 5, 2013

Dan Knorr, John Lukas, and Paul Schoen
Harris Group Inc.
Atlanta, Georgia

NREL Technical Monitor: Mary J. Biddy

Prepared under Subcontract No. AGV-2-22552-01

The National Advanced Biofuels Consortium is a partnership of industry, national laboratory, and university members that is developing technologies to convert lignocellulosic biomass to biofuels that are compatible with the existing transportation infrastructure.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Subcontract Report
NREL/SR-5100-60462
November 2013

Contract No. DE-AC36-08GO28308

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

TABLE OF CONTENTS

Section		Page
1	EXECUTIVE SUMMARY	1-1
2	INTRODUCTION	2-1
	2.1. General	2-1
	2.2. Study Objectives	2-2
	2.3. Reactor Cases	2-2
	2.4. Methods and Assumptions	2-6
3	HEAT TRANSFER COEFFICIENT DETERMINATION	3-1
	3.1. Importance	3-1
	3.2. Methods and Results	3-1
4	REACTOR DESIGN DESCRIPTIONS	4-1
	4.1. Common Process Equipment	4-1
	4.2. Case A: Indirect Heating by Feed Recycle	4-2
	4.3. Case B (and B-L): Full Heat Integration	4-3
	4.4. Case D (and D-L): Recycle Water Mixing at High Pressure	4-4
5	COST ESTIMATES	5-1
	5.1. Approach	5-1
	5.2. Capital Cost Estimates	5-4
	5.3. Operating Cost Estimates	5-10
	5.4. Comparison of Cost Estimates	5-12
6	SENSITIVITY STUDIES	6-1
	6.1. Overview	6-1
	6.2. Liquid Hourly Space Velocity	6-1
	6.3. Pump Selection	6-2
	6.4. Heat Transfer Coefficient	6-2

7 PROCESS OPTIONS INVESTIGATED 7-1
7.1. Overview 7-1
7.2. Inclusion of CSTR in Reactor Design: Case C 7-1
7.3. Energy Recovery Using Let-Down Pump Turbine 7-2
7.4. Use of 409 Stainless Steel Rather than 316L 7-2
7.5. Evaluation of Using Molten Salt System for Heating Medium 7-3
7.6. Evaluation of Jacketed Plug-Flow Reactor 7-3
7.7. Evaluation of Case D with All Indirect Heating 7-3
7.8. Evaluation of Alternative Reactor Configurations 7-4

8 CONCLUSIONS AND RECOMMENDATIONS 8-1
8.1. Comparison of Cases 8-1
8.2. Recommended Experiments and Future Development 8-1

Appendices

A Process Flow Diagrams
B Design Basis
C Priced Equipment Lists
D Capital Cost Information
E Recommended Experiments

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 1
EXECUTIVE SUMMARY

National Renewable Energy Laboratory (NREL) in Golden, Colorado, contracted with Harris Group Inc. (Harris Group) to develop detailed reactor designs and capital cost and operating cost estimates for the hydrothermal liquefaction reactor system under development at Pacific Northwest National Laboratories (PNNL). The goal of the design and costing efforts was to provide guidance on the expected cost of the reactor systems as well as to highlight areas where research efforts could reduce project costs.

The primary challenges associated with the reactor section design were (1) maximizing heat integration, (2) managing the potential for poor heat transfer from the reactor effluent to the reactor feed due to the potential for high viscosities in the feed streams, and (3) minimizing cost associated with the reactor system itself, given the very high required pressures. As such, five cases were developed to try to address these challenges. In Case A, a recycle stream already at reactor temperature is immediately contacted with the feed from the feed pumps to provide indirect heating. This results in a feed stream at sufficiently high temperatures to avoid high viscosity in the feed and the corresponding low heat transfer coefficients. In Case B, feed is pumped and heated through a series of pre-heaters prior to a final trim heating in a hot-oil heater prior to entering a reactor to maximize heat integration. Unfortunately, the expected heat transfer coefficients for Case B are quite low, resulting in large heat exchanger area requirements. Another case, Case D, was selected to explore the possibility that the feed pumps would be able to handle a high solid loading of 36.6 wt% dry solids. This allows the majority of the desired recycle water, which is at reactor temperatures, to be added just downstream of the pumps resulting in a feed stream at sufficiently high temperatures to avoid high viscosity in the feed and the corresponding low heat transfer coefficients. Cases B-L and D-L were variations of Cases B and D wherein the separation unit operation downstream of the reactor required low temperature operation. All cases were designed for a feed rate of 2000 dry metric tons of wood chips per day.

Sizing of the heat exchangers associated with these cases and detailed estimates of overall heat transfer coefficients were based on correlations found in published literature.

The overall costs associated with all of the cases investigated are provided in Table 1-1 below. As shown, Case D represents the lowest capital and operating costs, while Case D-L is the next lowest. This is primarily due to the elimination of several heat exchangers and several of the high-pressure pumps exchangers in Case D. The primary risk associated with Case D is that it may not be possible to pump solutions with such high solids concentrations. Case A shows an intermediate capital and operating cost and may be suitable if pumping problems are encountered in testing under Case D conditions. Finally, Cases B and B-L are extremely expensive due to the expected low heat transfer coefficients originating from the high feedstock viscosity.

Table 1-1. Costs Associated with All Cases (2011 Dollars)

	Case A	**Case B**	**Case B-L**	**Case D**	**Case D-L**
Purchased Equipment Cost ($MM)	$ 97	$ 386	$ 404	$ 61	$ 87
Installed Equipment Cost ($MM)	$ 195	$ 837	$ 877	$ 120	$ 176
Total Direct Costs ($MM)	$ 227	$ 981	$ 1,029	$ 139	$ 205
Total Indirect Costs ($MM)	$ 136	$ 589	$ 617	$ 83	$ 123
Fixed Capital Investment ($MM)	$ 364	$ 1,570	$ 1,646	$ 222	$ 328
Working Capital ($MM)	$ 18	$ 79	$ 82	$ 11	$ 16
Total Capital Investment ($MM)	$ 382	$ 1,649	$ 1,728	$ 233	$ 344
TOTAL OPERATING COST ($MM/yr)	$ 35	$ 47	$ 47	$ 22	$ 29

Sensitivity analysis indicated that the primary areas of future research be focused on: (1) increasing the acceptable liquid hourly space velocity (LHSV) in the system, (2) pumpability assessments for high solids content streams, (3) experimental determination of expected heat transfer coefficients, and (4) determination of whether or not the separation unit operation can be conducted at reactor temperature and pressure.

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 2
INTRODUCTION

2.1. GENERAL

The National Advanced Biofuels Consortium (NABC) is a group of 17 partners from industry, universities, and national laboratories. NABC is developing cost-effective processes to produce biofuels that are compatible with today's transportation infrastructure. This project is funded by the American Recovery and Reinvestment Act (ARRA), supported by the U.S. Department of Energy (DOE) and is led by NREL and PNNL. Once commercialized, processes developed by the NABC will help the United States increase energy security, reduce greenhouse gas emissions, and develop new economic opportunities.

Engineering and economic analysis for the NABC is being led by the National Bioenergy Center (NBC) at NREL. NBC supports the science and technology goals of the DOE Biomass Program. NBC advances technology for producing liquid fuels from biomass. Integrated system analyses, technoeconomic analyses, and life cycle assessments (LCAs) are essential to NBC's research and development efforts. Analysis activities provide an understanding of the economic, technical, and even global impacts of renewable technologies. These analyses also provide direction, focus, and support to the development and commercialization of various biomass conversion technologies. The economic feasibility and environmental benefits of biomass technologies revealed by these analyses are useful for the government, regulators, and the private sector.

One of the routes for production of advanced biofuels under development in the NABC is hydrothermal liquefaction (HTL) of biomass. HTL entails processing biomass in liquid-phase media at temperatures of 300–400 °C and at pressures fixed by the vapor pressure of the media. In biomass HTL, water usually is the medium, and the temperature is held at or below the critical temperature of water (374 °C), resulting in pressures of 2,500–3,000 psi.

No catalyst is used in the PNNL HTL process but alkali carbonate reagent is commonly added as a buffering agent to maintain a pH greater than four. Product oils from HTL of biomass have low water content and are lower in oxygen (ca. < 20%) than oils from fast pyrolysis, but they have other undesirable physico-chemical properties, such as high viscosity.

Among the key uncertainties central economic analyses of the HTL process are the capital cost and reactor design needed for the reactor. The reactor system includes all necessary feeding equipment, the reactor system and pressure let-down, and product recovery sections. As such, NREL engaged Harris Group to provide engineering support to develop preliminary designs for the reactor systems and to provide associated capital and operating costs to support decisions pertaining to the development of HTL technology.

2.2. STUDY OBJECTIVES

The objective of this study is to develop detailed reactor designs and capital cost estimates for the HTL reactor system. In addition, Harris Group estimated the cost impacts of variations to the basic designs and process conditions.

2.3. REACTOR CASES

In order to meet the project objectives, Harris Group developed heat and material balances for three separate cases and two sub-cases. A simplified block flow diagram showing process elements common to all cases is presented in Figure 2-1 below. Detailed process flow diagrams for these cases can be found in Appendix A. We have provided brief process descriptions and simplified diagrams of the region highlighted within the dotted line, wherein the differences in the cases lie. We initially reviewed Case C, too, but found it to be unfeasible; we discuss this further in Section 7: Process Options Investigated.

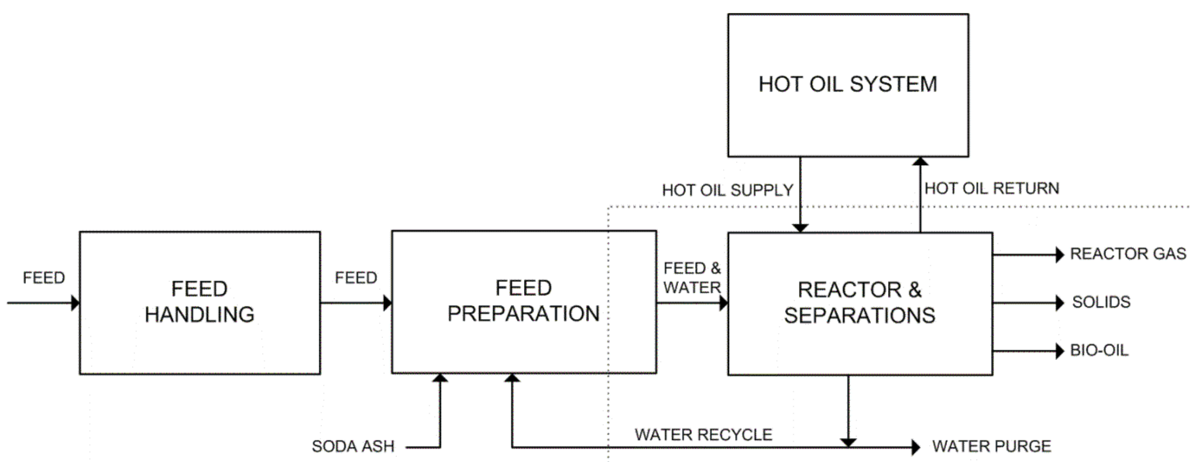


Figure 2-1. Block Flow Diagram for Processes

The primary challenges associated with the reactor section design were (1) maximizing heat integration, (2) managing the potential for poor heat transfer from the reactor effluent to the reactor feed due to the potential for high viscosities of the feed stream, and (3) minimizing cost associated with the reactor system itself given the very high required pressures. As such, we developed five cases to address these challenges.

2.3.1. Case A: Indirect heating by recycling feed prior to reactor

Summary: As shown in Figure 2-2, in Case A, the 15 wt% dry solids feed coming from the biomass feed pumps immediately meets a recycle stream of hot feed that is already at 350 °C. This results in a feed stream at 250 °C, which we expect to be hot enough to avoid high viscosity in the feed and the corresponding low heat transfer coefficients.

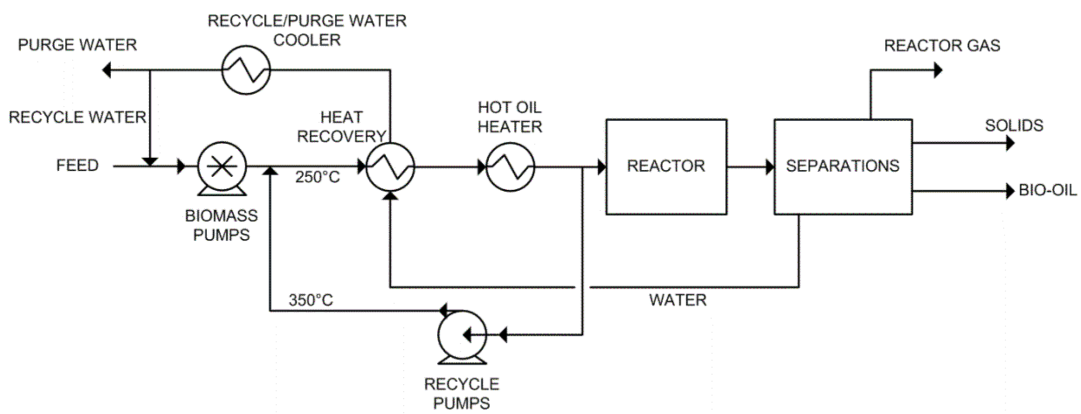


Figure 2-2. Illustration of Flow Scheme for Case A

Advantages: This case avoids potential for high viscosity and the related low heat transfer coefficients and allows for operation of the feed pumps at 15% wt dry solids. Several vendors stated that they were confident their pumps were capable of pumping this material.

Disadvantages: This case provides very poor heat integration, due to the fact that the internal recycle stream has to be quite large to achieve 250 °C after mixing. Further, this design requires the recycle pumps to be able to handle 15 wt% dry solids and effectively increases overall residence time of the reactor feed due to the recycle stream.

2.3.2. Case B (and B-L): Full heat integration

We selected Case B, Figure 2-2, to understand the potential benefit if full heat integration were achievable. Specifically, a 15 wt% dry solids feed is fed from the pump and heated through a series of heat recovery exchangers prior to a final trim heating in a hot oil heater prior to entering the reactor. Case B-L, Figure 2-3, is essentially identical to Case B except that the bio-oil/water separation occurs at low temperature, downstream of the heat integration.

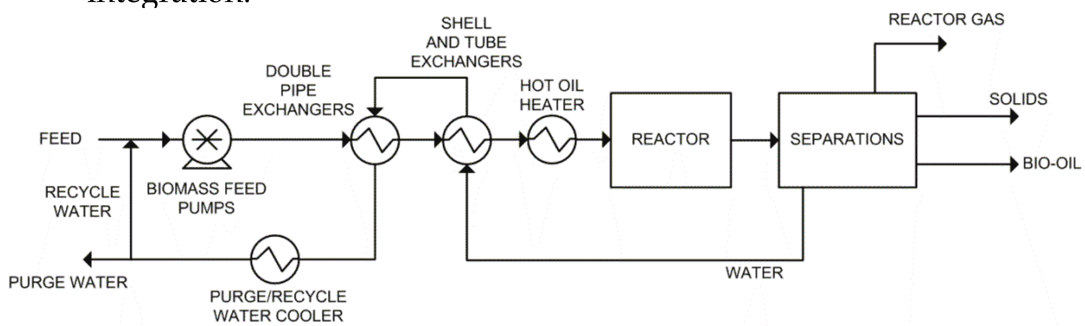


Figure 2-2. Illustration of Flow Scheme for Case B

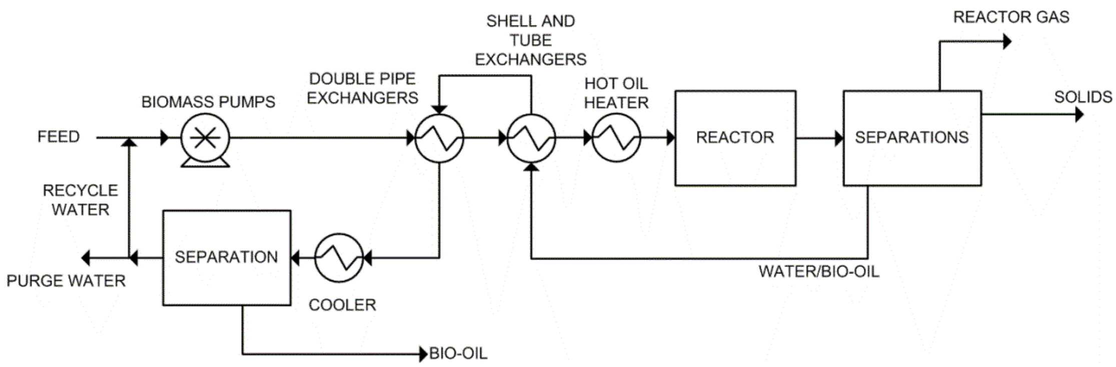


Figure 2-3. Illustration of Flow Scheme for Case B-L

Advantages: Lowest overall utility costs are expected with this design, and it also requires the lowest heat duties associated with the hot oil systems.

Disadvantages: Given the high viscosity values measured by PNNL personnel, it is likely that heat transfer coefficients of the feed stream could be extremely low in this design, necessitating enormous heat transfer areas, thus making this option cost-prohibitive.

2.3.3. Case D (and D-L): Recycle water mixing at high pressure

We selected Case D, Figure 2-4, to explore the possibility that the biomass feed pumps would be able to pump much higher solids content than first thought. In these cases, a high solid loading of 36.6 wt% solids (dry basis) was fed to the feed pumps, and the majority of the desired recycle water was added at reactor outlet temperature just downstream of the pump. As in Case A, this increased the temperature of the feed stream to approximately 250 °C to prevent high viscosity problems.

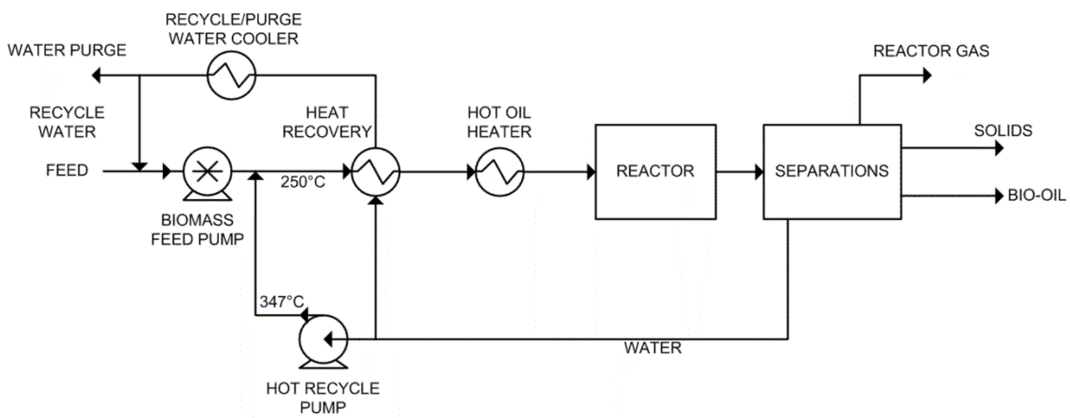


Figure 2-4. Illustration of Flow Scheme for Case D

Case D-L is similar to Case D in concept, but, due to the fact that the bio-oil/water separation occurs at low temperature, heat recovery exchangers are needed for cooling prior to this separation. This is followed by heating after the separation to reduce the need for further heating of the recycle water used to indirectly heat the feed coming from the biomass pump discharge.

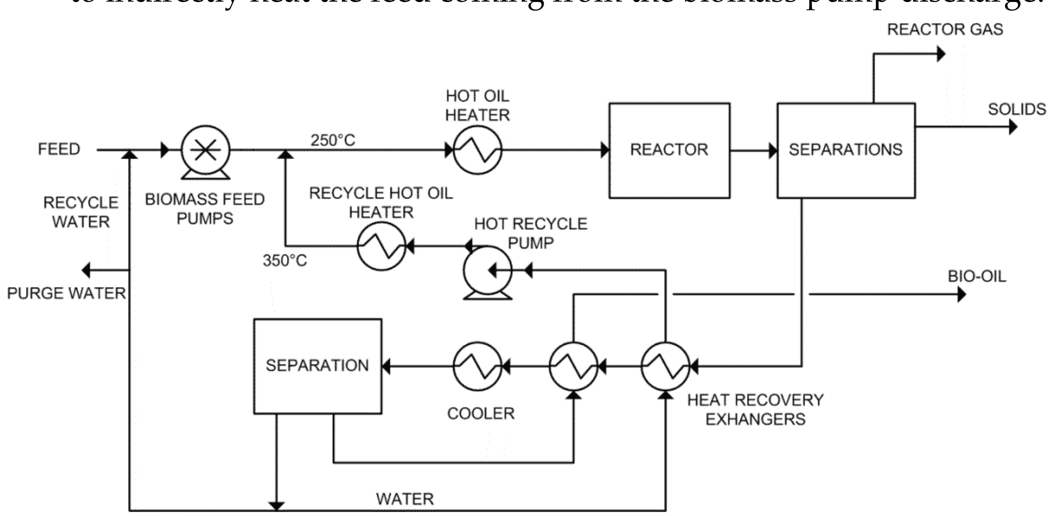


Figure 2-5. Illustration of Flow Scheme for Case D-L

Advantages: Better heat integration than Case A, and no need for recycle pump to accommodate solids.

Disadvantages: There is some risk that it may not be possible to pump the high solids content presented in this case. Case D-L requires additional equipment due to need for heat integration.

2.4. METHODS AND ASSUMPTIONS

During the development of the design, Harris Group set the design criteria and used certain assumptions to proceed with the feasibility study and cost estimates. The design criteria and assumptions were based either on information from NREL and PNNL, process and performance information from equipment vendors, or from Harris Group historical data. A full list of the design criteria can be found in Appendix B: Design Basis. Included in the design basis are side notes regarding the source of the design data or assumptions.

Material balances that are presented in the process flow diagrams in Appendix A were developed in Excel. These material balances include the following components: water, wood, i.e., dry wood, bio-oil, char, gas, aqueous organics, fully soluble aqueous organics, soda ash, air and heating oil. These components were chosen to simplify the heat and material balance, as the bio-oil itself is composed of possibly thousands of individual components. Aqueous organics and fully soluble aqueous organics categories were based on the AspenPlus model provided by NREL. The primary difference is that the fully soluble aqueous organics were those molecules that are soluble in water over the entire composition range, while aqueous organics were those that showed a solubility limit (approximately 0.014lb/lb water from the AspenPlus model).

Within the material balance, a recycle rate of 80% of the product water was targeted to allow for recovery of some of the aqueous organic materials in the bio-oil. However, this target was balanced with the more important objective of achieving 15 wt% dry solids in the feed to the reactor. Given that the wood feed contains 48 wt% water, some recycle had to be displaced; as such, the recycle rate in most cases was 77.5%, rather than 80%. Based on information provided by NREL and PNNL, the assumed yield from wood across the reactor was 3.0 wt% char, 3.0 wt% water, 37.7 wt% fully soluble aqueous organics, 9.1 wt% aqueous organics, 29.4 wt% bio-oil, and 17.8 wt% gas.

The energy balance for the cases developed in AspenPlus is based on a key assumption that the thermal properties of the streams were best modeled by using water. The justification for this is that (1) the reactor feed stream is mostly water, and (2) the process operates near the critical point of water, where thermal properties can change dramatically. For example, the heat capacity increases dramatically and goes through a maximum near the critical point. The thermodynamic package, based on the International Association for the Properties of Water and Steam (IAPWS), was utilized in AspenPlus to ensure that the thermal properties of water were modeled accurately.

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 3
HEAT TRANSFER COEFFICIENT DETERMINATION

3.1 IMPORTANCE

For all of the cases developed, multiple heat exchangers are included. Heat exchanger and piping costs are a significant part of the overall capital cost because of the wall thicknesses required for the high pressure. Total heat exchanger area is, of course, dictated to a large extent by the heat transfer coefficient expected for a particular application. Furthermore, the reactor feed contains solids, which, even suspended in liquid water, can result in very high viscosities (e.g., 2000 to 65,000 cSt at 40 °C — see Design Basis, Appendix B); this may result in low Reynold's numbers, and, by extension, low heat transfer coefficients. This was one motivation for the indirect heating options (Cases A and D), to avoid trying to do heat transfer at low temperatures with high viscosities. In this section, we present the methods and results of heat transfer coefficient calculations, as well as the values assumed for the capital cost estimates provided, and the range of values assumed for the sensitivity studies provided in subsequent sections.

3.2 METHODS AND RESULTS

Due to the fact that the heat transfer covered a wide range of temperature, various heat exchangers were examined to determine heat transfer coefficient over a number of cases listed below.

3.2.1 Case B: Preheater (80 °C<T<160 °C), Low Viscosity

For one option in Case B, we assumed that the viscosity of the 15 wt% dry solids slurry is essentially the same as that of water. This is not justified by the data so far obtained by PNNL; however, that data is based on wood particles with significantly smaller diameters than that assumed in the design basis for the production facility. Furthermore, literature data[1] shows that, as particle size increases, the viscosity of water/biomass and water/coal mixtures decreases dramatically. As such, this case represents the "best case"

1 He, W., C.S. Park, and J. M. Norbeck, *Energy & Fuels*, **23**(2009), 4763-4767.

that can be expected for heat transfer coefficients in a fully heat integrated design.

The tube-side material here is assumed to be reactor feed, at low temperature, while the shell-side (really the annular space in a double pipe heat exchanger) is assumed to be hot recycled water that is being cooled prior to pressure let-down. In this case, the classical Coburn equation was used to estimate the heat transfer coefficient and all properties were assumed to be that of water, in keeping with the design basis. Several cases were calculated with velocities ranging from 0.1 ft/s to 8 ft/s, and fouling factors ranging from that suggested for muddy/silty water (333 BTU/hr/ft^2/°F) to that suggested for sanitary canals (125 BTU/hr/ft^2/°F)[2]. Overall heat transfer coefficients were in the range of 26-274 BTU/hr/ft^2/°F, with a base case value of 150 BTU/hr/ft^2/°F. In most cases studied, the fouling factor showed the most significant contribution to the overall coefficient.

3.2.2 Case B: Preheater (80 °C<T<160 °C), High Viscosity

This case was selected to understand the cost of full heat integration if high viscosity dominates at low temperature. Here, the viscosity was assumed to be 1000 cP for the purposes of this assessment, which is reasonably in line with the range of data provided by PNNL for rheology of immersion milled feedstock (250 to 4000 cP over a temperature range of 50 to 175 °C). Similar fouling factors to those above were assumed. In this case, the inner-tube heat transfer coefficient was calculated assuming hydrodynamically developed, thermally developing laminar flow.[3] In these cases, overall heat transfer was clearly dictated by the inner-tube heat transfer coefficient, and values were 13-15 BTU/hr/ft^2/°F, approximately an order of magnitude lower than those obtained for low viscosity cases above. The overall heat transfer coefficient for fully developed (hydrodynamic and thermally) laminar flow is even lower, in the 3-4 BTU/hr/ft^2/°F range.

3.2.3 Reactor Feed/Water Product Cross Exchanger (250 °C<T<300 °C)

Cross exchange between the reactor feed and either product water (Cases A, B, and D) or reactor effluent (Cases B-L and D-L) was incorporated. As such, the heat transfer coefficients were estimated. Here, the viscosity of both the shell and tube-side fluid was taken to be that of water, with an additional case run wherein the viscosity was 10 times that of water, as suggested in the

2 *Perry's Chemical Engineering Handbook*, 5th Ed., Table 10-9.
3 Ozisik, M., *Heat Transfer: A Basic Approach*, p. 301.

literature[4], which did not change the result significantly. As these temperatures approach the critical point of water, correlations for heat transfer in tubes near the critical point by Yamagata et al. were employed[5] along with more conventional correlations like the Zukauskas correlation, where appropriate. Heat transfer coefficients in these cases were largely determined by the assumed fouling factor, and the results are provided in Table 3-1 below.

3.2.4 Reactor Feed/Hot Oil Heat Exchanger (T>300 °C)

The final case examined for heat transfer coefficients was that of reactor feed/hot oil heat transfer. After numerous conversations with thermal oil vendors, Harris Group found that heating oils do exist which have appropriate stability for use in the temperature range in question. While these fluids could be used in condensing service, there is ultimately no advantage to doing this since improvements in heat transfer coefficient on the heating fluid side are not expected to be the limiting factor governing heat transfer. Furthermore, discussions with fired heater vendors suggested capital costs associated with condensing service were likely to be much higher than running the oil in the condensed phase. For these cases, heating oil properties were provided by vendors. Heating oil was assumed to be on the shell-side, and heat transfer coefficients were calculated using Nusselt's correlations. The reactor feed was assumed to be on the tube-side, and, again, the correlations by Yamagata were employed. In these cases, heat transfer coefficients were relatively high and were dictated largely by the choice of fouling factor. The range of values obtained is found in Table 3-1 below.

3.2.5 Results

A summary of heat transfer coefficient results are provided in Table 3-1 below. Again, in most cases, a fouling factor corresponding to a heat transfer coefficient of 333 BTU/hr/ft^2/°F was assumed. The base cases provided below served as a basis for sizing the exchangers, while the high and low values were used for sensitivity analysis. High values generally represent those with negligible fouling.

4 Nakamura et al., "Detailed Analysis of Heat and Mass Balance for Supercritical Water Gasification," *J. Chem. Engr. Japan*, v. 41, pp. 817-828, 2008.

5 Yamagata et al., "Forced Convective Heat Transfer to Supercritical Water Flow in Tubes," Int. J. Heat Mass Transfer, v. 15, pp. 2575-2593, 1972.

Table 3-1. Heat Transfer Coefficient Results

	Minimum U (BTU/hr/ft^2/°F)	Base U (BTU/hr/ft^2/°F)	Maximum U (BTU/hr/ft^2/°F)
Case B: Preheater, low viscosity	20	144	380
Case B: Preheater, high viscosity	3	14	15
Reactor feed/water product cross exchanger	25	170	443
Reactor feed/hot oil exchanger	40	154	446

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 4
REACTOR DESIGN DESCRIPTIONS

4.1 COMMON PROCESS EQUIPMENT

All of the reactor design cases include some common process equipment, shown in the process flow diagrams in Appendix A in Sections 100 and 200. The process begins with feed handling, in which trucks bringing in wood chips are unloaded using a truck tipper, onto an offload conveyor. From that point, the chip storage and reclaim is provided with a stacker/reclaimer. Chips from the reclaimer are screened and the rejects (primarily dirt in this case) are discarded. Accepted chips are conveyed to Section 200 for milling.

In Section 200, chips are conveyed with chip elevating conveyors to a drag chain conveyor that transport the chips to seven separate mill feed bins. The green wood is then milled in two stages of hammer mills. During milling, fines are removed via an air stream to a cyclonic separator, where the collected fines are fed back into the process by means of a rotary air lock. The transportation air containing volatile organic compounds (VOCs), is ducted to the hot oil system and used as combustion air where VOCs are oxidized. Milled chips are fed to a drag chain conveyor that feeds four separate live bottom bins, each of which feeds one of the four process reactor trains. From the live bottom bin, the milled chips are routed to a dilution conveyor, where they are mixed with the recycled water. Upstream of this point, recycle water is mixed with soda ash in an agitated tank. Downstream of the dilution conveyor, the wood/water feed enters a twin screw feeder that feeds the positive displacement pump used to pressurize the feed to reactor temperatures (>3000 psig).

Due to the high pressures, we determined that a single train would be unfeasible because of the excessively thick walls that the larger diameter piping would require. Hence, four process trains were chosen to both reduce pipe diameter and to provide process redundancy. Section 7.8 discusses the evaluation of other reactor configurations considered.

In addition to feed handling and milling, all cases include a hot oil system (Section 400) to heat the reactor feed. These are all package units, and the number required were varied from case to case to obtain the required duty. Multiple units were employed because it was determined that the maximum capacity available of such package systems is 60-75 MMBTU/hr.

4.2 CASE A: INDIRECT HEATING BY FEED RECYCLE

Section 300 represents the reactor section in all cases. Case A was selected to determine a feasible alternative if high pressure drops and low heat transfer coefficients occur due to the high viscosity of the biomass slurry. In Case A, the biomass in water (15% dry solids) from the feed pump discharge is immediately combined with a recycle stream of pre-heated reactor feed and is then routed through a static mixer. Sufficient recycle is added such that the temperature of the final stream from the static mixer is 250 °C, which is expected to be sufficiently high to avoid viscosity problems. From that point, the stream is cross-exchanged (E-301) with the purge/recycle water and is then heated to a reaction temperature of 350 °C in the final heat exchanger (E-302). After heating, the stream is split into reactor feed and a recycle stream is used for indirect heating. The stream used for indirect heating is routed to knock-out drums to ensure that any vapors produced can disengage before being pumped by the recycle pump.

The reactor feed goes through the reactor and then is routed to a gas knock-out drum to separate the gas produced from the liquid fraction. Then, the liquid is routed to a solids filter to remove char. The solids filter is cleaned by back flushing with recycled water at temperature and pressure to avoid thermal cycling. Downstream of the solids filter, the reactor product is routed to a bio-oil/water separator, where the bio-oil is disengaged from the aqueous phase. Bio-oil is cooled in a heat recovery steam generator producing 150 psig steam, and is let down in pressure and sent for further processing. Recycle water coming from the bio-oil/water separator is cross-exchanged in E-301 with reactor feed and is then cooled in a steam generator E-304 to generate 150 psig steam. The recycle water stream is then let down in pressure across a control valve, and cooled in a purge water cooler (E-305). It is important to note that this cooling water step represents an opportunity for heat integration elsewhere in an integrated facility. Downstream of E-305, the aqueous product is split into recycle water and purge water.

The advantages of Case A are that it reduces concerns about the viscosity of the feed and eliminates the need for double pipe heat exchangers. The disadvantages are that heat integration suffers considerably, the sizes of the exchangers increase, and the potential exists for a superficial increase in residence time at reactor temperatures. A summary of utility requirements for all cases is presented in

Table 1. The electrical load is based on 70% of the installed horsepower. As shown, Case A has the highest natural gas and electrical load of all cases evaluated.

Table 1. Summary of Utilities for Cases Developed

	Case A	Case B	Case B-L	Case D	Case D-L
Natural gas (MMTU/hr)	509	142	123	256	382
Electricity required (kW)	10,600	9,700	9,700	7,700	7,700
150 psig steam produced (MMBTU/hr)	135.3	17.1	0	45.9	0
Cooling water duties — potential for heat integration (MMBTU/hr)	229	31	47	86	255

4.3 CASE B (AND B-L): FULL HEAT INTEGRATION

Case B was selected to understand the potential benefit if full heat integration were achievable, specifically, if a 15 wt% dry solids feed pumped through a series of pre-heaters and heated. The first set of pre-heaters (E-301 and E-302) is composed of double-pipe heat exchangers to try to achieve lower pressure drop on the tube (cold feed side) and avoid potential plugging problems that may be associated with small tubes in a shell and tube heat exchanger. Once the feed temperature is above 200 °C, resulting in reduced viscosity, shell and tube heat exchangers are employed for the final feed/recycle water cross exchange. The final preheater then employs hot oil (E-304) to bring the feed to reaction temperature.

The feed is then routed through the reactor system to knock-out drums to disengage the vapor from the liquid. The liquid is filtered through a solids filter (F-301), followed by bio-oil/aqueous phase separation in the bio-oil/water separator (C-301). As with Case A, bio-oil is cooled via steam generation and is let down for further processing. The recycle water is routed back through the heat integration section before being cooled to 80 °C prior to being split into purge and recycle water streams.

As shown in Table 1, Case B has an intermediate electrical requirement and one of the lowest natural gas requirements of the cases examined, making it attractive from an operating cost perspective. However, this case is likely unfeasible due to high pressure drop and operating problems associated with high feed viscosity.

Case B-L is an alternative to Case B, wherein the bio-oil/water separator is operated at low temperature (80 °C) to ensure that sufficient density difference exists between the bio-oil and water phases for successful separation. The only additional piece of equipment in Case B-L is a small filter purge heater required to prevent thermal cycling in F-301.

As shown in Table 1, Case B-L shows an intermediate electrical requirement and the lowest natural gas requirements. This is due to the fact that heat is recovered in the heat integration section from both the bio-oil and the aqueous phase, whereas only the aqueous phase is used for heat recovery in Case B. The additional heat recovery is only advantageous to the extent that the bio-oil does not need to be re-heated for further processing. In Case B, the bio-oil was kept at relatively high temperature to relieve heat duties during downstream processing.

4.4 CASE D (AND D-L): RECYCLE WATER MIXING AT HIGH PRESSURE

Given the enormous natural gas load required for Case A and the potential operating problems with Case B, Case D was developed to explore the potential benefit of being able to pump a higher dry solids content to the reactor section. This case may be able to utilize half as many high-pressure feed pumps, thereby reducing both capital and operating costs.

In Case D, the feed is pumped as 36.6 wt% dry solids and is immediately mixed with recycle water at reactor outlet temperatures. This is followed by mixing in a static mixer to achieve an outlet temperature of over 250 °C. Subsequently, heat recovery with the purge/recycle water stream is performed in E-301, followed by final heating in E-302 with hot oil as the heating medium. The feed then proceeds through the reactor (R-301), knock out drums (V-301), solids filter (F-301), and bio-oil/water separator (C-301) as in the previous cases. Bio-oil is again cooled and the pressure is let down for further processing. The aqueous phase from the bio-oil/water separator is routed to the recycle pump (P-301), except for the portion routed to recycle/purge. The purge stream goes to a waste heat boiler (E-304) to generate steam and is cooled using a purge water cooler (E-305) prior to recycle or purging.

As shown in Table 1, the natural gas loadings for Case D are about half that of Case A but are still significantly higher than Case B. As such, the heat integration for Case D is better than A. Another advantage over Case A is that the centrifugal recycle pump does not need to accommodate solids. Relative to Case B, Case D avoids the operation problems associated with high viscosity and avoids the need for the very expensive double-pipe heat exchangers. The primary risk associated with Case D is that it may not be possible to pump 36.6 wt% dry solids. Though testing will be necessary to determine the feasibility, in conversations with vendors, Harris Group was led to believe that it was possible.

Case D-L is an analogue to Case D, except that the bio-oil/aqueous phase separation occurs at low temperature. In terms of process flow, the primary difference is that a series of heat exchangers, i.e., E-302, E-303, E-304, downstream of the solids filter, is used for heat integration. Essentially, the bio-oil/water separator feed must be cooled to 80 °C, and this is done while heating the aqueous phase from the bio-oil/water separator for use as the feed indirect heating medium. In contrast to Case B-L, here the bio-oil is heated prior to further processing to recover some heat from the bio-oil/water feed stream. After heat recovery, the water recycle stream is routed to the recycle pump (P-301), followed by heating to 350 °C in a recycle heater (E-305), also employing hot oil as the heating medium.

As shown in Table 1, the total natural gas requirement for Case D-L is much higher than that for Case D. This is primarily due to the need for cooling the recycle water stream prior to bio-oil/aqueous phase separation, which eliminates the benefit of a direct recycle in Case D.

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 5
COST ESTIMATES

5.1 APPROACH

The ultimate purpose for developing the process design provided was to develop capital cost estimates associated with HTL. We also provided operating cost estimates. This subsection details our approach in developing these estimates; the estimates themselves are provided in subsequent subsections.

We obtained pricing for individual pieces of equipment from vendor quotes and from the Harris Group database, based on the designs presented in previously. It is important to note that for the reactor system and many of the heat exchangers, we obtained quotes for a piece of equipment of a certain size, e.g., a heat exchanger with an area of 1500 ft^2, and it was assumed that multiple units would be used where required by heat transfer demands or poor heat transfer coefficients. Furthermore, given the high operating pressures, Harris Group expected that multiple smaller units would be less expensive than single, large units, which was confirmed by vendors. This is largely due to the increase in wall thickness required for large diameter vessels and exchangers with a design pressure of 3,500 psig.

Much of the equipment pricing obtained occurred in late 2012 and early 2013. However, to be consistent with NREL's direction, capital cost numbers were adjusted to 2011 dollars to permit direct comparison with other projects and options. Capital costs provided by Harris Group were adjusted using the Plant Cost Index from *Chemical Engineering Magazine*[6] to a common basis year of 2011 (a value of 585.7). The final cost index for a given year is generally not made until the spring of the following year. Therefore, for the equipment quoted in late 2012 and early 2013, the Plant Cost Index from October 2012 was used (a value of 575.4). The general formulation for year-dollar adjustments is:

$$2011\ Cost \quad Base\ Cost \quad \frac{2011\ Cost\ Index}{Base\ Year\ Index}$$

6 Chemical Engineering Magazine Plant Cost Index. *Chemical Engineering Magazine*. http://www.che.com/pci/ .

A priced equipment list for each case is provided in Appendix C. In cases where changes in capacity were considered, the equipment size may be different than that originally quoted or designed. Instead of re-costing in detail, an exponential scaling method was utilized:

$$New\ Cost \quad Base\ Cost \quad \frac{New\ Size}{Base\ Size}$$

Here, n is a characteristic scaling exponent based on some characteristic of the equipment related to production capacity such as flow rate or heat duty. To be consistent with previous work Harris Group has performed for NREL,[7] we utilized exponents proposed in the 1994 Chem Systems Report on biomass production from ethanol, provided in Table 5-1.

Table 5-1. Scaling Exponents

Item	Exponent
Agitators	0.5
Compressors, motor driven	0.6
Heat exchangers	0.7
Inline mixers	0.5
Package quotes/skidded equipment	0.6
Pressure vessels	0.7
Pumps	0.8
Tanks, atmospheric	0.7
Solids handling equipment	0.8

In some cases, quotes were provided for metallurgies other than 316L. For example, quotes provided by some vendors were for 304 stainless steel, rather than 316L. In these cases, an appropriate factor was assumed to account for the cost difference, for example, 316L is approximately 33% more expensive than 304, based on vendor information received by Harris Group, but the overall difference is approximately 14%, so the quotes were adjusted accordingly.

While we could choose from a variety of ways of determining total capital cost from a priced equipment list, we chose a factored approach here, wherein multipliers are applied to the purchased equipment cost to determine the installed cost. This choice, and the method itself, were selected to be consistent with previous work that Harris Group has done for NREL.[8] These factors are largely based on the work of

7 D. Humbird et al., "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol," May 2011, TP-5100-47764.

8 D. Humbird et al., "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol," May 2011, TP-5100-47764.

Cran,[9] with the exception that instrumentation costs were excluded in this method. As such, a factor of 0.30 cost was added to the Cran factors, which is consistent with the 30% estimate for instrumentation given by Peters and Timmerhaus.[10] The installation factors used herein are provided in Table 5-2 below. A complete listing of equipment, along with its purchased and installed cost is provided in Appendix C.

Table 5-2. Installation Factors

Item	**Multiplier**[a]
Agitators, stainless steel	1.5
Boiler	1.8
Compressors, motor driven	1.6
Heat exchangers, shell and tube, stainless steel	2.2
Heat exchangers, double pipe, stainless steel	2.2
Inline mixers	1.0
Skidded equipment	1.8
Solids handling equipment (including filters)	1.7
Pressure vessels, stainless steel	2.0
Pumps, stainless steel	2.3
Tanks, field erected stainless steel	1.5

[a] Installed cost = (purchased equipment cost) x (multiplier).

Once the total equipment cost was determined for the year of interest, several other direct and indirect costs were added to determine the total capital investment (TCI). Site development and warehouse costs were based on inside-battery-limits (ISBL) equipment costs and were considered part of the total direct cost (TDC). Project contingency, field expenses, home-office engineering and construction activities, and other costs related to construction were computed relative to the TDC and give the fixed capital investment (FCI) when summed. The sum of FCI and the working capital for the project is the TCI. Table 5-3 summarizes these categories and factors, which were chosen to be the same as those previously used by Harris Group for work done for NREL.

9 Cran, J., "Improved factored method gives better preliminary cost estimates." Chemical Engineering, April 6, 1981; pp. 65-79.

10 Peters, M.S.; Timmerhaus, K.D., Plant Design and Economics for Chemical Engineers. 5th Ed., New York: McGraw-Hill, 2003.

Table 5-3. Additional Costs for Determining Total Capital Investment

Item	Description	Amount
Additional Direct Costs		
Warehouse	On-site storage of equipment and supplies	4% of installed equipment cost
Site development	Fencing, curbing, parking lot, roads, drainage, general paving. This allows for minimum site development assuming a clear site with no unusual problems.	9% of ISBL
Additional piping	To connect ISBL equipment to storage and utilities	4.5% of ISBL
Indirect Costs		
Proratable expenses	This includes fringe benefits, burdens, and insurance of the construction contractor	10% of total direct cost (TDC)
Field expenses	Consumables, small tool and equipment rental, field services, temporary construction facilities, and field construction supervision	10% of TDC
Home office and construction	Engineering plus incidentals, purchasing, and construction	20% of TDC
Project contingency	Extra cash on hand for unforeseen issues during construction	10% of TDC
Other costs	Start-up, commissioning costs. Land, rights of way, permits, and fees. Piling, soil compaction, unusual foundations. Sales, use, and other taxes. Freight, insurance in transit, and import duties on equipment. Overtime pay during construction. Field insurance. Project team. Transportation equipment, bulk shipping containers, plant vehicles, etc.	10% of TDC

5.2 CAPITAL COST ESTIMATES

As previously mentioned, Harris Group evaluated five reactor cases including three primary configurations for the reactor section, and two additional cases wherein the product separation occurs at temperatures below the reaction temperature. We obtained heat exchanger quotes for fixed sizes, and we used multiples of these units in developing the cost estimates. For example, we obtained a quote for the reactor feed/hot oil exchanger having an area of 4500 ft^2; then, if the required area was, say, 9000 ft^2, we included two of these units. Similarly, for the reactor section, we obtained a price for 480 feet of eight-inch XXH pipe with 40-foot sections and hairpin turns. Then, we used multiples of this cost until the required reactor volume was obtained. The cases presented here assume a LHSV of 4L/L/h for the reactor, with a total of eight parallel reactor trains, providing a pressure drop of less than 25 psig (see Appendix A PFDs). A sensitivity study related to LHSV is presented in

Section 6 of the report. We based most costs included here on 316L metallurgy. We discuss use of 409 in lieu of 316L in Section 7 of this report.

Harris Group did not include spare equipment in the estimated costs given herein. This is primarily due to the way we have laid out the design of the reactor system with four parallel trains. The critical pieces of equipment most likely to be subject to downtime are the mills, the biomass feed pumps, and the recycle pumps. Given that none of these pieces of equipment is stand-alone (i.e., there are many units in parallel), inherent protection against occasional mechanical failure is achieved in the existing design. For example, if a mill goes down, only $^1/_7$ of the capacity is temporarily lost. Similarly, if a biomass feed pump goes down, $^1/_{12}$ of the capacity is lost, while ¼ of the capacity is lost if a recycle pump (Cases A and D) goes down. However, the recycle pumps are specified to be canned motor pumps, which are highly reliable and have excellent on-line monitoring systems, so that problems can be detected long before an outage occurs. Furthermore, use of installed spares in systems transporting solids can create additional problems in that plugging is likely to occur in piping dead legs, due to the accumulation of solids. Given this, Harris Group does not believe installed spares provide significantly increased plant availability.

The heat exchangers were very expensive due to the high design pressures required. Many of the vendors Harris Group contacted to provide quotes for these exchangers declined due to the required design pressures above 3000 psig. Furthermore, for many heat exchanger fabricators, they are only ASTM-certified to fabricate exchangers or vessels up to design pressures of 3000 psig, and, beyond this value, they would need to be qualified for a different stamp. As such, we found that the number of shops that can do this work is relatively small, which may also contribute to increased cost.

The capital costs for Case A, which included indirect heating with an internal recycle stream prior to the reactor, is provided in Table 5-4. As shown, the total purchased equipment cost in 2011 dollars is $97 million, with a total installed cost of $195 million. The bulk of the cost is in Area 300. Heat exchangers account for about half of the purchased equipment cost in Area 300, while the reactor (LHSV = 4) accounts for about 34% of the purchased equipment cost. Priced equipment lists for the various case are provided in Appendix C.

Table 5-4. Capital Costs Associated with Case A (2011 Dollars)

Process Area					
			Purchased Cost		Installed Cost
Area 100: FEED HANDLING			$ 6,656,000		$ 11,315,000
Area 200: FEED PREPARATION			$ 8,007,000		$ 16,207,000
Area 300: HTL REACTION SECTION			$ 70,018,000		$ 147,155,000
Area 400: HOT OIL SYSTEM			$ 12,264,000		$ 20,364,000
		Totals:	$ 96,945,000		$ 195,041,000
Warehouse		4%	of ISBL		$ 7,349,000
Site Development		9%	of ISBL		$ 16,535,000
Additional Piping		4.50%	of ISBL		$ 8,268,000
Total Direct Costs (TDC)					$ 227,193,000
Indirect Costs					
Proratable expenses		10%	of TDC		$ 22,719,000
Field Expenses		10%	of TDC		$ 22,719,000
Home office and Constr. Feed		20%	of TDC		$ 45,439,000
Project Contingency		10%	of TDC		$ 22,719,000
Other costs (start-up, permits, etc.)		10%	of TDC		$ 22,719,000
TOTAL INDIRECT COSTS					$ 136,315,000
FIXED CAPITAL INVESTMENT (FCI)					$ 363,508,000
Working Capital		5%	of FCI		$ 18,175,000
TOTAL CAPITAL INVESTMENT (TCI)					**$ 381,683,000**
		Estimate Range			
		Upper Limit (+40%)		**Lower Limit (-30%)**	
Total Project Cost:		**$ 534,356,000**		**$ 267,178,000**	

Capital costs associated with Cases B and B-L are provided in Tables 5-5 and 5-6, respectively. As shown in Table 5-5, the purchased equipment cost of Area 300 for Case B is $386 million, while the installed cost is $837 million. The vast majority of this cost is due to Area 300, and, more specifically, to the heat exchanger costs, which account for 90% of the purchased equipment cost. The reason for this is the low heat transfer coefficient (see Section 3) of 14 BTU/hr/ft^2/°F, due to high viscosities, which results in needing an exorbitant area for heat exchange. Furthermore, it is important to note that pressure drop estimates provided in the process flow diagrams of Cases B and B-L did not account for these high viscosities, which would certainly make these cases unfeasible due to the extreme pressure drop required through the many double pipe heat exchangers. A sensitivity study is provided in Section 6 of the report that provides an evaluation of the difference in cost if a more reasonable heat transfer coefficient could be obtained for Case B.

Table 5-5. Capital Costs Associated with Case B (2011 Dollars)

Process Area				
		Purchased Cost		Installed Cost
Area 100: FEED HANDLING		$ 6,656,000		$ 11,315,000
Area 200: FEED PREPARATION		$ 8,007,000		$ 16,207,000
Area 300: HTL REACTION SECTION		$ 367,940,000		$ 803,650,000
Area 400: HOT OIL SYSTEM		$ 3,492,000		$ 5,659,000
	Totals:	$ 386,095,000		$ 836,831,000
Warehouse	4%	of ISBL		$ 33,021,000
Site Development	9%	of ISBL		$ 74,296,000
Additional Piping	4.50%	of ISBL		$ 37,148,000
Total Direct Costs (TDC)				$ 981,296,000
Indirect Costs				
Proratable expenses	10%	of TDC		$ 98,130,000
Field Expenses	10%	of TDC		$ 98,130,000
Home office and Constr. Feed	20%	of TDC		$ 196,259,000
Project Contingency	10%	of TDC		$ 98,130,000
Other costs (start-up, permits, etc.)	10%	of TDC		$ 98,130,000
TOTAL INDIRECT COSTS				$ 588,779,000
FIXED CAPITAL INVESTMENT (FCI)				$ 1,570,075,000
Working Capital	5%	of FCI		$ 78,504,000
TOTAL CAPITAL INVESTMENT (TCI)				**$ 1,648,579,000**
		Estimate Range		
		Upper Limit (+40%)		**Lower Limit (-30%)**
Total Project Cost:		**$ 2,308,011,000**		**$ 1,154,005,000**

As shown in Table 5-6, the capital costs associated with Case B-L, where the bio-oil/water separator is located downstream of the heat integration, are very similar to those of Case B. Again, the primary reason for this high capital cost is that the heat exchanger costs are extremely high due to the low heat transfer coefficient.

Table 5-6. Capital Costs Associated with Case B-L (2011 Dollars)

Process Area					
			Purchased Cost		Installed Cost
Area 100: FEED HANDLING			$ 6,656,000		$ 11,315,000
Area 200: FEED PREPARATION			$ 8,028,000		$ 16,239,000
Area 300: HTL REACTION SECTION			$ 386,407,000		$ 844,277,000
Area 400: HOT OIL SYSTEM			$ 3,240,000		$ 5,206,000
	Totals:		$ 404,331,000		$ 877,037,000
Warehouse	4%	of ISBL			$ 34,629,000
Site Development	9%	of ISBL			$ 77,915,000
Additional Piping	4.50%	of ISBL			$ 38,957,000
Total Direct Costs (TDC)					$ 1,028,538,000
Indirect Costs					
Proratable expenses	10%	of TDC			$ 102,854,000
Field Expenses	10%	of TDC			$ 102,854,000
Home office and Constr. Feed	20%	of TDC			$ 205,708,000
Project Contingency	10%	of TDC			$ 102,854,000
Other costs (start-up, permits, etc.)	10%	of TDC			$ 102,854,000
TOTAL INDIRECT COSTS					$ 617,124,000
FIXED CAPITAL INVESTMENT (FCI)					$ 1,645,662,000
Working Capital	5%	of FCI			$ 82,283,000
TOTAL CAPITAL INVESTMENT (TCI)					**$ 1,727,945,000**
			Estimate Range		
			Upper Limit (+40%)		**Lower Limit (-30%)**
Total Project Cost:			**$ 2,419,123,000**		**$ 1,209,562,000**

Capital costs associated with Cases D and D-L are provided in Tables 5-7 and 5-8. As shown in Table 5-7, the purchased equipment cost is $61 million, while the installed equipment cost is $120 million, by far the lowest of the cases. Here, the bulk of the purchased equipment cost is in the reactor itself, which accounts for about 40% of the purchased cost of Area 300, while heat exchangers account for 30% of the purchased cost in this case. Part of the reason for the relatively low cost is that heat exchange occurs at higher temperatures where the reactor feed is expected to have a reasonable viscosity and, therefore, reasonable heat transfer coefficients (see Section 3). Further, the indirect heating due to the direct recycle of the product water at reactor temperatures eliminates the need for many heat exchangers, dramatically reducing cost. In addition, since the feed is being introduced at a high dry solids content (36.6 wt%), fewer positive displacement pumps are required since there is much less recycle water going to the feed pumps.

Table 5-7. Capital Costs Associated with Case D (2011 Dollars)

Process Area				
		Purchased Cost		Installed Cost
Area 100: FEED HANDLING		$ 6,656,000		$ 11,315,000
Area 200: FEED PREPARATION		$ 5,819,000		$ 11,174,000
Area 300: HTL REACTION SECTION		$ 42,183,000		$ 86,990,000
Area 400: HOT OIL SYSTEM		$ 6,236,000		$ 10,302,000
	Totals:	$ 60,894,000		$ 119,781,000
Warehouse	4%	of ISBL		$ 4,339,000
Site Development	9%	of ISBL		$ 9,762,000
Additional Piping	4.50%	of ISBL		$ 4,881,000
Total Direct Costs (TDC)				$ 138,763,000
Indirect Costs				
Proratable expenses	10%	of TDC		$ 13,876,000
Field Expenses	10%	of TDC		$ 13,876,000
Home office and Constr. Feed	20%	of TDC		$ 27,753,000
Project Contingency	10%	of TDC		$ 13,876,000
Other costs (start-up, permits, etc.)	10%	of TDC		$ 13,876,000
TOTAL INDIRECT COSTS				$ 83,257,000
FIXED CAPITAL INVESTMENT (FCI)				$ 222,020,000
Working Capital	5% of FCI			$ 11,101,000
TOTAL CAPITAL INVESTMENT (TCI)				**$ 233,121,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 326,369,000**	**$ 163,185,000**

As shown in Table 5-8, the purchased equipment cost for Case D-L is $87 million, while the installed equipment cost is $176 million, the second lowest of the cases. In contrast to Case D, the bulk of the purchased equipment cost in Area 300 is in the heat exchangers, accounting for 57% of the purchased equipment cost, while the reactors account for approximately 27%. Part of the reason for this is that the bio-oil/water separator feed must be cooled, and additional heat exchangers are required to try to recapture some of the energy lost during the cooling step. Also, an additional heater is required to bring the recycle stream up to process temperature prior to indirect heating, which also adds to the expense.

Table 5-8. Capital Costs Associated with Case D-L (2011 Dollars)

Process Area				
		Purchased Cost		Installed Cost
Area 100: FEED HANDLING		$ 6,427,000		$ 11,315,000
Area 200: FEED PREPARATION		$ 5,819,000		$ 11,174,000
Area 300: HTL REACTION SECTION		$ 65,858,000		$ 138,905,000
Area 400: HOT OIL SYSTEM		$ 8,897,000		$ 14,599,000
	Totals:	$ 87,001,000		$ 175,993,000
Warehouse	4%	of ISBL		$ 6,587,000
Site Development	9%	of ISBL		$ 14,821,000
Additional Piping	4.50%	of ISBL		$ 7,411,000
Total Direct Costs (TDC)				$ 204,812,000
Indirect Costs				
Proratable expenses	10%	of TDC		$ 20,481,000
Field Expenses	10%	of TDC		$ 20,481,000
Home office and Constr. Feed	20%	of TDC		$ 40,962,000
Project Contingency	10%	of TDC		$ 20,481,000
Other costs (start-up, permits, etc.)	10%	of TDC		$ 20,481,000
TOTAL INDIRECT COSTS				$ 122,886,000
FIXED CAPITAL INVESTMENT (FCI)				$ 327,698,000
Working Capital	5%	of FCI		$ 16,385,000
TOTAL CAPITAL INVESTMENT (TCI)				**$ 344,083,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 481,716,000**	**$ 240,858,000**

5.3 OPERATING COST ESTIMATES

Variable operating costs in these designs include chemicals and utility usage, and these are provided for all cases in Table 5-9, based on 7,884 operating hours per year. The only chemical consumed in the process is soda ash. Pricing for soda ash was obtained from data from the United States Geological Survey[11], and was $260-$285/short ton from 2008 to 2012. As such, a value of $280/short ton was taken for this study. According to guidance provided by NREL, electricity cost was assumed to be $0.06695/kWh, while natural gas costs were $0.0932/lb, or approximately $4.25/MMBTU. Apart from steam and natural gas usage, several cases presented here produce significant amounts of 150 psig steam for heat recovery. The total quantity of steam produced is provided in Table 5-9 for information and to illustrate the opportunities available for heat integration with other processing areas of the biofuel liquefaction facility. Since cooling water supply was outside the scope of

11 Kostick, Dennis, Soda Ash Mineral Commodity Summary, http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/ .

Harris Group's work, the total usage, assuming a 15 °F temperature increase, is provided for information.

Looking at the various cases, Cases B and B-L require the lowest utility costs due to the high degree of heat integration. However, Case D also shows reasonable utility costs due to the indirect heating and because fewer pumps are required. Cases A and D-L suffer from poor heat integration, resulting in high operating costs. This is evidenced by the higher cooling water flow rate requirements. In the context of an integrated facility, however, these energy losses may be recoverable by heat integration with external units, but that work is beyond the scope of this project.

Table 5-9. Operating Costs Associated with All Cases (2011 Dollars)

	Case A	Case B	Case B-L	Case D	Case D-L
Natural Gas Demand (MMBTU/hr)	509.0	142.4	123.0	256.2	382.0
Natural Gas Cost ($/MMBTU)	$4.25	$4.25	$4.25	$4.25	$4.25
Annual Natural Gas Cost	$17,054,000	$4,773,000	$4,122,000	$8,583,000	$12,800,000
Electrical Load (kW)	10,555	9,668	9,668	7,736	7,997
Electrical cost ($/kWh)	$ 0.06695	$ 0.06695	$ 0.06695	$ 0.06695	$ 0.06695
Annual Electricity Cost	$ 5,571,000	$ 5,103,000	$ 5,103,000	$ 4,084,000	$ 4,221,000
Soda Ash Requirement (lb/hr)	2806	2806	2806	2821	2821
Soda Ash Cost ($/short ton)	$ 280.00	$ 280.00	$ 280.00	$ 280.00	$ 280.00
Annual Soda Ash Cost	$ 3,097,000	$ 3,097,000	$ 3,097,000	$ 3,114,000	$ 3,114,000
Total Cost of Chemicals and Utilities ($/year)	$ 25,722,000	$ 12,973,000	$ 12,322,000	$ 15,781,000	$20,135,000
Quantity of 150psig steam produced (MMlb/year)	1244	157	0	422	0
Cooling Water Flow Required (MMgal/year)	14442	1927	2953	5423	15727
Labor Cost ($/yr)	$ 2,249,000	$ 2,249,000	$ 2,249,000	$ 2,249,000	$ 2,249,000
Maintenance ($/yr) (3% of ISBL)	$ 5,512,000	$ 25,853,000	$ 26,311,000	$ 3,593,000	$ 5,280,000
Property Insurance ($/yr) (0.7% of ISBL)	$ 1,286,000	$ 6,032,000	$ 6,139,000	$ 838,000	$ 1,232,000
TOTAL OPERATING COST ($/yr)	$ 34,769,000	$ 47,107,000	$ 47,021,000	$ 22,461,000	$28,896,000

Fixed operating costs include employee salaries, maintenance, and property insurance. Employee salaries were obtained in 2007 dollars from those used in a previous NREL report,[12] and these were escalated to 2011 dollars assuming a 3% inflation rate. The number of employees was estimated by considering the likely degree of automation for each area and adding a reasonable number of management and support employees.

Overall, Case D has the lowest total operating cost, at $23 million per year due to relatively low utility costs and low maintenance costs, due to the relatively low ISBL

12 D. Humbird et al., "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol," May 2011, TP-5100-47764.

capital cost. Cases D-L and A represent the next lowest operating costs at $30 million per year and $36 million per year, respectively. Cases B and B-L have the highest operating cost due to the maintenance costs, which are influenced by the high capital costs.

5.4 COMPARISON OF COST ESTIMATES

A comparison of the cost estimates is provided in Table 5-10. As shown, Case D is clearly the least expensive option in terms of both operating cost and total capital investment. Case D-L is the second most favorable option but has both higher capital and higher operating costs than Case D. Case A is the third most attractive option in terms of capital cost and operating expenses. Cases B and B-L are far too costly in terms of capital to be considered as potential cases.

Table 5-10. Operating Costs Associated with All Cases (2011 Dollars)

	Case A	Case B	Case B-L	Case D	Case D-L
Purchased Equipment Cost ($MM)	$ 97	$ 386	$ 404	$ 61	$ 87
Installed Equipment Cost ($MM)	$ 195	$ 837	$ 877	$ 120	$ 176
Total Direct Costs ($MM)	$ 227	$ 981	$ 1,029	$ 139	$ 205
Total Indirect Costs ($MM)	$ 136	$ 589	$ 617	$ 83	$ 123
Fixed Capital Investment ($MM)	$ 364	$ 1,570	$ 1,646	$ 222	$ 328
Working Capital ($MM)	$ 18	$ 79	$ 82	$ 11	$ 16
Total Capital Investment ($MM)	$ 382	$ 1,649	$ 1,728	$ 233	$ 344
TOTAL OPERATING COST ($MM/yr)	$ 35	$ 47	$ 47	$ 22	$ 29

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 6
SENSITIVITY STUDIES

6.1 OVERVIEW

As part of Harris Group's study, we looked at a few sensitivity studies, including the effect of LHSV, pump selection and heat transfer coefficient.

6.2 LIQUID HOURLY SPACE VELOCITY

The LHSV chosen has an impact strictly on the size of the reactor for any given case. Since reactor feed rates and compositions are essentially identical in all cases, we selected Case D to determine how this change influences the capital cost. According to information provided by NREL, the LHSV should be in the range of 2 to 8 L/L/h. For all design cases previously discussed, a base LHSV value of 4 was used for convenience. Given that the quotes obtained for the reactor itself were based on prefabricated piping, Harris Group scaled these appropriately and found that the equipment cost for an LHSV of 2 was $36.3 million, while that for an LHSV of 8 was $4.5 million, corresponding to 16 and 4 reactors in parallel, respectively. These compare directly to that of the base case (4) of $18.2 million, with 8 parallel reactors. All cases After scaling these and accounting for changes in direct and indirect costs, the total capital investment for Case D changed from $307 million to $233 million to $182 million, moving from 2 to 4 to 8 L/L/h LHSV, respectively. So, increasing the allowable LHSV is very important from the perspective of trying to minimize required capital cost. A summary of the results is provided in Table 6-1 below.

Table 6-1. Effect of LHSV on Capital Cost

LHSV (L/L/h)	2	4	8
Number of reactors in parallel	16	8	4
Calculated pressure drop (psig)	3	15	45
Equipment cost ($ millions)	$36.3	$18.2	$4.5
Total capital investment ($ millions)	$307	$233	$182

6.3 PUMP SELECTION

Prior to Harris Group's involvement with the project, an excellent pumpability assessment was performed by PNNL's Eric Berglin. Mr. Berglin had contacted six potential candidate vendors and obtained quotes for pumping 15 wt% dry solids. Harris Group reviewed the assessment and concurred with the subjective rankings of the various vendors. Furthermore, we contacted the top two vendors, referred to here as Vendor A and Vendor B, to obtain revised quotes based on metallurgy changes. The quote from Vendor B changed dramatically from $9.6 million to $12.5 million from the quotes that Eric Berlin obtained, primarily due to the metallurgy change. In contrast, Vendor A indicated that its cost would increase only by 5% or so due to the fact that its pump internals should be able to handle the process conditions. The cost differences between Vendor A and Vendor B pumps are provided below in Table 6-2. It should be pointed out that the Vendor B pumps would require about 1,150 HP less installed horsepower for Cases A, B, and B-L, and about 575 HP less installed horsepower for cases D and D-L than for the Vendor A pumps.[13]

Table 6-2. Changes in Cost Employing Vendor B Rather than Vendor A Pumps

Cases	Difference in Equipment Cost ($ millions)	Difference in Installed Cost ($ millions)	Difference in Total Capital Investment ($ millions)
Cases A, B, B-L	$8.5	$19.5	$38.5
Cases D, D-L	$3.8	$9.0	$17.8

6.4 HEAT TRANSFER COEFFICIENT

As previously discussed, the assumption made with respect to the heat transfer coefficient is important in determining total cost. In order to get a feel for the magnitude of this impact, we conducted several sensitivity tests. Table 6-3 provides the minimum, base, and maximum possible heat transfer coefficients, as described in Section 3 of the report. For the purpose of the sensitivity study, we investigated Cases A, B, and D for each of the three sets of heat transfer coefficients. In addition, we also performed a sensitivity study around Case B with low viscosity, i.e., water-like, to determine the influence of viscosity on overall cost.

13 Berglin EJ, CW Enderlin, and AJ Schmidt. November 2012. "Review and Assessment of Commercial Vendors/ Options for Feeding and Pumping Biomass Slurries for Hydrothermal Liquefaction." PNNL-21981, Pacific Northwest National Laboratory, Richland, WA.

Table 6-3. Heat Transfer Coefficient Results

	Minimum U (BTU/hr/ft^2/˚F)	Base U (BTU/hr/ft^2/˚F)	Maximum U (BTU/hr/ft^2/˚F)
Case B: Preheater, low viscosity (water)	20	144	380
Case B: Preheater, high viscosity (1000 cP)	3	14	15
Reactor feed/water product cross-exchanger	25	170	443
Reactor feed/hot oil exchanger	40	154	446

Results of the estimated TCI are provided in Table 6-4 below. As shown, the minimum, or worst-case, heat transfer coefficients all significantly increase the area required for heat transfer and thereby increase the overall capital cost substantially. On the other hand, optimistic expectations for the heat transfer coefficients decrease the overall TCI, but generally only on the order of $50 million or so. This sensitivity study serves to show that experimental determination of the expected heat transfer coefficient is critical to appropriately estimating expected capital costs.

Table 6-4. TCI (2011 Million Dollars) for Various Sets of Heat Transfer Coefficients

	Minimum U	Base U	Maximum U
Case A	$1,002	$382	$321
Case B, high viscosity	$7,363	$1,649	$1,608
Case B, low viscosity	$1,703	$395	$267
Case D	$464	$233	$202

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 7
PROCESS OPTIONS INVESTIGATED

7.1 OVERVIEW

As part of the evaluation of the reactor section, Harris Group evaluated various options associated with the process design. These included: (1) the inclusion of a continuously stirred tank reactor (CSTR) in the reactor design upstream of the plug flow reactor, (2) the inclusion of a let-down turbine to achieve energy recovery, (3) using 409 stainless steel rather than 316L stainless steel, (4) evaluation of using a molten salt heating medium rather than heating oil, (5) evaluation of a jacketed plug flow reactor, (6) evaluation of Case D with all indirect heating, and (6) evaluation of alternate reactor configurations. These cases are described in detail below along with conclusions reached by Harris Group regarding the options.

7.2 INCLUSION OF CSTR IN REACTOR DESIGN: CASE C

As previously mentioned, five reactor cases include three primary configurations for the reactor section, and two additional cases wherein the product separation occurs at temperatures below the reaction temperature were evaluated. An additional case, Case C, which included a CSTR upstream of the plug flow reactor, was initially included in the preliminary evaluation. However, this case was deemed by Harris Group to be infeasible for several reasons. Preliminary sizing of a CSTR to handle the total flow resulted in a vessel that was about 10 feet in diameter and 40 feet tall. Given the design pressure of 3,500 psig, the thickness of the vessel would be in excess of 11 inches and would require that the vessel be forged, thus making it very expensive. Further, none of the vendors that Harris Group contacted would quote such a vessel. Secondly, the high pressure would make it extremely difficult to operate a vessel with an external agitator drive, given that the seals would have to resist the high pressure. Finally, based on conversations with personnel at PNNL and NREL, the primary reason for including the CSTR is plugging issues that currently occur on the bench-scale unit; specifically, the plugging of the CSTR outlet line in the current configuration. We believe that the larger piping sizes associated with commercial-scale process designs will prevent this problem. Therefore, we did not pursue this case for costing or further development.

7.3 ENERGY RECOVERY USING LET-DOWN PUMP TURBINE

Most cases that we evaluated required pressure let-down of recycle water or purge water from approximately 3,000 psig to near ambient pressure. Obviously, it would be beneficial to recover the energy associated with this let-down, if possible. Harris Group evaluated the use of a pump turbine, a pump that runs backwards where the shaft is connected to a generator, for this application. Harris Group contacted several vendors to evaluate this option and found that, to let down 390,000 lb/hr (the recycle stream in Case D), the equipment cost would be $1.1 million, with an installed cost close to $3.3 million to recover approximately 1,550 kW. Assuming an on-stream factor of 90%, this would be about 12.2 million kWh per year. Assuming an electricity cost of $0.06695/kWh, this would result in a savings of only about $820,000 per year with a payout of approximately four years. This was deemed to be too low to include in the base design, but the information is provided here for reference.

7.4 USE OF 409 STAINLESS STEEL RATHER THAN 316L

During the course of the project, the metallurgy testing required in the reaction section was ongoing. We found early in the testing that either 316L or 409 stainless steel would be acceptable alternatives, but we wanted to understand the expected difference in cost. These grades of stainless steel are quite different, with significant differences in manganese, chromium, nickel, molybdenum, and titanium content, as shown in Table 7-1 below.

Table 7-1. Exotic Metal Content of 316L and 409 Stainless Steels

	316L	**409**
Manganese	2 wt %	1 wt %
Chromium	17 wt %	11 wt %
Nickel	12 wt%	0.5 wt %
Molybdenum	2.5 wt %	0 wt %
Titanium	0 wt %	0.25 wt %

Inquiries to vendors related to material cost yielded a 316L to 409 cost ratio from 1.38 to 1.67 (an average of approximately 1.5), which is not surprising, given the higher exotic metal content in 316L. In this case, the designs will be determined by the minimum yield strengths for the design temperature region of interest (800 °F). These values are approximately 17.7ksi for 316L and 13.3ksi for 409. Since the thickness required is related to yield strength, the relative thickness required for 409 versus 316L is 1.33. That is, approximately 33% more metal would be required for 409 relative to 316L. Combining the cost and difference in required metal, i.e., 1.5 divided by 1.33, 316L should be approximately 13% more expensive than a comparable unit made from 409. This does not, however, account for the fact that 409 is not as common as 316L. Several metal vendors that Harris Group contacted either did not stock 409 or stocked it as a specialty item. Given that a very large amount of material would be required for any of the proposed reactor systems, it may be difficult to obtain a sufficient supply of 409, or a price premium may apply, thus negating any cost advantage associated with the use of 409. Furthermore, the additional mass required for the 409 would also require more robust foundations and support structures. As such, there is likely no cost advantage to using 409 as opposed to 316L.

7.5 EVALUATION OF USING MOLTEN SALT SYSTEM FOR HEATING MEDIUM

Due to the high temperatures required in the reactor that approach the critical temperature of water, it would be preferable to use a heating medium other than steam. Hence, Harris Group obtained pricing for a molten salt system to compare with a more conventional hot oil system employing. The quote for the system shows that a 60 MMBTU/hr system is approximately $4 million for equipment. Quotes for a comparable hot oil system were $1.2 million, making hot oil a much more attractive alternative.

7.6 EVALUATION OF JACKETED PLUG-FLOW REACTOR

During the initial stages of the projects, NREL expressed interest in having a plug flow reactor jacketed with a heating fluid. Essentially, this would make the plug-flow reactor more like a double-pipe heat exchanger. However, as included in the design basis, NREL provided information that the maximum heat consumption during the reaction was expected to be at most 10 MMBTU/hr for the current scale. Using AspenPlus software and assuming the thermal properties of water, we calculated the expected temperature drop of the product in the reactor to be about 3 °C. Furthermore, given problems associated with the high viscosity of the wood particle/water mixture at low temperature is not expected above about 250 °C, it is possible to perform the final heat exchange in a shell and tube heat exchanger, which is preferable from a cost perspective. As such, we did not include a jacked plug-flow reactor in any case.

7.7 EVALUATION OF CASE D WITH ALL INDIRECT HEATING

One of the primary advantages of Case D is that much of the heating of the reactor inlet stream occurs indirectly, that is, based on mixing with recycle water that is close to reaction temperature. Thus, in a single step, the feed mixture is heated to above 250 °C, eliminating the problems associated with high viscosities and low heat transfer coefficients expected for other cases. An additional option, in this regard, is to do all of the heating indirectly. This would include a heater on the recycle water stream that would add enough energy to this stream such that, after mixing with the wood/water feed, the entire mixture would be at a reactor temperature of about 350 °C. The primary advantage here is the lack of need for any cross-exchange, thereby potentially saving a good deal of equipment costs.

This option was briefly investigated in AspenPlus and it was found that the recycle water stream would have to be entirely vaporized and even superheated to enable the full extent of temperature increase required for the feed. The primary problem here is that performing superheated steam injection to a 36.6 wt% solid (dry basis) slurry at these pressures is problematic, given the viscous nature of the feed. Furthermore, the lack of heat integration in this scenario means that over 100 MMBTU/hr more heating is required relative to the current Case D. While this case eliminates the need for some heat exchangers, a fired boiler operating above 3000 psig to vaporize and superheat the recycle water would be required. Harris Group obtained a budgetary quote for a fired heater of similar size while exploring the option of using vapor-phase hot oil. This heater (operating at only about 150 psig) was approximately $8 million for equipment costs, and a 3000-psig fired heater would certainly be even more expensive. Given these drawbacks, this option seemed unattractive.

7.8 EVALUATION OF ALTERNATIVE REACTOR CONFIGURATIONS

As part of the effort to minimize cost, Harris Group briefly investigated two alternatives relative to the reactor design. Given that the current selected design is a long run of 316L piping, Harris Group looked at cladded carbon steel piping as an alternative. Conversations with vendors led Harris Group to believe that carbon steel piping cladded with 316L (0.125 to 0.25 inches thick) would be of a similar price to the regular 316L piping, thereby not providing a significant advantage. A second option, one of using large carbon steel vessels (~4200 gallons) cladded with stainless steel, was also investigated. The total equipment cost for the reactors operating at an LHSV of 4 L/L/h was $18.2 million (Table 6-1). The total cost using the cladded vessels was estimated to be $20.1 million based on vendor quotes. As such, the piping option was selected. However, given that these costs are similar, we recommend that cladded vessels be evaluated based on stainless steel costs in future development.

April 5, 2013

REPORT 30352.00/01
HYDROTHERMAL LIQUEFACTION REACTOR DESIGN REPORT

SECTION 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 COMPARISON OF CASES

Based on the capital and operating costs presented in Section 5, Case D clearly represents the most economical option for commercialization of the HTL process. Case D-L would be suitable if the bio-oil/process water separation were not feasible at high temperatures. Furthermore, if pumping high solids material is not possible, either Case A, or a hybrid between Case A and Case D that would accommodate the maximum allowable solids content in the feed pumps could be utilized. Extensive heat integration, as illustrated by Cases B and B-L, is not cost-effective unless experiments show that the in-service heat transfer coefficients are much higher than those estimated herein.

8.2 RECOMMENDED EXPERIMENTS AND FUTURE DEVELOPMENT

We recommend that future development of the HTL focus primarily on the items that clearly have a large cost impact, specifically:

8.2.1. Determining the ability to pump high solids concentration feed (up to 36.6 wt% dry solids).

8.2.2. Determining expected heat transfer coefficients at various points in the process.

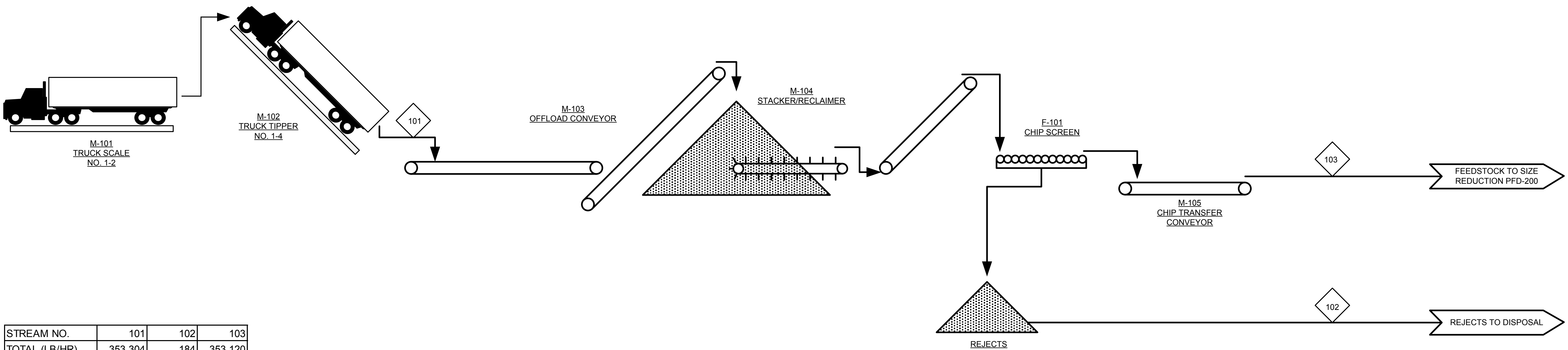
8.2.3. Determining the feasibility of performing bio-oil/water separation at high temperatures.

8.2.4. Increasing the acceptable LHSV in the system.

A more extensive list also is provided in Appendix E.

APPENDIX A

PROCESS FLOW DIAGRAMS



STREAM NO.	101	102	103
TOTAL (LB/HR)	353,304	184	353,120
T (°C)	25	25	25
P (psig)	0	0	0
WATER (LB/HR)	169,586	0	169,586
WOOD	183,718	184	183,534
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	0	0	0
WATER (wt%)	48.0%	0.0%	48.0%
WOOD	52.0%	100.0%	52.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

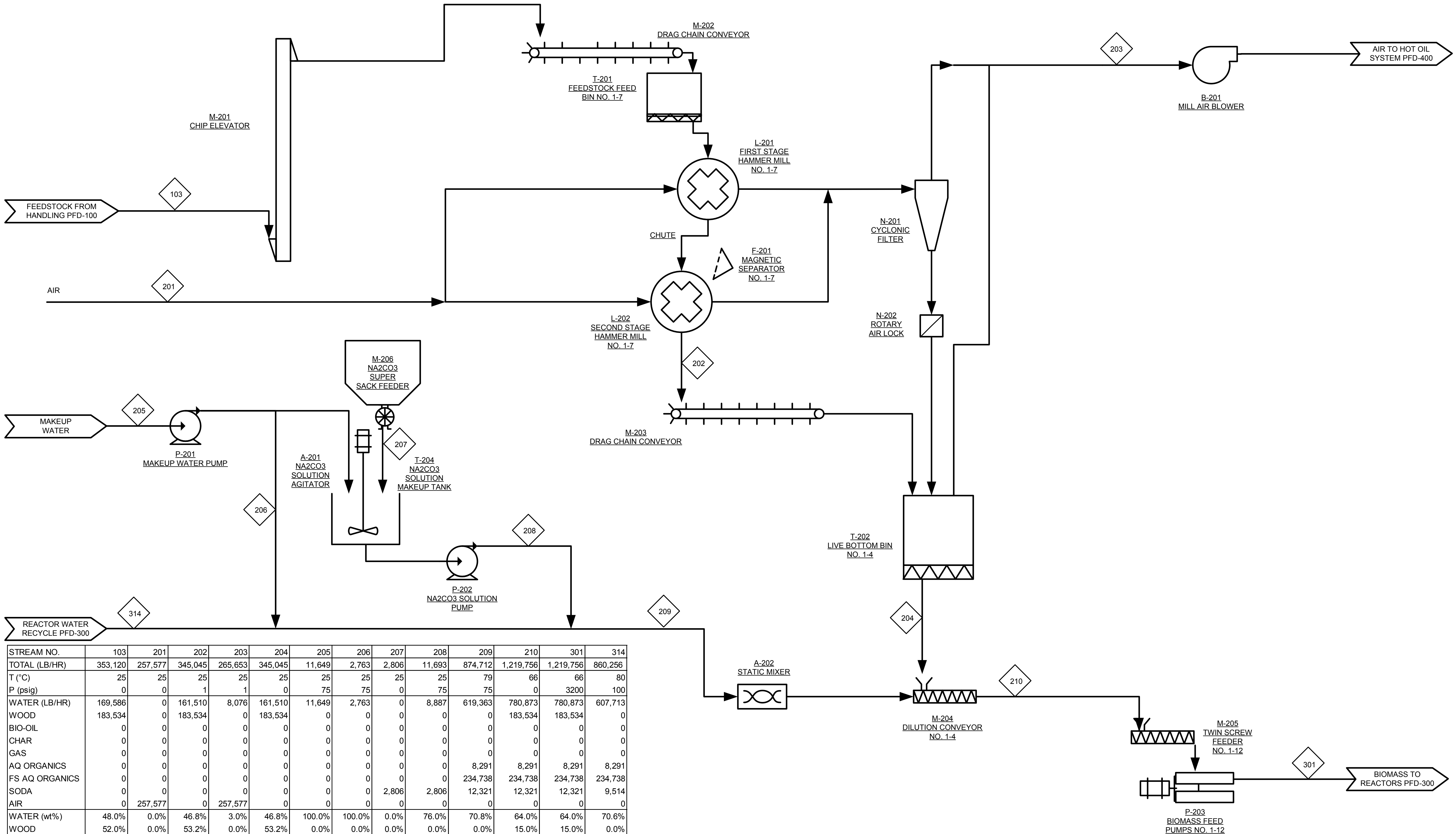
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 100: FEED HANDLING

Project No: 30352.00
Drawing: PFD-100A
Rev: B



STREAM NO.	103	201	202	203	204	205	206	207	208	209	210	301	314
TOTAL (LB/HR)	353,120	257,577	345,045	265,653	345,045	11,649	2,763	2,806	11,693	874,712	1,219,756	1,219,756	860,256
T (°C)	25	25	25	25	25	25	25	25	25	79	66	66	80
P (psig)	0	0	1	1	0	75	75	0	75	75	0	3200	100
WATER (LB/HR)	169,586	0	161,510	8,076	161,510	11,649	2,763	0	8,887	619,363	780,873	780,873	607,713
WOOD	183,534	0	183,534	0	183,534	0	0	0	0	0	183,534	183,534	0
BIO-OIL	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0	0	0	0	0	8,291	8,291	8,291	8,291
FS AQ ORGANICS	0	0	0	0	0	0	0	0	0	234,738	234,738	234,738	234,738
SODA	0	0	0	0	0	0	0	2,806	2,806	12,321	12,321	12,321	9,514
AIR	0	257,577	0	257,577	0	0	0	0	0	0	0	0	0
WATER (wt%)	48.0%	0.0%	46.8%	3.0%	46.8%	100.0%	100.0%	0.0%	76.0%	70.8%	64.0%	64.0%	70.6%
WOOD	52.0%	0.0%	53.2%	0.0%	53.2%	0.0%	0.0%	0.0%	0.0%	0.0%	15.0%	15.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.7%	0.7%	1.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.8%	19.2%	19.2%	27.3%
SODA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	24.0%	1.4%	1.0%	1.0%	1.1%
AIR	0.0%	100.0%	0.0%	97.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

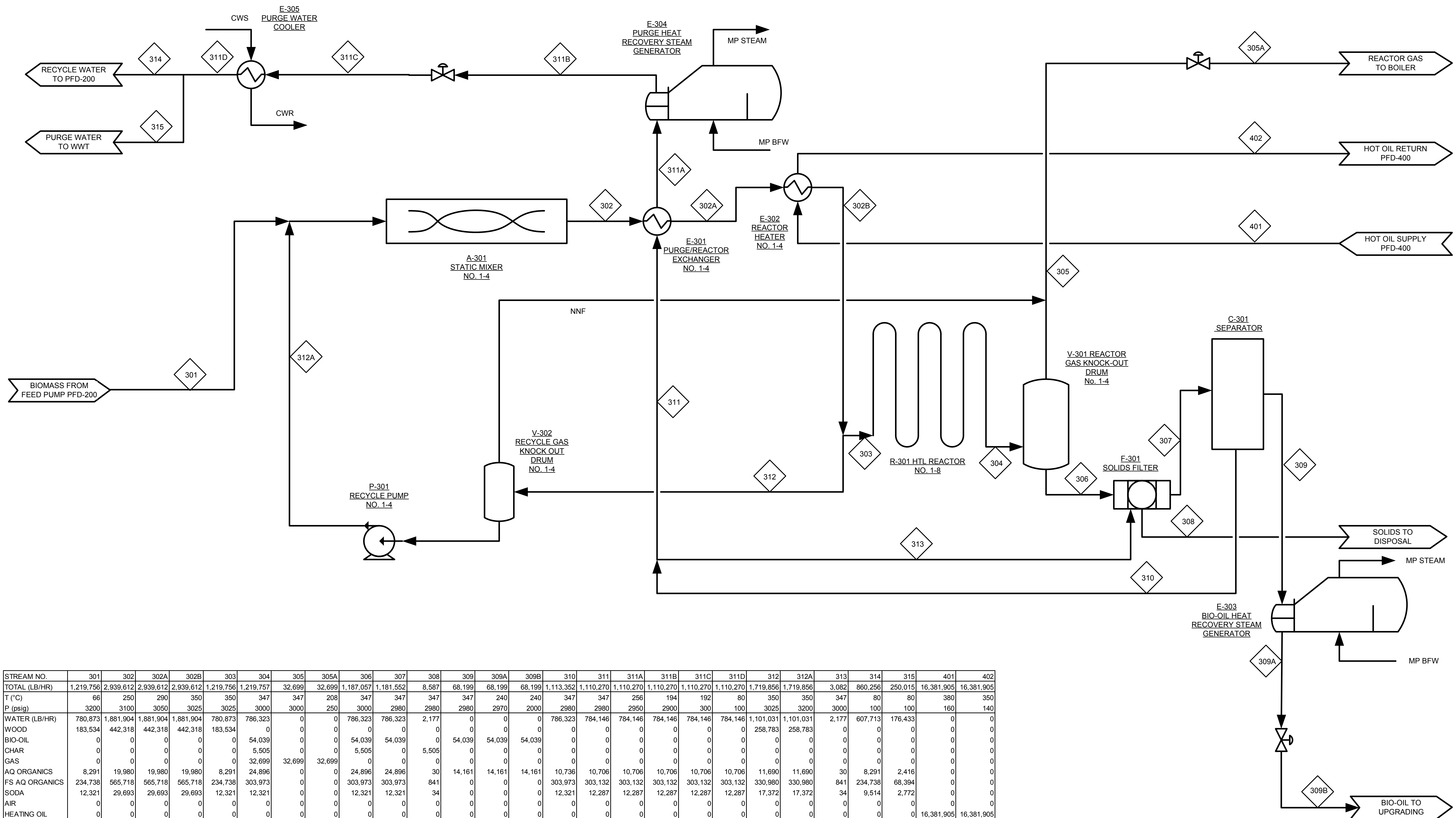
Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-			
Drawn: DBK	-	Check:	-	
Engr: DBK	-	Check:	-	
Appr:	-	PMgr: JCL	-	

PROCESS FLOW DIAGRAM
AREA 200: FEED PREPARATION

Project No: 30352.00 | Drawing: PFD-200A | Rev: B



STREAM NO.	301	302	302A	302B	303	304	305	305A	306	307	308	309	309A
TOTAL (LB/HR)	1,219,756	2,939,612	2,939,612	2,939,612	1,219,756	1,219,757	32,699	32,699	1,187,057	1,181,552	8,587	68,199	68,199
T (°C)	66	250	290	350	350	347	347	208	347	347	347	347	240
P (psig)	3200	3100	3050	3025	3025	3000	3000	250	3000	2980	2980	2980	2970
WATER (LB/HR)	780,873	1,881,904	1,881,904	1,881,904	780,873	786,323	0	0	786,323	786,323	2,177	0	0
WOOD	183,534	442,318	442,318	442,318	183,534	0	0	0	0	0	0	0	0
BIO-OIL	0	0	0	0	0	54,039	0	0	54,039	54,039	0	54,039	54,039
CHAR	0	0	0	0	0	5,505	0	0	5,505	0	5,505	0	0
GAS	0	0	0	0	0	32,699	32,699	32,699	0	0	0	0	0
AQ ORGANICS	8,291	19,980	19,980	19,980	8,291	24,896	0	0	24,896	24,896	30	14,161	14,161
FS AQ ORGANICS	234,738	565,718	565,718	565,718	234,738	303,973	0	0	303,973	303,973	841	0	0
SODA	12,321	29,693	29,693	29,693	12,321	12,321	0	0	12,321	12,321	34	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	0	0	0	0	0
WATER (WT%)	64.0%	64.0%	64.0%	64.0%	64.0%	64.5%	0.0%	0.0%	66.2%	66.6%	25.3%	0.0%	0.0%
WOOD	15.0%	15.0%	15.0%	15.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	79.2%	79.2%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	4.4%	0.0%	0.0%	4.6%	4.6%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.5%	0.0%	64.1%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	100.0%	100.0%	0.0%	0.0%	0.0%	20.8%	20.8%
AQ ORGANICS	0.7%	0.7%	0.7%	0.7%	0.7%	2.0%	0.0%	0.0%	2.1%	2.1%	0.3%	0.0%	0.0%
FS AQ ORGANICS	19.2%	19.2%	19.2%	19.2%	19.2%	24.9%	0.0%	0.0%	25.6%	25.7%	9.8%	0.0%	0.0%
SODA	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%	1.0%	1.0%	0.4%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

STREAM NO.	309B	310	311	311A	311B	311C	311D	312	312A	313	314	315	401	402
TOTAL (LB/HR)	68,199	1,113,352	1,110,270	1,110,270	1,110,270	1,110,270	1,110,270	1,719,856	1,719,856	3,082	860,256	250,015	16,381,905	16,381,905
T (°C)	240	347	347	256	194	192	80	350	350	347	80	80	380	350
P (psig)	2000	2980	2980	2950	2900	300	100	3025	3200	3000	100	100	160	140
WATER (LB/HR)	0	786,323	784,146	784,146	784,146	784,146	784,146	1,101,031	1,101,031	2,177	607,713	176,433	0	0
WOOD	0	0	0	0	0	0	0	258,783	258,783	0	0	0	0	0
BIO-OIL	54,039	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	14,161	10,736	10,706	10,706	10,706	10,706	10,706	11,690	11,690	30	8,291	2,416	0	0
FS AQ ORGANICS	0	303,973	303,132	303,132	303,132	303,132	303,132	330,980	330,980	841	234,738	68,394	0	0
SODA	0	12,321	12,287	12,287	12,287	12,287	12,287	17,372	17,372	34	9,514	2,772	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	0	0	0	0	16,381,905	16,381,905
WATER (WT%)	0.0%	70.6%	70.6%	70.6%	70.6%	70.6%	70.6%	15.0%	15.0%	70.6%	70.6%	70.6%	0.0%	0.0%
WOOD	79.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	20.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	19.2%	19.2%	1.0%	1.0%	1.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	1.0%	1.0%	27.3%	27.3%	27.4%	0.0%	0.0%
SODA	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%	1.1%	1.1%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

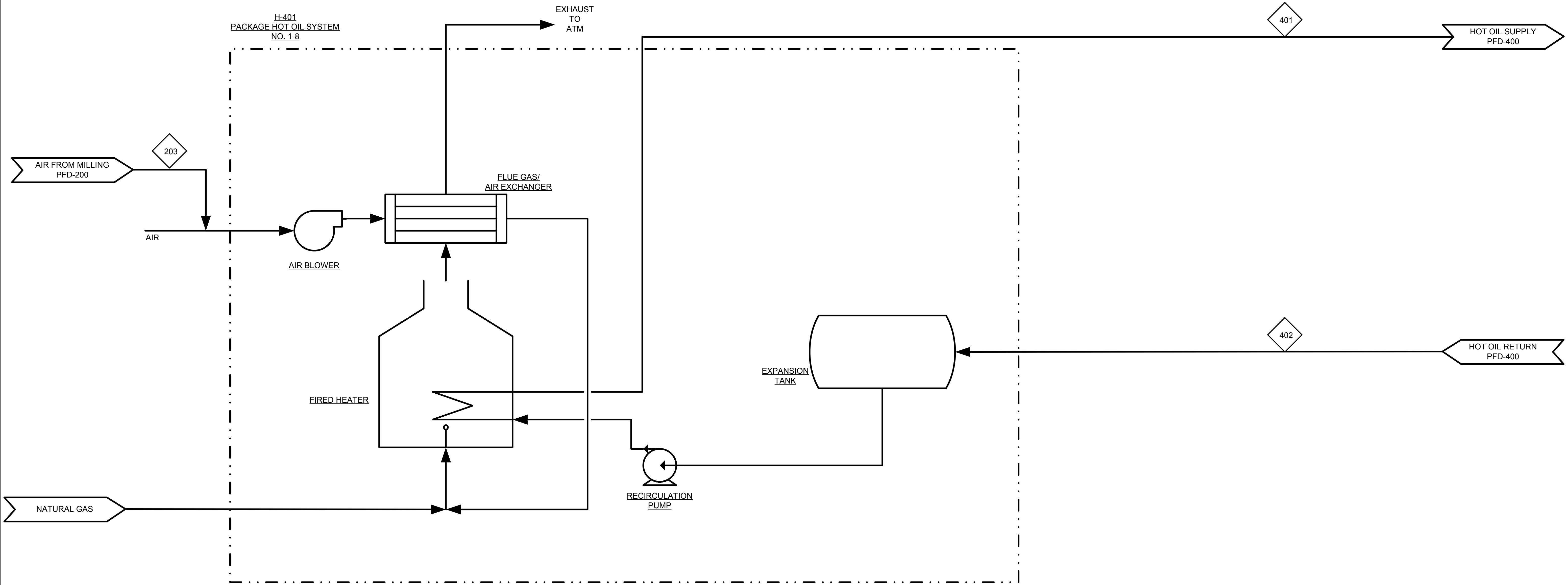
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 300: HTL REACTOR OPTION D

Project No: 30352.00
Drawing: PFD-300A
Rev: B



STREAM NO.	203	401	402
TOTAL (LB/HR)	265,653	16,381,905	16,381,905
T (°C)	25	380	350
P (psig)	1	160	140
WATER (LB/HR)	8,076	0	0
WOOD	0	0	0
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	257,577	0	0
HEATING OIL	0	16,381,905	16,381,905
WATER (WT%)	3.0%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	97.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%

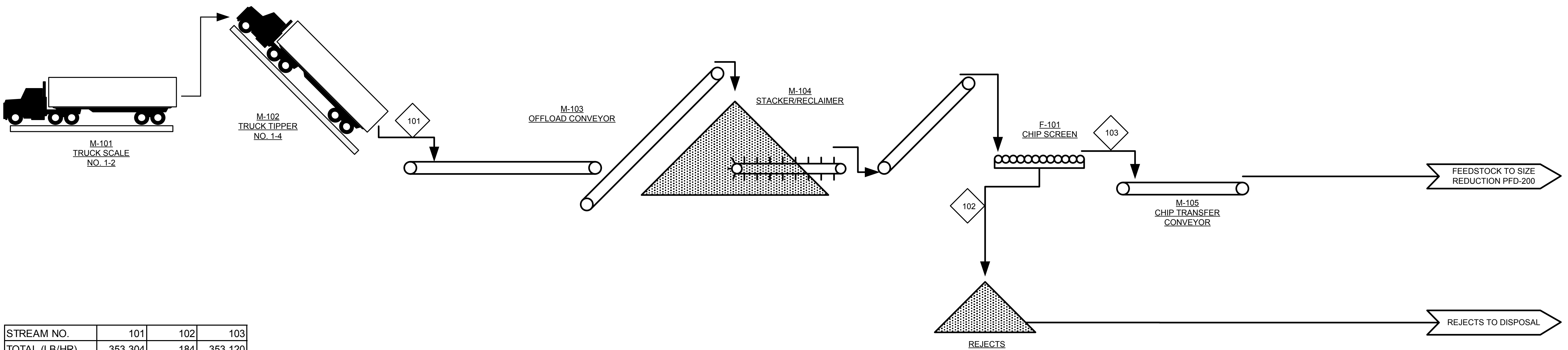
Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 400: HOT OIL SYSTEM

Project No:	Drawing:	Rev:
30352.00	PFD-400A	B



STREAM NO.	101	102	103
TOTAL (LB/HR)	353,304	184	353,120
T (°C)	25	25	25
P (psig)	0	0	0
WATER (LB/HR)	169,586	0	169,586
WOOD	183,718	184	183,534
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	0	0	0
WATER (wt%)	48.0%	0.0%	48.0%
WOOD	52.0%	100.0%	52.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

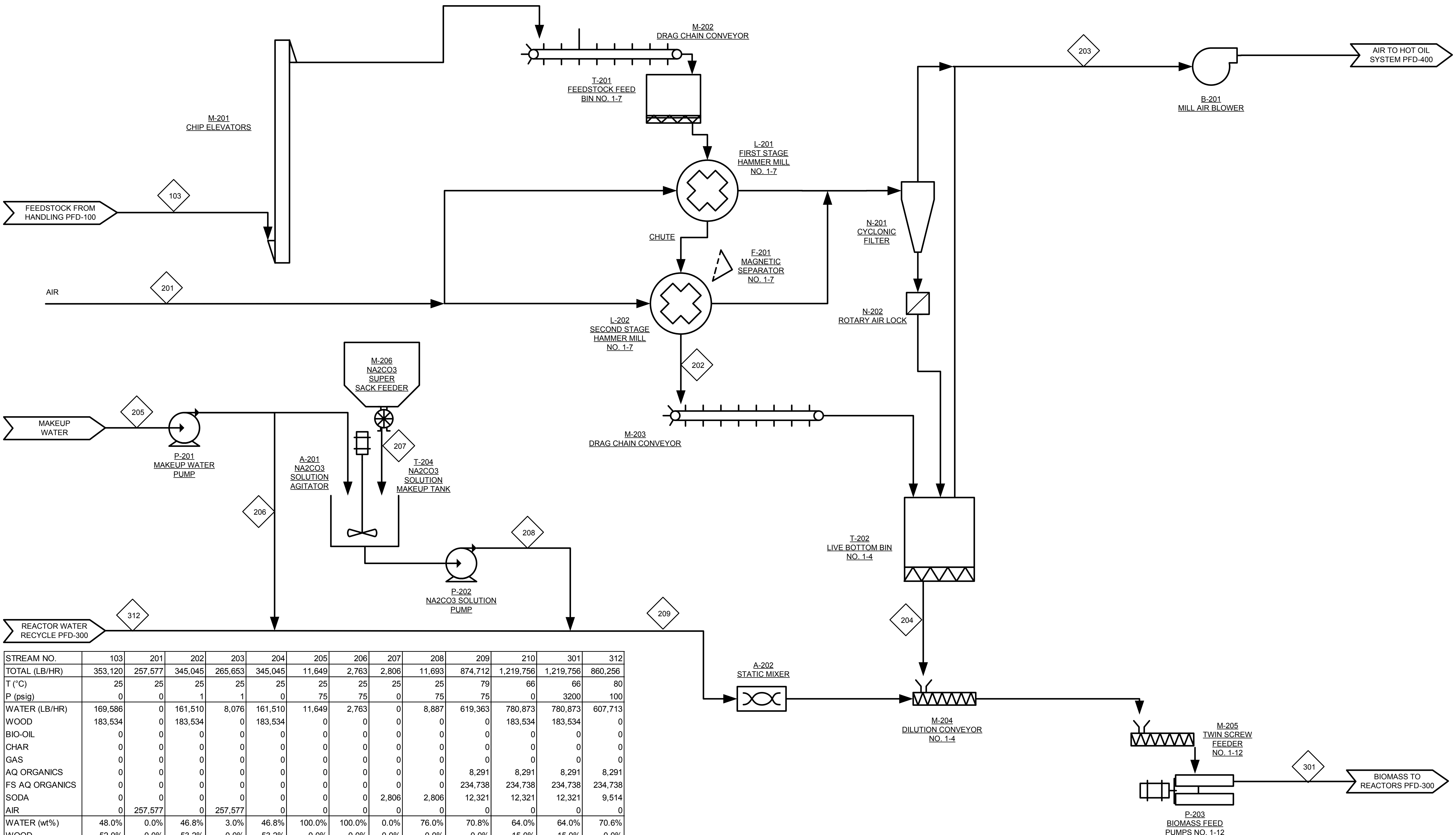
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 100: FEED HANDLING

Project No: 30352.00 | Drawing: PFD-100B | Rev: B



STREAM NO.	103	201	202	203	204	205	206	207	208	209	210	301	312
TOTAL (LB/HR)	353,120	257,577	345,045	265,653	345,045	11,649	2,763	2,806	11,693	874,712	1,219,756	1,219,756	860,256
T (°C)	25	25	25	25	25	25	25	25	25	79	66	66	80
P (psig)	0	0	1	1	0	75	75	0	75	75	0	3200	100
WATER (LB/HR)	169,586	0	161,510	8,076	161,510	11,649	2,763	0	8,887	619,363	780,873	780,873	607,713
WOOD	183,534	0	183,534	0	183,534	0	0	0	0	0	183,534	183,534	0
BIO-OIL	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0	0	0	0	0	8,291	8,291	8,291	8,291
FS AQ ORGANICS	0	0	0	0	0	0	0	0	0	234,738	234,738	234,738	234,738
SODA	0	0	0	0	0	0	0	2,806	2,806	12,321	12,321	12,321	9,514
AIR	0	257,577	0	257,577	0	0	0	0	0	0	0	0	0
WATER (wt%)	48.0%	0.0%	46.8%	3.0%	46.8%	100.0%	100.0%	0.0%	76.0%	70.8%	64.0%	64.0%	70.6%
WOOD	52.0%	0.0%	53.2%	0.0%	53.2%	0.0%	0.0%	0.0%	0.0%	0.0%	15.0%	15.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.7%	0.7%	1.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.8%	19.2%	19.2%	27.3%
SODA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	24.0%	1.4%	1.0%	1.0%	1.1%
AIR	0.0%	100.0%	0.0%	97.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

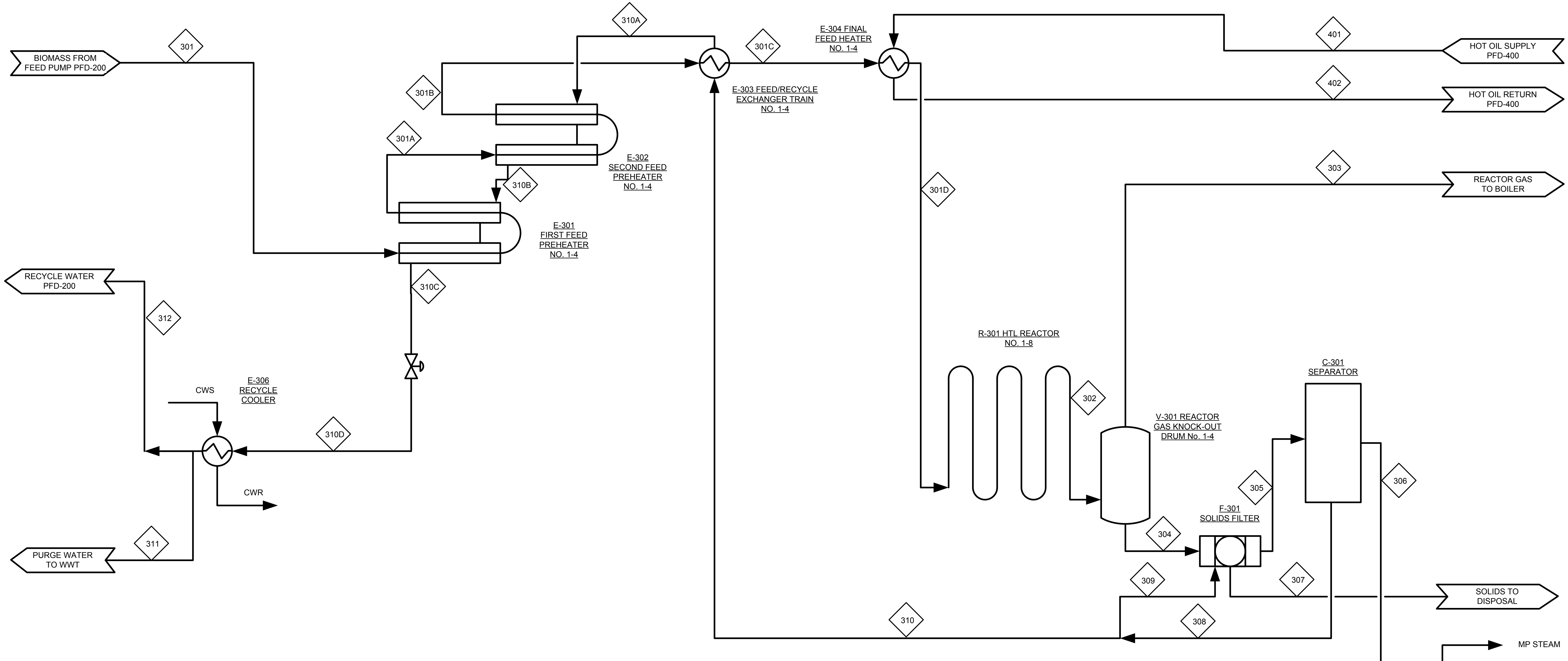
NREL NATIONAL RENEWABLE ENERGY LABORATORY

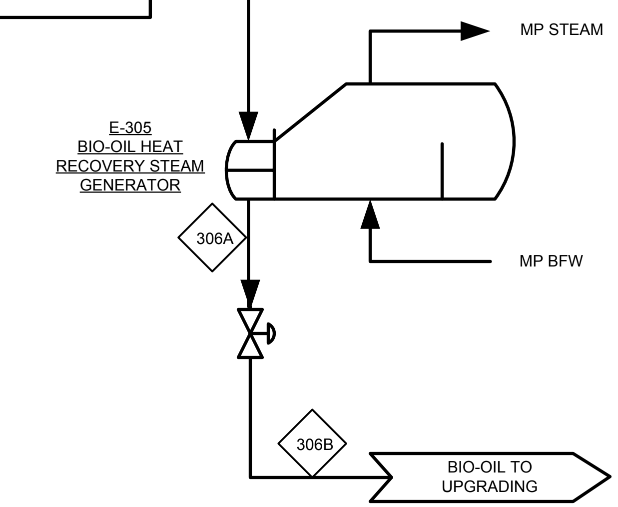
NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 200: FEED PREPARATION

Project No: 30352.00 | Drawing: PFD-200B | Rev: B





STREAM NO.	301	301A	301B	301C	301D	302	303	304	305	306	306A
TOTAL (LB/HR)	1,219,756	1,219,756	1,219,756	1,219,756	1,219,756	1,219,757	32,699	1,187,057	1,181,552	68,199	68,199
T (°C)	66	146	208	312	350	348	348	348	348	348	240
P (psig)	3130	3085	3055	3010	3000	2975	2975	2975	2960	2960	2930
WATER (LB/HR)	780,873	780,873	780,873	780,873	780,873	786,323	0	786,323	786,323	0	0
WOOD	183,534	183,534	183,534	183,534	183,534	0	0	0	0	0	0
BIO-OIL	0	0	0	0	0	54,039	0	54,039	54,039	54,039	54,039
CHAR	0	0	0	0	0	5,505	0	5,505	0	0	0
GAS	0	0	0	0	0	32,699	32,699	0	0	0	0
AQ ORGANICS	8,291	8,291	8,291	8,291	8,291	24,896	0	24,896	24,896	14,161	14,161
FS AQ ORGANICS	234,738	234,738	234,738	234,738	234,738	303,973	0	303,973	303,973	0	0
SODA	12,321	12,321	12,321	12,321	12,321	12,321	0	12,321	12,321	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	0	0	0
WATER (WT%)	64.0%	64.0%	64.0%	64.0%	64.0%	64.5%	0.0%	66.2%	66.6%	0.0%	0.0%
WOOD	15.0%	15.0%	15.0%	15.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	4.4%	0.0%	4.6%	4.6%	79.2%	79.2%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.5%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	100.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.7%	0.7%	0.7%	0.7%	0.7%	2.0%	0.0%	2.1%	2.1%	20.8%	20.8%
FS AQ ORGANICS	19.2%	19.2%	19.2%	19.2%	19.2%	24.9%	0.0%	25.6%	25.7%	0.0%	0.0%
SODA	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	1.0%	1.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

STREAM NO.	306B	307	308	309	310	310A	310B	310C	310D	311	312	401	402
TOTAL (LB/HR)	68,199	8,587	1,113,352	3,082	1,110,270	1,113,352	1,113,352	1,113,352	1,113,352	250,015	860,256	4,526,735	4,526,735
T (°C)	240	348	348	348	348	247	181	96	96	80	80	380	350
P (psig)	2000	2900	2990	2990	2960	2915	2885	2840	300	100	100	160	140
WATER (LB/HR)	0	2,177	786,323	2,177	784,146	786,323	786,323	786,323	786,323	176,433	607,713	0	0
WOOD	0	0	0	0	0	0	0	0	0	0	0	0	0
BIO-OIL	54,039	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	5,505	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	14,161	30	10,736	30	10,706	10,736	10,736	10,736	10,736	2,416	8,291	0	0
FS AQ ORGANICS	0	841	303,973	841	303,132	303,973	303,973	303,973	303,973	68,394	234,738	0	0
SODA	0	34	12,321	34	12,287	12,321	12,321	12,321	12,321	2,772	9,514	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	1	1	0	0	0	0	0	0	4,526,735	4,526,735
WATER (WT%)	0.0%	25.3%	70.6%	70.6%	70.6%	70.6%	70.6%	70.6%	70.6%	70.6%	70.6%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	79.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	64.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	20.8%	0.3%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	9.8%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	27.4%	27.3%	0.0%	0.0%
SODA	0.0%	0.4%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

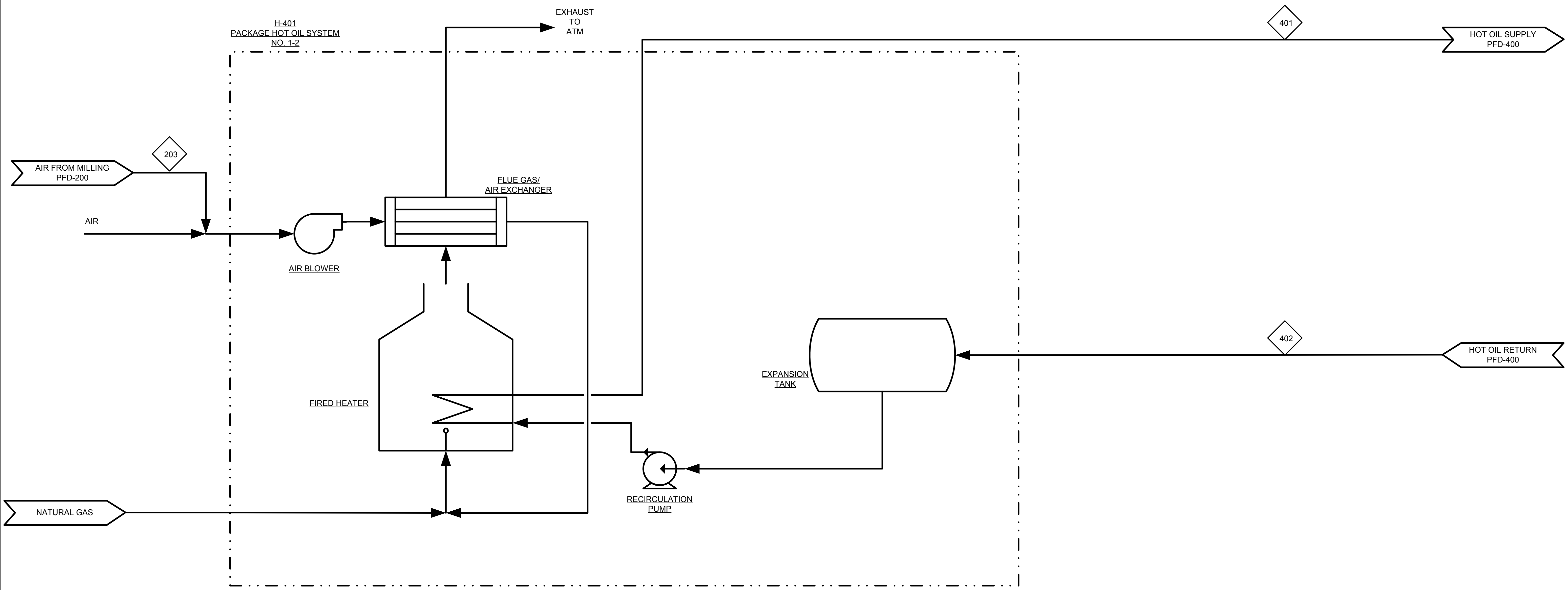
Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

NREL NATIONAL RENEWABLE ENERGY LABORATORY
NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 300: HTL REACTOR OPTION B

Project No:	Drawing:	Rev:
30352.00	PFD-300B	B



STREAM NO.	203	401	402
TOTAL (LB/HR)	265,653	4,526,735	4,526,735
T (°C)	25	380	350
P (psig)	1	160	140
WATER (LB/HR)	8,076	0	0
WOOD	0	0	0
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	257,577	0	0
HEATING OIL	0	4,526,735	4,526,735
WATER (WT%)	3.0%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	97.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

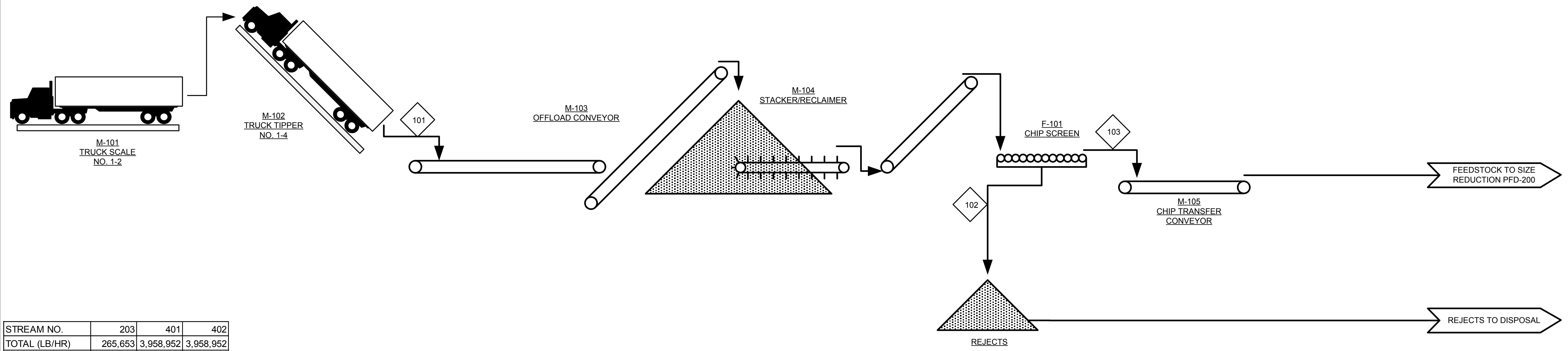
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 400: HOT OIL SYSTEM

Project No:	Drawing:	Rev:
30352.00	PFD-400B	B



STREAM NO.	203	401	402
TOTAL (LB/HR)	265,653	3,958,952	3,958,952
T (°C)	25	380	350
P (psig)	1	160	140
WATER (LB/HR)	8,076	0	0
WOOD	0	0	0
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	257,577	0	0
HEATING OIL	0	3,958,952	3,958,952
WATER (WT%)	3.0%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	97.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

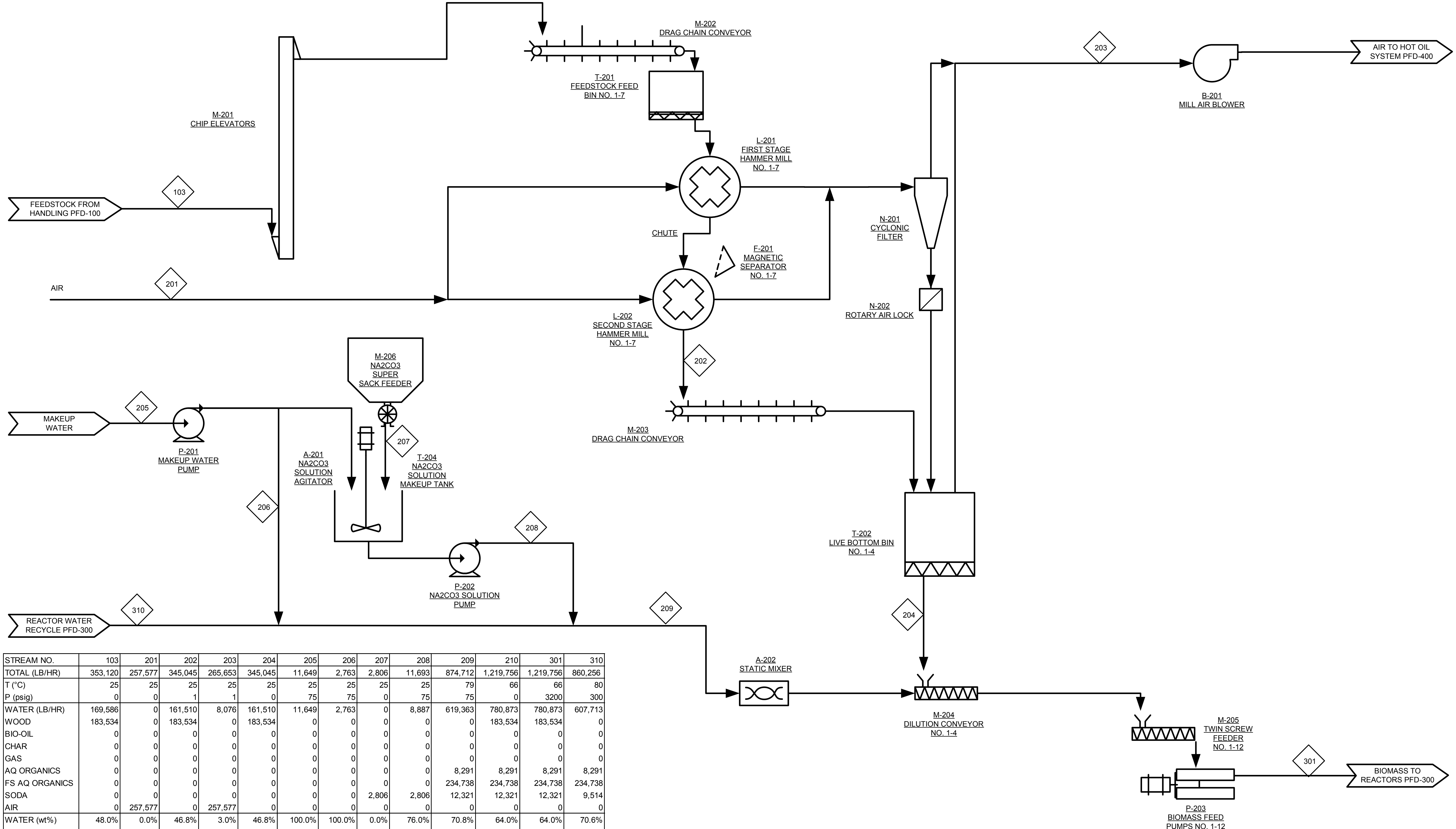
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 100: FEED HANDLING

Project No:	Drawing:	Rev:
30352.00	PFD-100B-L	B



STREAM NO.	103	201	202	203	204	205	206	207	208	209	210	301	310
TOTAL (LB/HR)	353,120	257,577	345,045	265,653	345,045	11,649	2,763	2,806	11,693	874,712	1,219,756	1,219,756	860,256
T (°C)	25	25	25	25	25	25	25	25	25	79	66	66	80
P (psig)	0	0	1	1	0	75	75	0	75	75	0	3200	300
WATER (LB/HR)	169,586	0	161,510	8,076	161,510	11,649	2,763	0	8,887	619,363	780,873	780,873	607,713
WOOD	183,534	0	183,534	0	183,534	0	0	0	0	0	183,534	183,534	0
BIO-OIL	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0	0	0	0	0	8,291	8,291	8,291	8,291
FS AQ ORGANICS	0	0	0	0	0	0	0	0	0	234,738	234,738	234,738	234,738
SODA	0	0	0	0	0	0	0	2,806	2,806	12,321	12,321	12,321	9,514
AIR	0	257,577	0	257,577	0	0	0	0	0	0	0	0	0
WATER (wt%)	48.0%	0.0%	46.8%	3.0%	46.8%	100.0%	100.0%	0.0%	76.0%	70.8%	64.0%	64.0%	70.6%
WOOD	52.0%	0.0%	53.2%	0.0%	53.2%	0.0%	0.0%	0.0%	0.0%	0.0%	15.0%	15.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.7%	0.7%	1.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.8%	19.2%	19.2%	27.3%
SODA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	24.0%	1.4%	1.0%	1.0%	1.1%
AIR	0.0%	100.0%	0.0%	97.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

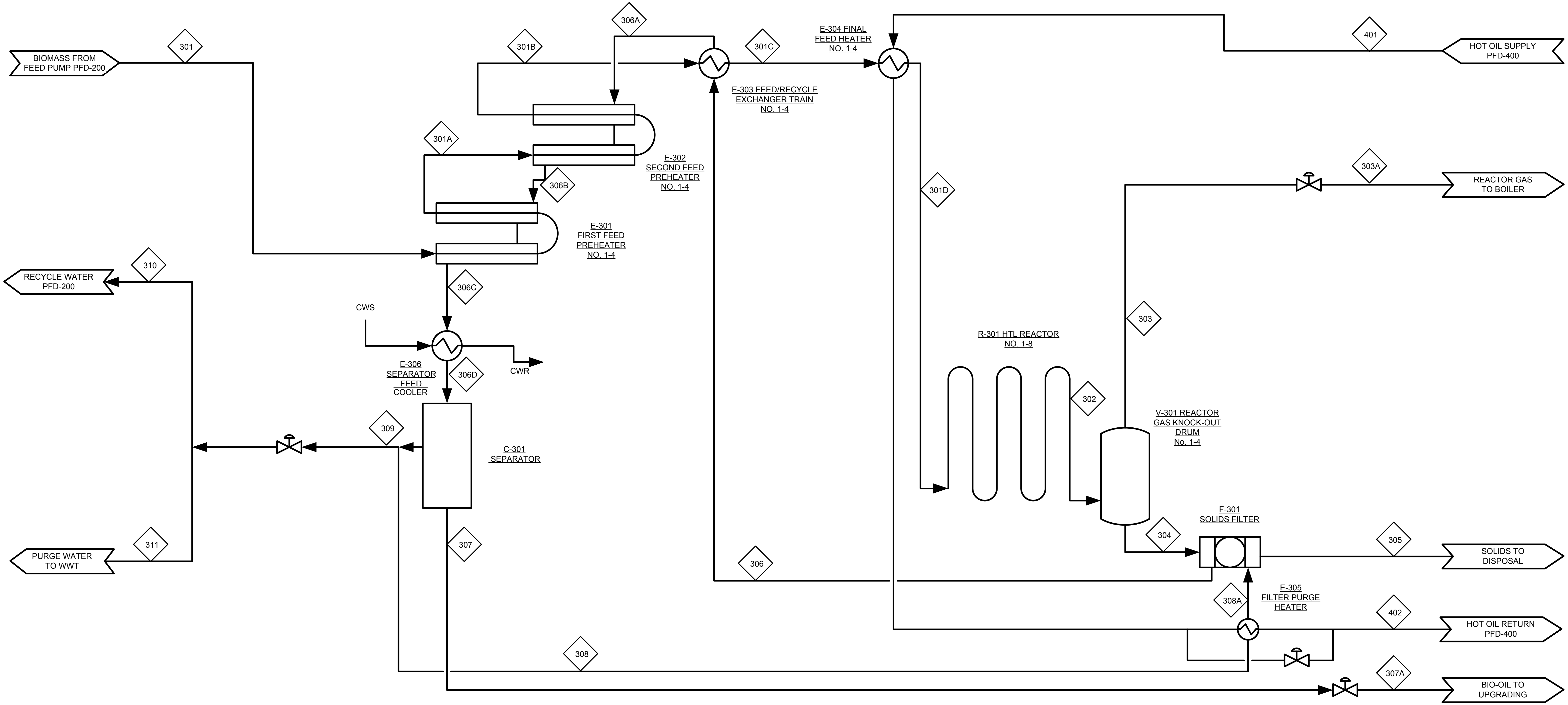
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 200: FEED PREPARATION

Project No: 30352.00 | Drawing: PFD-200B-L | Rev: B



STREAM NO.	301	301A	301B	301C	301D	302	303	303A	304	305	306
TOTAL (LB/HR)	1,219,756	1,219,756	1,219,756	1,219,756	1,219,756	1,219,757	32,699	32,699	1,187,057	8,587	1,181,552
T (°C)	66	161	227	318	350	348	347	208	347	347	347
P (psig)	3130	3085	3055	3010	3000	2975	2975	250	2975	2840	2965
WATER (LB/HR)	780,873	780,873	780,873	780,873	780,873	786,323	0	0	786,323	2,177	786,323
WOOD	183,534	183,534	183,534	183,534	183,534	0	0	0	0	0	0
BIO-OIL	0	0	0	0	0	54,039	0	0	54,039	0	54,039
CHAR	0	0	0	0	0	5,505	0	0	5,505	5,505	0
GAS	0	0	0	0	0	32,699	32,699	32,699	0	0	0
AQ ORGANICS	8,291	8,291	8,291	8,291	8,291	24,896	0	0	24,896	30	24,896
FS AQ ORGANICS	234,738	234,738	234,738	234,738	234,738	303,973	0	0	303,973	841	303,973
SODA	12,321	12,321	12,321	12,321	12,321	12,321	0	0	12,321	34	12,321
AIR	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	0	0	0
WATER (WT%)	64.0%	64.0%	64.0%	64.0%	64.0%	64.5%	0.0%	0.0%	66.2%	25.3%	66.6%
WOOD	15.0%	15.0%	15.0%	15.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	4.4%	0.0%	0.0%	4.6%	0.0%	4.6%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.5%	64.1%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	100.0%	100.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.7%	0.7%	0.7%	0.7%	0.7%	2.0%	0.0%	0.0%	2.1%	0.3%	2.1%
FS AQ ORGANICS	19.2%	19.2%	19.2%	19.2%	19.2%	24.9%	0.0%	0.0%	25.6%	9.8%	25.7%
SODA	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%	1.0%	0.4%	1.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

STREAM NO.	306A	306B	306C	306D	307	307A	308	308A	309	310	311	401	402
TOTAL (LB/HR)	1,181,552	1,181,552	1,181,552	1,181,552	68,199	68,199	3,082	3,082	1,110,270	860,256	250,015	3,958,952	3,958,952
T (°C)	264	199	102	80	80	81	80	80	80	80	80	380	350
P (psig)	2935	2910	2860	2840	2840	2000	2840	2840	2840	300	300	150	150
WATER (LB/HR)	786,323	786,323	786,323	786,323	0	0	2,177	2,177	784,146	607,713	176,433	0	0
WOOD	0	0	0	0	0	0	0	0	0	0	0	0	0
BIO-OIL	54,039	54,039	54,039	54,039	54,039	54,039	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	24,896	24,896	24,896	24,896	14,161	14,161	30	30	10,706	8,291	2,416	0	0
FS AQ ORGANICS	303,973	303,973	303,973	303,973	0	0	841	841	303,132	234,738	68,394	0	0
SODA	12,321	12,321	12,321	12,321	0	0	34	34	12,287	9,514	2,772	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	1	0	0	3,958,952	3,958,952
WATER (WT%)	66.6%	66.6%	66.6%	66.6%	0.0%	0.0%	70.6%	70.6%	70.6%	70.6%	70.6%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	4.6%	4.6%	4.6%	4.6%	79.2%	79.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	2.1%	2.1%	2.1%	2.1%	20.8%	20.8%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%
FS AQ ORGANICS	25.7%	25.7%	25.7%	25.7%	0.0%	0.0%	27.3%	27.3%	27.3%	27.3%	27.4%	0.0%	0.0%
SODA	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance ®
® www.harrisgroup.com

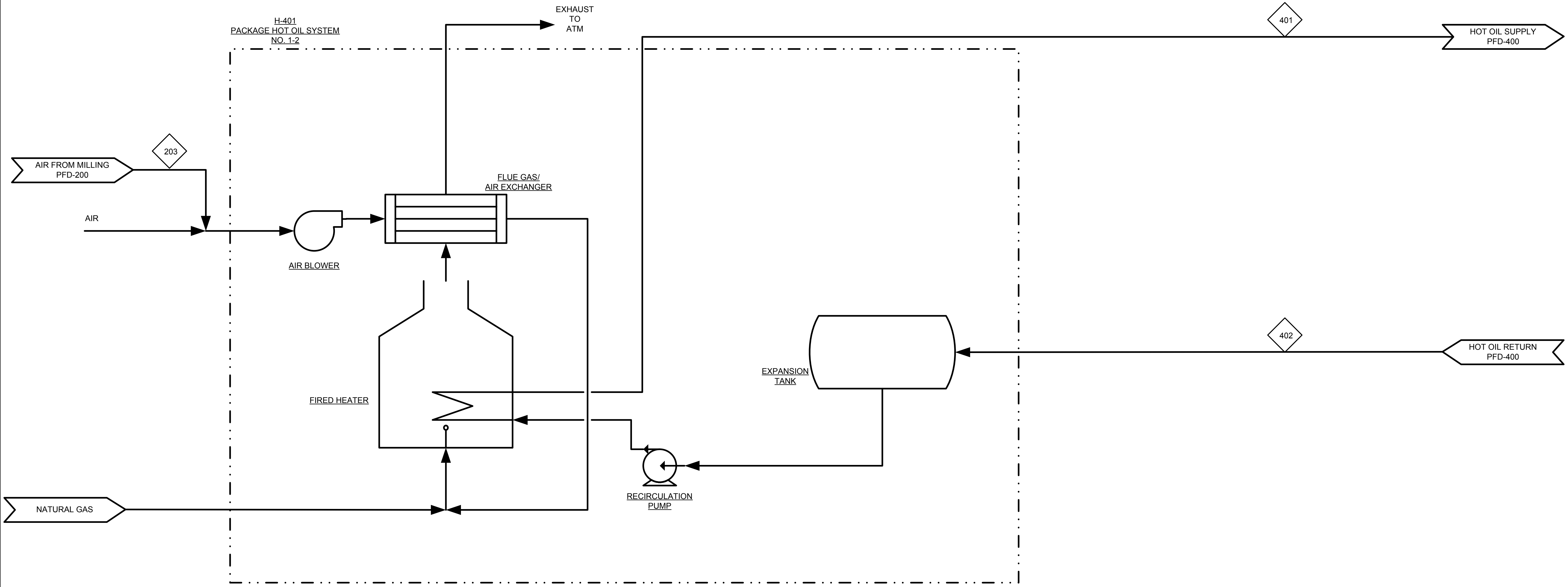
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 300: HTL REACTOR OPTION B

Project No: 30352.00 | Drawing: PFD-300B-L | Rev: B



STREAM NO.	203	401	402
TOTAL (LB/HR)	265,653	3,958,952	3,958,952
T (°C)	25	380	350
P (psig)	1	160	140
WATER (LB/HR)	8,076	0	0
WOOD	0	0	0
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	257,577	0	0
HEATING OIL	0	3,958,952	3,958,952
WATER (WT%)	3.0%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	97.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%

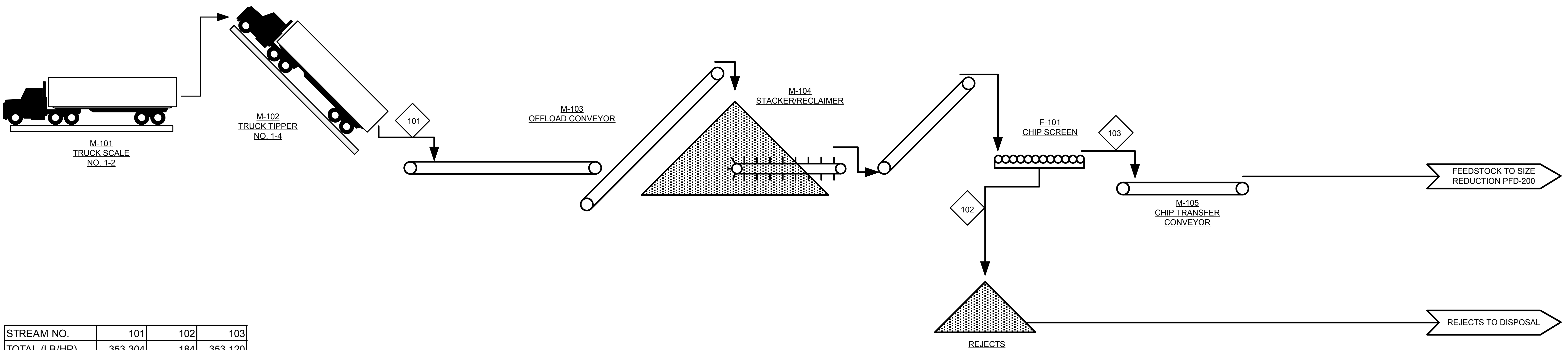
Harris Group Inc.
Engineering for Optimum Performance ®
www.harrisgroup.com

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 400: HOT OIL SYSTEM

Project No: 30352.00 | Drawing: PFD-400B-L | Rev: B



STREAM NO.	101	102	103
TOTAL (LB/HR)	353,304	184	353,120
T (°C)	25	25	25
P (psig)	0	0	0
WATER (LB/HR)	169,586	0	169,586
WOOD	183,718	184	183,534
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	0	0	0
WATER (wt%)	48.0%	0.0%	48.0%
WOOD	52.0%	100.0%	52.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%

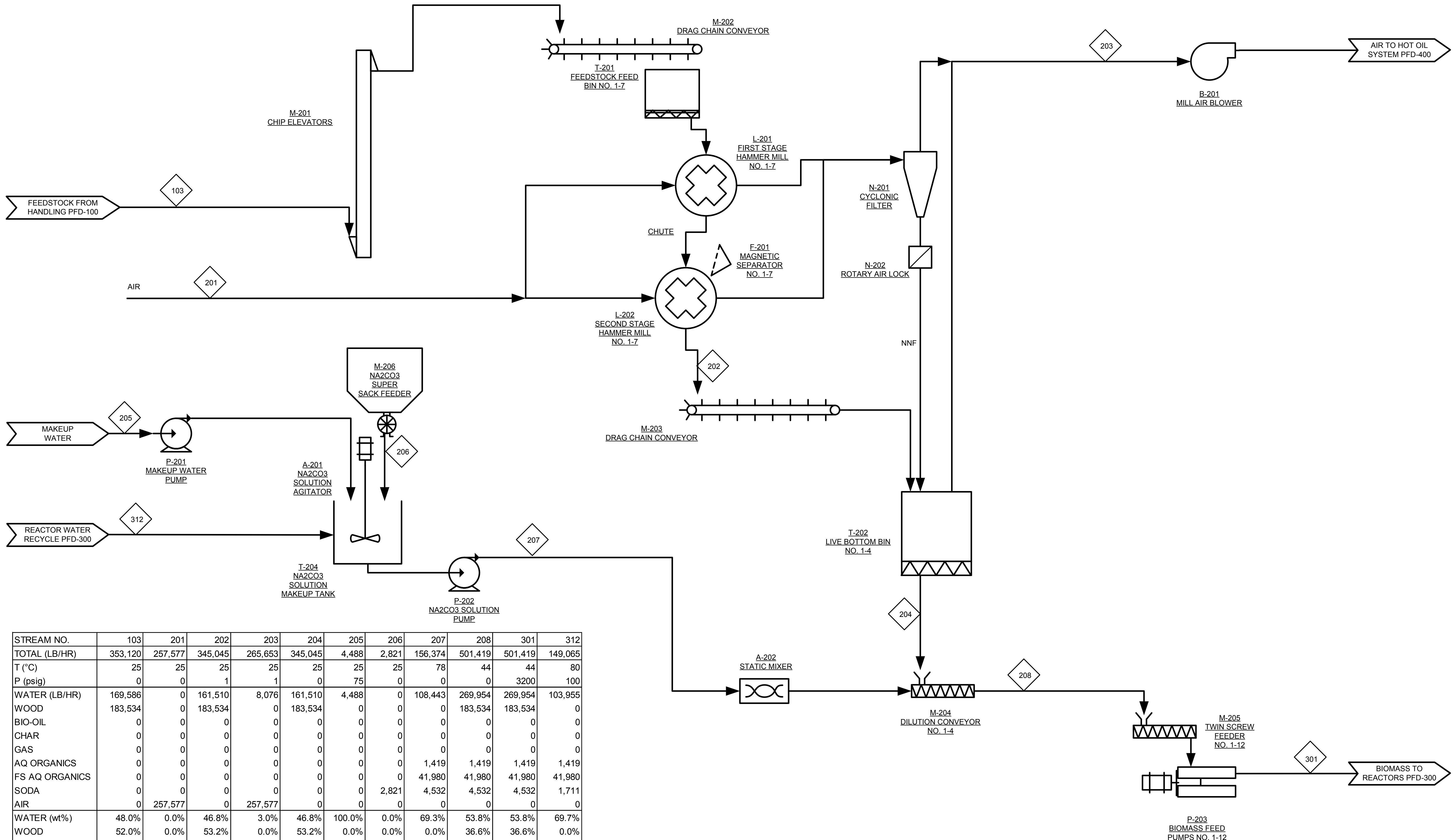
Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 100: FEED HANDLING

Project No: 30352.00 | Drawing: PFD-100D | Rev: B



STREAM NO.	103	201	202	203	204	205	206	207	208	301	312
TOTAL (LB/HR)	353,120	257,577	345,045	265,653	345,045	4,488	2,821	156,374	501,419	501,419	149,065
T (°C)	25	25	25	25	25	25	25	78	44	44	80
P (psig)	0	0	1	1	0	75	0	0	0	3200	100
WATER (LB/HR)	169,586	0	161,510	8,076	161,510	4,488	0	108,443	269,954	269,954	103,955
WOOD	183,534	0	183,534	0	183,534	0	0	0	183,534	183,534	0
BIO-OIL	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0	0	0	1,419	1,419	1,419	1,419
FS AQ ORGANICS	0	0	0	0	0	0	0	41,980	41,980	41,980	41,980
SODA	0	0	0	0	0	0	2,821	4,532	4,532	4,532	1,711
AIR	0	257,577	0	257,577	0	0	0	0	0	0	0
WATER (wt%)	48.0%	0.0%	46.8%	3.0%	46.8%	100.0%	0.0%	69.3%	53.8%	53.8%	69.7%
WOOD	52.0%	0.0%	53.2%	0.0%	53.2%	0.0%	0.0%	0.0%	36.6%	36.6%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.3%	0.3%	1.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.8%	8.4%	8.4%	28.2%
SODA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	2.9%	0.9%	0.9%	1.1%
AIR	0.0%	100.0%	0.0%	97.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance ®
www.harrisgroup.com

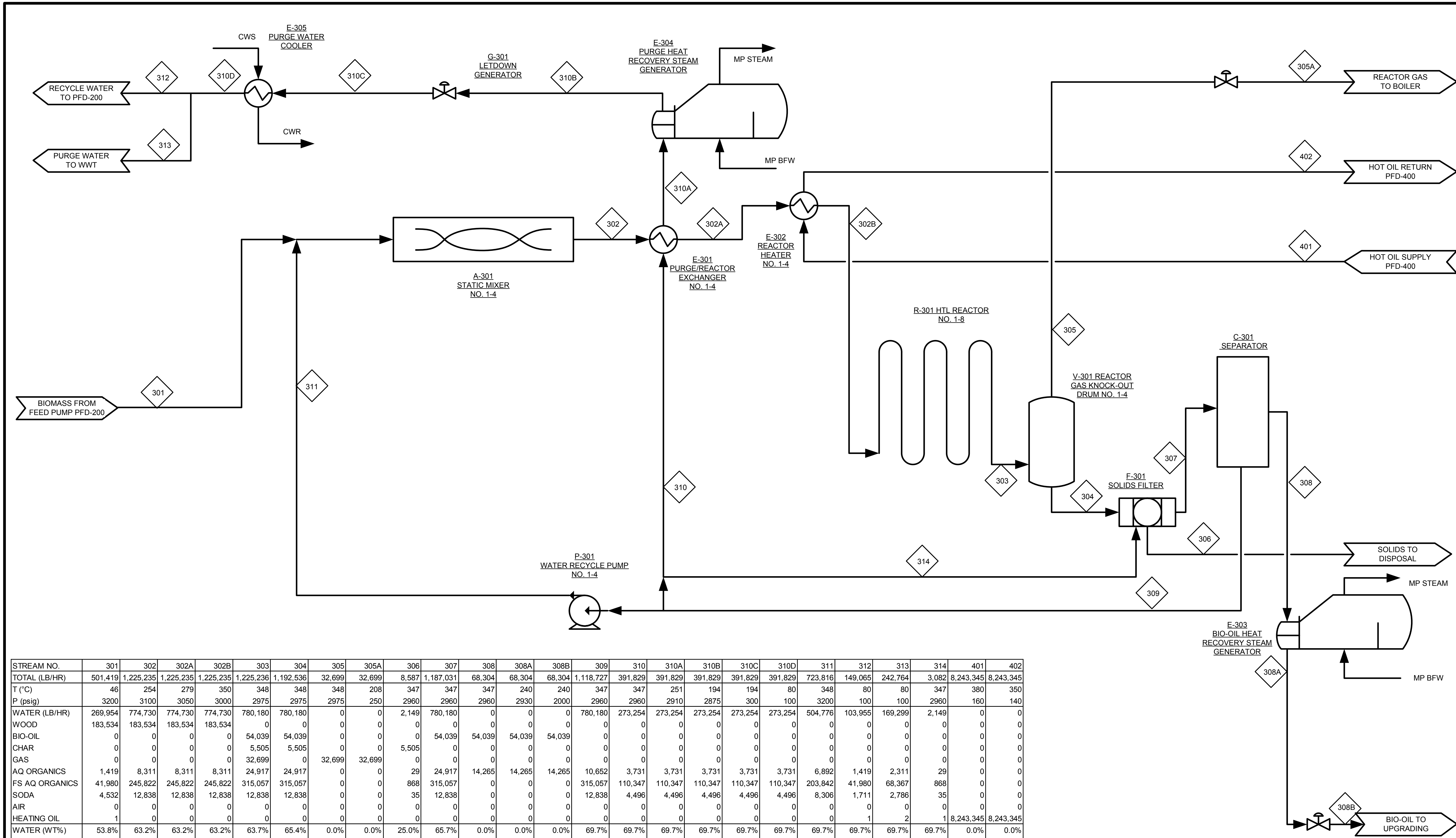
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 200: FEED PREPARATION

Project No: 30352.00
Drawing: PFD-200D
Rev: B



STREAM NO.	301	302	302A	302B	303	304	305	305A	306	307	308	308A
TOTAL (LB/HR)	501,419	1,225,235	1,225,235	1,225,235	1,225,236	1,192,536	32,699	32,699	8,587	1,187,031	68,304	68,304
T (°C)	46	254	279	350	348	348	348	208	347	347	347	240
P (psig)	3200	3100	3050	3000	2975	2975	2975	250	2960	2960	2960	2930
WATER (LB/HR)	269,954	774,730	774,730	774,730	780,180	780,180	0	0	2,149	780,180	0	0
WOOD	183,534	183,534	183,534	183,534	0	0	0	0	0	0	0	0
BIO-OIL	0	0	0	0	54,039	54,039	0	0	0	54,039	54,039	54,039
CHAR	0	0	0	0	5,505	5,505	0	0	5,505	0	0	0
GAS	0	0	0	0	32,699	0	32,699	32,699	0	0	0	0
AQ ORGANICS	1,419	8,311	8,311	8,311	24,917	24,917	0	0	29	24,917	14,265	14,265
FS AQ ORGANICS	41,980	245,822	245,822	245,822	315,057	315,057	0	0	868	315,057	0	0
SODA	4,532	12,838	12,838	12,838	12,838	12,838	0	0	35	12,838	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	1	0	0	0	0	0	0	0	0	0	0	0
WATER (WT%)	53.8%	63.2%	63.2%	63.2%	63.7%	65.4%	0.0%	0.0%	25.0%	65.7%	0.0%	0.0%
WOOD	36.6%	15.0%	15.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	4.4%	4.5%	0.0%	0.0%	0.0%	4.6%	79.1%	79.1%
CHAR	0.0%	0.0%	0.0%	0.0%	0.4%	0.5%	0.0%	0.0%	64.1%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	2.7%	0.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.3%	0.7%	0.7%	0.7%	2.0%	2.1%	0.0%	0.0%	0.3%	2.1%	20.9%	20.9%
FS AQ ORGANICS	8.4%	20.1%	20.1%	20.1%	25.7%	26.4%	0.0%	0.0%	10.1%	26.5%	0.0%	0.0%
SODA	0.9%	1.0%	1.0%	1.0%	1.0%	1.1%	0.0%	0.0%	0.4%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

STREAM NO.	308B	309	310	310A	310B	310C	310D	311	312	313	314	401	402
TOTAL (LB/HR)	68,304	1,118,727	391,829	391,829	391,829	391,829	391,829	723,816	149,065	242,764	3,082	8,243,345	8,243,345
T (°C)	240	347	347	251	194	194	80	348	80	80	347	380	350
P (psig)	2000	2960	2960	2910	2875	300	100	3200	100	100	2960	160	140
WATER (LB/HR)	0	780,180	273,254	273,254	273,254	273,254	273,254	504,776	103,955	169,299	2,149	0	0
WOOD	0	0	0	0	0	0	0	0	0	0	0	0	0
BIO-OIL	54,039	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	14,265	10,652	3,731	3,731	3,731	3,731	3,731	6,892	1,419	2,311	29	0	0
FS AQ ORGANICS	0	315,057	110,347	110,347	110,347	110,347	110,347	203,842	41,980	68,367	868	0	0
SODA	0	12,838	4,496	4,496	4,496	4,496	4,496	8,306	1,711	2,786	35	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	1	2	1	8,243,345	8,243,345
WATER (WT%)	0.0%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	79.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	20.9%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	0.0%	0.0%
SODA	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

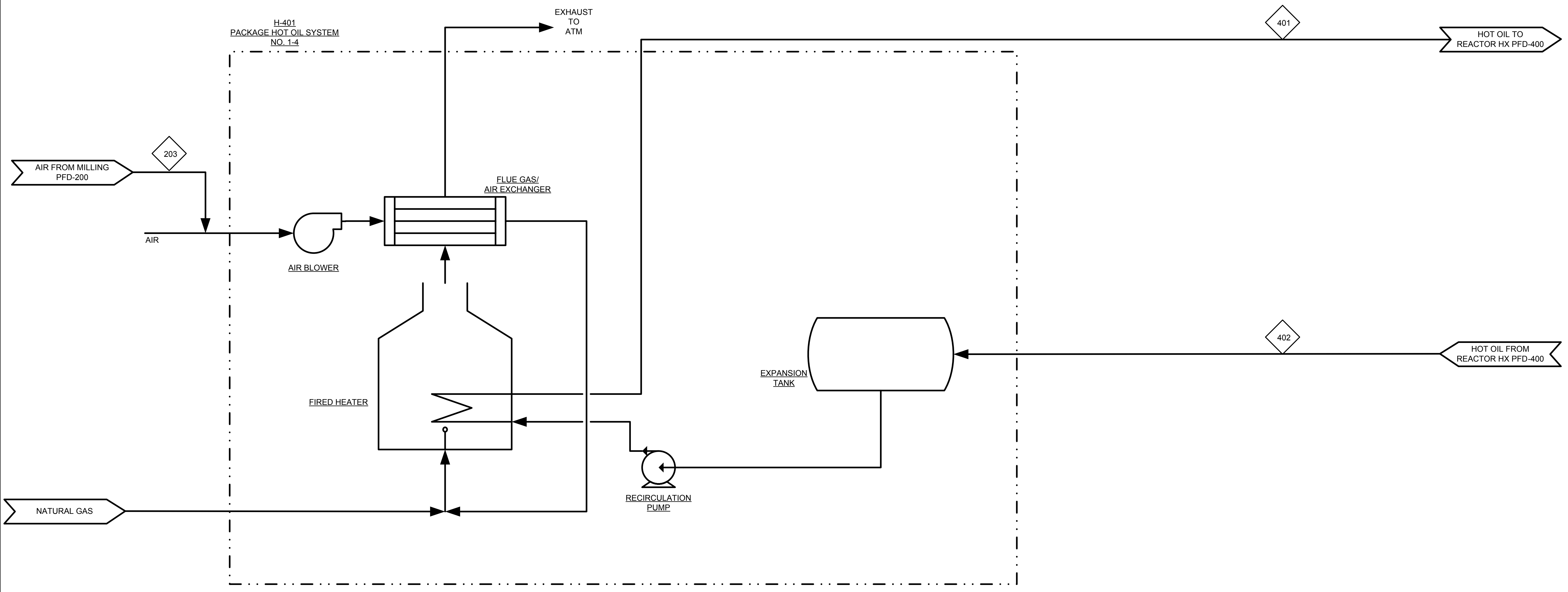
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 300: HTL REACTOR OPTION D

Project No:	Drawing:	Rev:
30352.00	PFD-300D	B



STREAM NO.	203	401	402
TOTAL (LB/HR)	265,653	9,008,535	9,008,535
T (°C)	25	380	350
P (psig)	1	160	140
WATER (LB/HR)	8,076	0	0
WOOD	0	0	0
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	257,577	0	0
HEATING OIL	0	9,008,535	9,008,535
WATER (WT%)	3.0%	69.7%	69.7%
WOOD	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	1.0%	1.0%
FS AQ ORGANICS	0.0%	28.2%	28.2%
SODA	0.0%	1.1%	1.1%
AIR	97.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

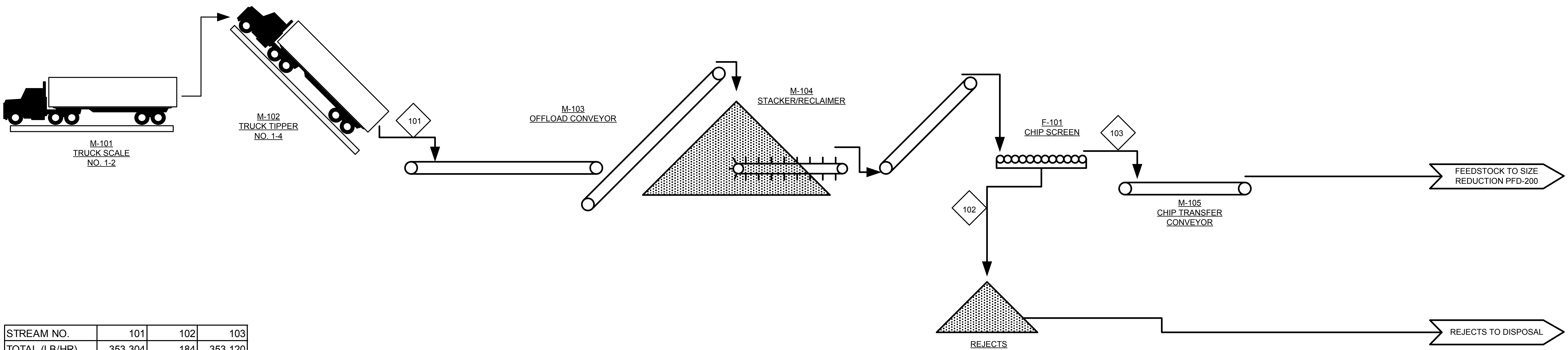
NREL NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 400: HOT OIL SYSTEM

Project No:	Drawing:	Rev:
30352.00	PFD-400D	B



STREAM NO.	101	102	103
TOTAL (LB/HR)	353,304	184	353,120
T (°C)	25	25	25
P (psig)	0	0	0
WATER (LB/HR)	169,586	0	169,586
WOOD	183,718	184	183,534
BIO-OIL	0	0	0
CHAR	0	0	0
GAS	0	0	0
AQ ORGANICS	0	0	0
FS AQ ORGANICS	0	0	0
SODA	0	0	0
AIR	0	0	0
WATER (wt%)	48.0%	0.0%	48.0%
WOOD	52.0%	100.0%	52.0%
BIO-OIL	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%
SODA	0.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

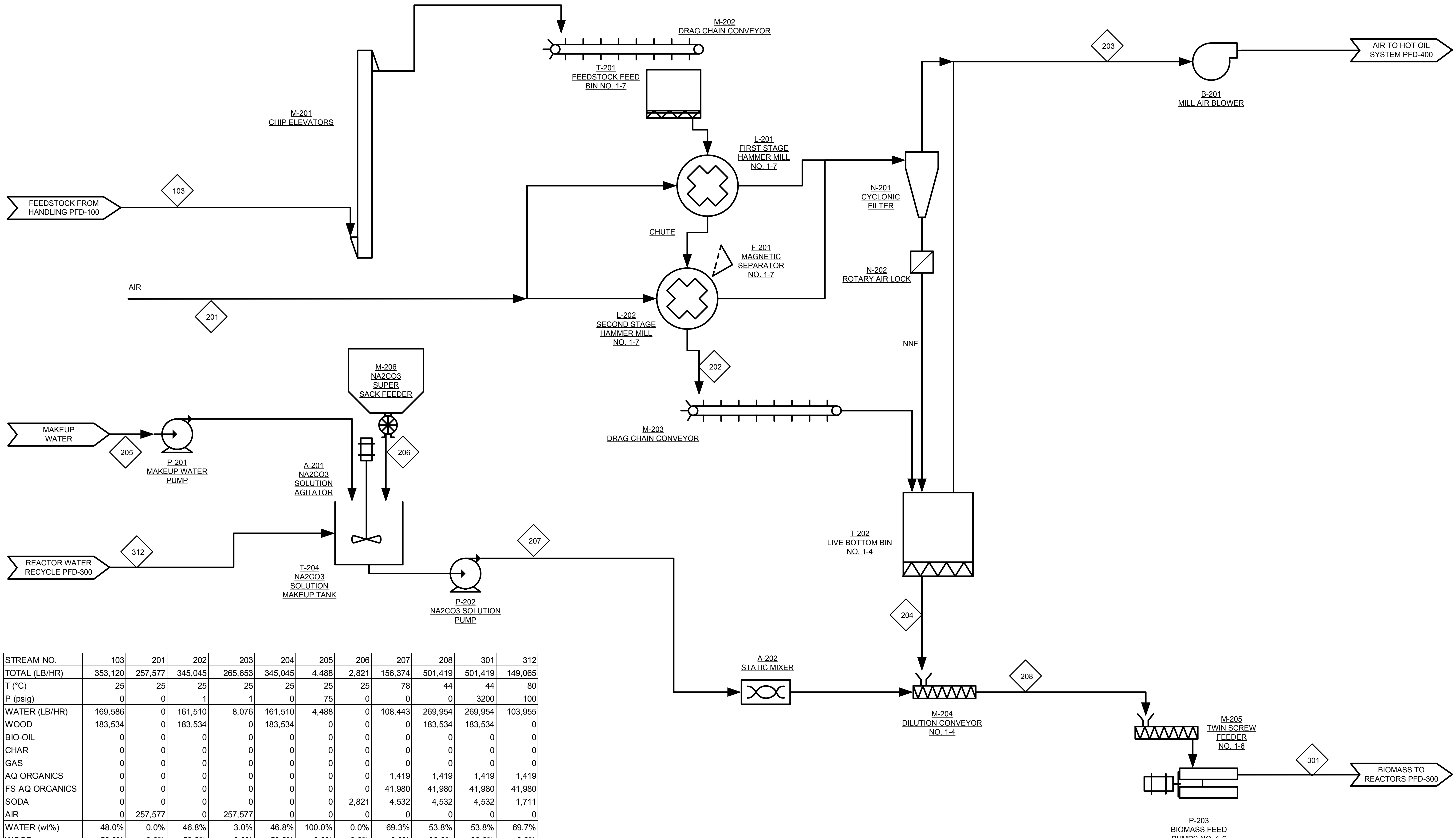
NREL NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 100: FEED HANDLING

Project No: 30352.00 | Drawing: PFD-100D-L | Rev: B



STREAM NO.	103	201	202	203	204	205	206	207	208	301	312
TOTAL (LB/HR)	353,120	257,577	345,045	265,653	345,045	4,488	2,821	156,374	501,419	501,419	149,065
T (°C)	25	25	25	25	25	25	25	78	44	44	80
P (psig)	0	0	1	1	0	75	0	0	0	3200	100
WATER (LB/HR)	169,586	0	161,510	8,076	161,510	4,488	0	108,443	269,954	269,954	103,955
WOOD	183,534	0	183,534	0	183,534	0	0	0	183,534	183,534	0
BIO-OIL	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0	0	0	1,419	1,419	1,419	1,419
FS AQ ORGANICS	0	0	0	0	0	0	0	41,980	41,980	41,980	41,980
SODA	0	0	0	0	0	0	2,821	4,532	4,532	4,532	1,711
AIR	0	257,577	0	257,577	0	0	0	0	0	0	0
WATER (wt%)	48.0%	0.0%	46.8%	3.0%	46.8%	100.0%	0.0%	69.3%	53.8%	53.8%	69.7%
WOOD	52.0%	0.0%	53.2%	0.0%	53.2%	0.0%	0.0%	0.0%	36.6%	36.6%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.3%	0.3%	1.0%
FS AQ ORGANICS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26.8%	8.4%	8.4%	28.2%
SODA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	2.9%	0.9%	0.9%	1.1%
AIR	0.0%	100.0%	0.0%	97.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

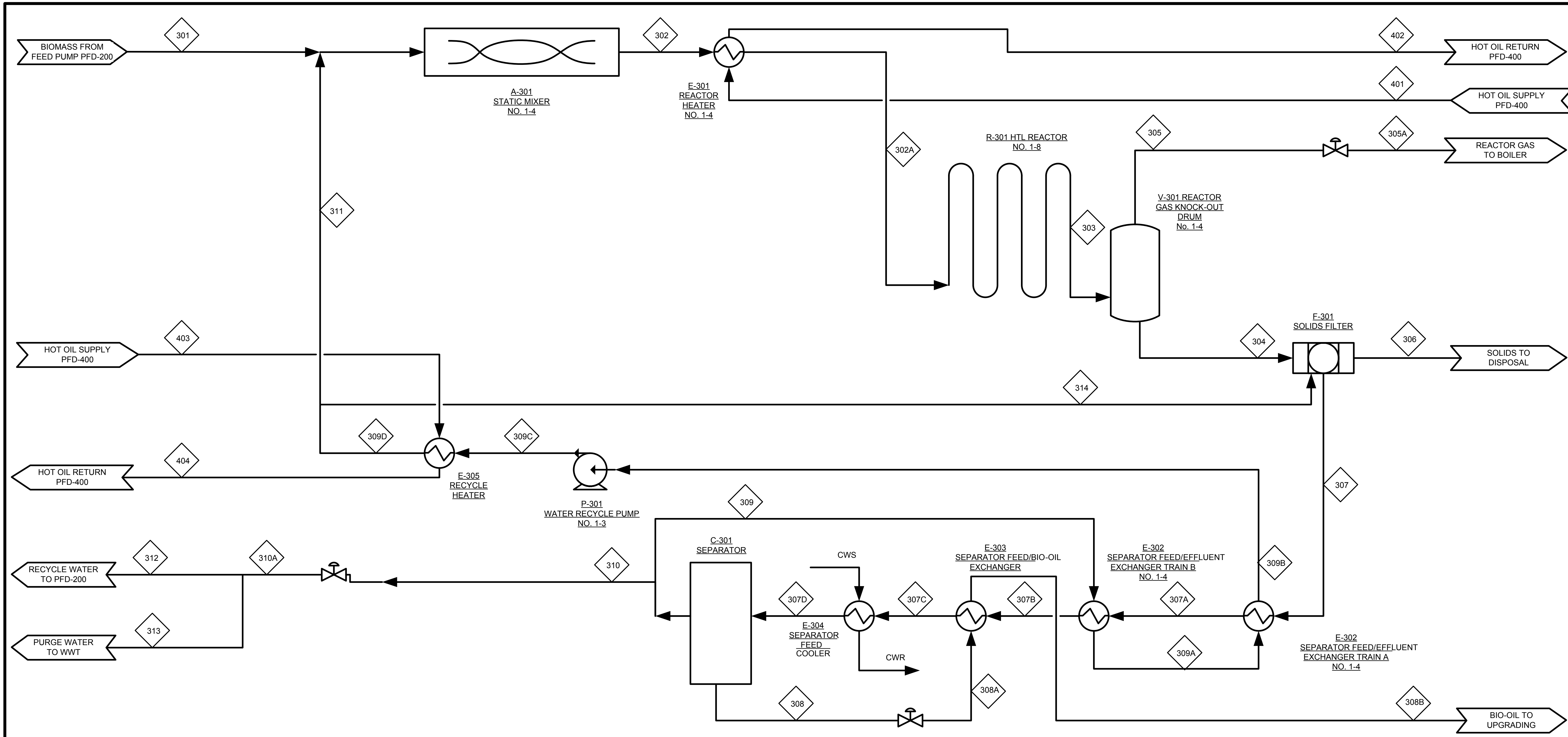
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 200: FEED PREPARATION

Project No: 30352.00 | Drawing: PFD-200D-L | Rev: B



STREAM NO.	301	302	302A	303	304	305	305A	306	307	307A	307B	307C	307D	308	308A
TOTAL (LB/HR)	501,419	1,225,235	1,225,235	1,225,236	1,192,536	32,699	32,699	8,587	1,187,031	1,187,031	1,187,031	1,187,031	1,187,031	68,304	68,304
T (°C)	48	242	350	348	348	348	208	347	347	327	204	147	80	80	81
P (psig)	3200	3100	3050	3025	3025	3025	250	3005	3005	2970	2940	2910	2890	2890	2015
WATER (LB/HR)	269,954	774,730	774,730	780,180	780,180	0	0	2,149	780,180	780,180	780,180	780,180	780,180	0	0
WOOD	183,534	183,534	183,534	0	0	0	0	0	0	0	0	0	0	0	0
BIO-OIL	0	0	0	54,039	54,039	0	0	0	54,039	54,039	54,039	54,039	54,039	54,039	54,039
CHAR	0	0	0	5,505	5,505	0	0	5,505	0	0	0	0	0	0	0
GAS	0	0	0	32,699	0	32,699	32,699	0	0	0	0	0	0	0	0
AQ ORGANICS	1,419	8,311	8,311	24,917	24,917	0	0	29	24,917	24,917	24,917	24,917	24,917	14,265	14,265
FS AQ ORGANICS	41,980	245,822	245,822	315,057	315,057	0	0	868	315,057	315,057	315,057	315,057	315,057	0	0
SODA	4,532	12,838	12,838	12,838	12,838	0	0	35	12,838	12,838	12,838	12,838	12,838	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WATER (WT%)	53.8%	63.2%	63.2%	63.7%	65.4%	0.0%	0.0%	25.0%	65.7%	65.7%	65.7%	65.7%	65.7%	0.0%	0.0%
WOOD	36.6%	15.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	4.4%	4.5%	0.0%	0.0%	0.0%	4.6%	4.6%	4.6%	4.6%	4.6%	79.1%	79.1%
CHAR	0.0%	0.0%	0.0%	0.4%	0.5%	0.0%	0.0%	64.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	2.7%	0.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.3%	0.7%	0.7%	2.0%	2.1%	0.0%	0.0%	0.3%	2.1%	2.1%	2.1%	2.1%	2.1%	20.9%	20.9%
FS AQ ORGANICS	8.4%	20.1%	20.1%	25.7%	26.4%	0.0%	0.0%	10.1%	26.5%	26.5%	26.5%	26.5%	26.5%	0.0%	0.0%
SODA	0.9%	1.0%	1.0%	1.0%	1.1%	0.0%	0.0%	0.4%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

STREAM NO.	308B	309	309A	309B	309C	309D	310	310A	311	312	313	314	401	402	403	404
TOTAL (LB/HR)	68,304	726,898	726,898	726,898	726,898	726,898	391,829	391,829	723,816	149,065	242,764	3,082	11,073,155	11,073,155	806,453	806,453
T (°C)	187	80	302	339	339	350	80	80	348	80	80	350	380	350	380	350
P (psig)	2000	2890	2860	2830	3220	3200	2890	300	3200	100	100	3200	160	140	160	140
WATER (LB/HR)	0	506,926	506,926	506,926	506,926	506,926	273,254	273,254	504,776	103,955	169,299	2,149	0	0	0	0
WOOD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BIO-OIL	54,039	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AQ ORGANICS	14,265	6,921	6,921	6,921	6,921	6,921	3,731	3,731	6,892	1,419	2,311	29	0	0	0	0
FS AQ ORGANICS	0	204,710	204,710	204,710	204,710	204,710	110,347	110,347	203,842	41,980	68,367	868	0	0	0	0
SODA	0	8,341	8,341	8,341	8,341	8,341	4,496	4,496	8,306	1,711	2,786	35	0	0	0	0
AIR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEATING OIL	0	0	0	0	0	0	0	0	0	1	2	1	11,073,155	11,073,155	806,453	806,453
WATER (WT%)	0.0%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	69.7%	0.0%	0.0%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	79.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	20.9%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	0.0%	0.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	28.2%	0.0%	0.0%	0.0%	0.0%
SODA	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	0.0%	0.0%	0.0%	0.0%
AIR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

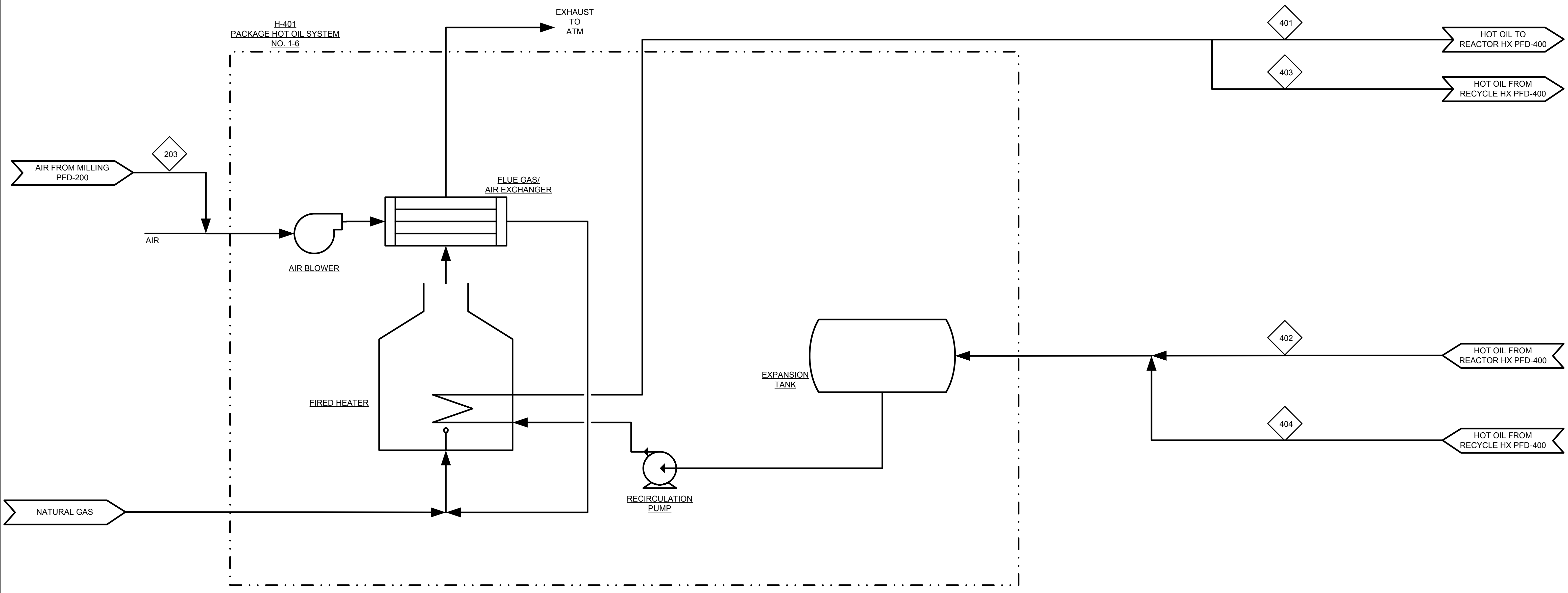
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 300: HTL REACTOR OPTION D

Project No: 30352.00
Drawing: PFD-300D-L
Rev: B



STREAM NO.	203	401	402	403	404
TOTAL (LB/HR)	265,653	11,073,155	11,073,155	806,453	806,453
T (°C)	25	380	350	380	350
P (psig)	1	160	140	160	140
WATER (LB/HR)	8,076	0	0	0	0
WOOD	0	0	0	0	0
BIO-OIL	0	0	0	0	0
CHAR	0	0	0	0	0
GAS	0	0	0	0	0
AQ ORGANICS	0	0	0	0	0
FS AQ ORGANICS	0	0	0	0	0
SODA	0	0	0	0	0
AIR	257,577	0	0	0	0
HEATING OIL	0	11,073,155	11,073,155	806,453	806,453
WATER (WT%)	3.0%	69.7%	69.7%	0.0%	0.0%
WOOD	0.0%	0.0%	0.0%	0.0%	0.0%
BIO-OIL	0.0%	0.0%	0.0%	0.0%	0.0%
CHAR	0.0%	0.0%	0.0%	0.0%	0.0%
GAS	0.0%	0.0%	0.0%	0.0%	0.0%
AQ ORGANICS	0.0%	1.0%	1.0%	0.0%	0.0%
FS AQ ORGANICS	0.0%	28.2%	28.2%	0.0%	0.0%
SODA	0.0%	1.1%	1.1%	0.0%	0.0%
AIR	97.0%	0.0%	0.0%	0.0%	0.0%
HEATING OIL	0.0%	100.0%	100.0%	100.0%	100.0%

Harris Group Inc.
Engineering for Optimum Performance®
www.harrisgroup.com

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NATIONAL RENEWABLE
ENERGY LABORATORY

Subconsultant:	-		
Drawn: DBK	-	Check:	-
Engr: DBK	-	Check:	-
Appr:	-	PMgr: JCL	-

PROCESS FLOW DIAGRAM
AREA 400: HOT OIL SYSTEM

Project No: 30352.00 | Drawing: PFD-400D-L | Rev: B

APPENDIX B

DESIGN BASIS

Harris Group Inc.		REV	DATE	BY	
Harris Group Project Number:	30352.00				NREL HTL Reactor Design: Utilities
Engr: DBK	Date: 3/20/2013				

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
UTILITIES					
Boilers supplied by others					
Cooling water supplied by others					
Electrical supplied by others					
STEAM					
Medium pressure steam pressure	psig	150			Assumed by Harris Group - approved by M. Biddy phone call 1/14/13
Low pressure steam pressure	psig	40			Assumed by Harris Group
Medium pressure steam value	$/short ton	0.4			Mary Biddy email 2/7/13
Low pressure steam value	$/short ton	0.4			Mary Biddy email 2/7/13
COOLING WATER					
Supply temperature	F	85			Assumed by Harris Group
Return temperature	F	100			Assumed by Harris Group
ELECTRICITY	$kWh	$0.06695			Mary Biddy email 2/7/13
Natural Gas	$/lb	$0.09230			Mary Biddy email 2/7/13
Natural Gas	BTU/scf	1,000			Assumed by Harris Group

Harris Group Inc.	REV	DATE	BY	
Harris Group Project Number: 30352.00				NREL HTL Reactor Design: Common
Engr: DBK Date: 3/20/2013				

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
GENERAL OPERATING BASIS					
On-Stream Factor	%	90			NREL Design Detail Spreadsheet
Feed Rate (solids)	DMTD	2,000			
Feed Type	Loblolly Pine Chips				
Temperature of streams coming from storage	C	25			Assumed by Harris Group
Components for PFD material balance:					
Water					
Wood					
Char					
Bio-oil					Assumed by Harris Group, simplified from Aspen model provided by NREL
Product Gas					
Fully Soluble Aqueous Organics					
Partially Soluble Aqueous Organics					
Soda Ash					

Harris Group Inc.		REV	DATE	BY	
Harris Group Project Number:	30352.00				NREL HTL Reactor Design: Area 100
Engr: DBK	Date: 3/20/2013				

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
OFFLOADING					
Bulk wood chip density	kg/m3	345	490		Wood fuels handbook ~22lb/ft3
Bulk wood chip moisture content	%	48%			NREL Design Detail Spreadsheet
Total mass of chips with moisture	MTD	3846			Calculated
Total volume chips	m3/day	11,148			Calculated
Wood chip truck volume	m3	50			Coford Connects Infosheet
Trucks/day		223			Calculated
Minutes/truck	min	10			Per Phelps Industries
Unloading day	h	10			Assumed by Harris Group
Required truck tippers		4			Calculated
STORAGE					
Chip storage capacity	day	14			Assumed by Harris Group/Suggested on NREL Design
Chip storage volume	m3	156,076			Calculated
SCREENING					
% rejects expected	wt%	0.1			Assumed by Harris Group

Harris Group Inc.		REV	DATE	BY	NREL NATIONAL RENEWABLE ENERGY LABORATORY
Harris Group Project Number:	30352.00				NREL HTL Reactor Design: Area 200
Engr: DBK	Date: 3/20/2013				

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
DISC or HAMMER MILL					
Average inlet size	in	2			NREL HTL design detail spreadsheet
Average outlet particle size	mm	3			Assumed by Harris Group noting that slump tests for particles >=1.6mm did not slump and showed some
Air flow requirement	CFM	7800			per mill per Andritz
Moisture loss of wood	%	4-6			per Andritz
Milled feed density	kg/m3	448			Assumed by Harris Group (wet, coarse sawdust)
Air static pressure (minimum)	in. H2O	6			per Andritz
MILLED FEED BIN					
Storage time	h	0.25			Assumed by Harris Group
NA2CO3 Mix Tank					
Capacity	hr	0.5			Assumed by Harris Group
Temperature	C	20			Assumed by Harris Group
Na2CO3 % of saturation solubility	%	75%			Assumed by Harris Group
NA2CO3 SUPER SACK FEEDER					
Super sack size	std tons	1			Assumed by Harris Group
MAKEUP WATER PUMP					
Required head	ft	150			Assumed by Harris Group
NA2CO3 SOLUTION PUMP					
Required head	ft	150			Assumed by Harris Group
STATIC MIXER					
Maximum pressure drop	psi	15			Assumed by Harris Group
LIVE BOTTOM BIN					
Feedstock bin capacity	hr	0.50			Assumed by Harris Group
DILUTION CONVEYOR					
Recycle water (% of product water)	%	80.0%			Kick-off meeting (ideal, will depend on water content in solid feed, organic content)
Solids content in pump feed	wt %	10-15%			NREL Design Details Spreadsheet
SLURRY TANK					
Slurry tank capacity	hr	4.00			Assumed by Harris Group
BIOMASS FEED PUMPS					
Discharge pressure	psig	2400-3000	3200		Plus delta P across exchangers, etc. NREL Design Details Spreadsheet
pH		8-10			NREL Design Details Spreadsheet
Outlet mass flow rate	lb/hr	1395740-2008135			NREL Design Details (depends on solid mass)

Harris Group Inc.

REV	DATE	BY

Harris Group Project Number:	30352.00	NREL HTL Reactor Design: Area 300
Engr: DBK	Date: 3/20/2013	

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
FEED PREHEATER(s)					
Maximum feed discharge temperature (Options A&C)	°C	150-160			Based on avoiding viscosity peak near 170 °C--NREL Design Detail Spreadsheet
Heat capacity, thermal conductivity		similar to water			Based on high water content and lack of data
Physical property package used		IAPWS-95 or SRK			Important due to proximity to critical point, Cp changes
Minimum tube ID (all 300 level exchangers)	in.	1.5			Assumed by Harris Group
FEED HEATER(s)					
Maximum wall temperature	°C	370-380			Per A. Schmidt, Kick-off meeting
Reactor feed discharge temperature	°C	330-350			NREL spreadsheet 12/4/2012
Reactor feed discharge pressure	psig	2400-3000			NREL spreadsheet 12/4/2012
Heat transfer coefficients		See heat transfer coefficient spreadsheet			Based on Literature: Yamagata et al., Int. J. Heat Mass Transfer, v. 15. pp. 2575-2593 (1972) and Nakamura et al. J. Chem. Eng. Jap., v. 41, pp. 817-828 (2008)
HTL REACTOR					
Sodium carbonate concentration in reactor feed	wt%	1.00			Kick-off meeting/Mid Stage 2 Report on HTL Strategy for
LHSV range	L/L/h	2-8			NREL spreadsheet 12/4/2012 based on feed volume at ambient temperature
pH		4-5			NREL spreadsheet 12/4/2012
TAN	mg KOH/g	20-50			NREL spreadsheet 12/4/2012
Viscosity	cSt	2000-65000			at 40C NREL spreadsheet 12/4/2012
Heat capacity, thermal conductivity		assume water			NREL spreadsheet 12/4/2012
Heat of reaction	MMBTU/hr	2-10			Endothermic based on aspen estimates (NREL spreadsheet
Yields: (mass% of wood)					
Gas		17.8%			Based on SOT Aspen model provided by NREL, in reasonable agreement with SOT Mass balance provided at kick-off meeting
Bio-oil		29.4%			
Partially water soluble organics		9.0%			
Fully water soluble organics		37.7%			
Solids		3.0%			
WATER		3.0%			
HEATER RECYCLE PUMP					
Head required	ft	150			Assumed by Harris Group
Recycle mixing point temperature	°C	250			Assumed by Harris Group
SOLIDS FILTER					
Pressure drop	psi	50			Based on conversation with Pall Corporation
SEPARATOR					
Pressure drop	psi	0			Based on conversation with Pall Corporation - depends on backflush rate
LET DOWN GENERATOR					
Max discharge pressure	psi	300.0			Or dictated by saturation point at temperature
RECYCLE COOLER					
Water recycle outlet temperature	°C	80			Assumed by Harris Group
BIO-OIL OUTLET					
Bio-oil outlet temperature	°C	240			M. Biddy email 12/13/2012 noting bio-oil should be hot and at high pressure for further processing
Bio-oil outlet pressure	psig	2,000			M. Biddy email 12/13/2012 noting bio-oil should be hot and at high pressure for further processing

Harris Group Inc.

REV	DATE	BY

NATIONAL RENEWABLE ENERGY LABORATORY

Harris Group Project Number:	30352.00
Engr: DBK	Date: 3/20/2013

NREL HTL Reactor Design: Area 400

PROCESS DESIGN BASIS

Basis Data	Units	Design	Max	Avg	Comment/Reference
THERMAL FLUID					
Energy source		Natural Gas			Assumed by Harris Group
Net heating value	BTU/scf	950			Assumed by Harris Group
Maximum thermal fluid temperature	C	380			Based on max wall temperature in reactor

APPENDIX C

PRICED EQUIPMENT LISTS

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE A

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
		FEED HANDLING																							
	M-101A	TRUCK SCALE NO. 1	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-101B	TRUCK SCALE NO. 2	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-102A	TRUCK TIPPER NO. 1	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102B	TRUCK TIPPER NO. 2	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102C	TRUCK TIPPER NO. 3	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102D	TRUCK TIPPER NO. 4	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-103	OFFLOAD CONVEYOR	100						2			CS		USD 250,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 250,000	$ 254,475	$ 432,608
	M-104	STACKER/RECLAIMER	100				350,000lb/hr		50			CS		USD 4,000,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 4,000,000	$ 4,071,602	$ 6,921,724
	F-101	CHIP SCREEN	100			10x18ft			30			CS		USD 173,820	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 173,820	$ 176,931	$ 300,784
	M-105	CHIP TRANSFER CONVEYOR	100			200ft			2			CS		USD 225,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 225,000	$ 229,028	$ 389,347
		FEED PREPARATION																							
	B-201	MILL AIR BLOWER	200			55000cfm			150			CS		USD 40,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 40,000	$ 40,716	$ 65,146
	N-201	CYCLONIC FILTER	200			9300ft3						CS		USD 125,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 125,000	$ 127,238	$ 203,580
	N-202	ROTARY AIR LOCK	200						5			CS		USD 10,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 10,000	$ 10,179	$ 16,286
	M-201	CHIP ELEVATOR	200			50ft			5			CS		USD 100,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 100,000	$ 101,790	$ 173,043
	M-202	DRAG CHAIN CONVEYOR	200			200ft			5			CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-201A	FEEDSTOCK FEED BIN NO. 1	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201B	FEEDSTOCK FEED BIN NO. 2	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201C	FEEDSTOCK FEED BIN NO. 3	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201D	FEEDSTOCK FEED BIN NO. 4	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201E	FEEDSTOCK FEED BIN NO. 5	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201F	FEEDSTOCK FEED BIN NO. 6	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201G	FEEDSTOCK FEED BIN NO. 7	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	L-201A	FIRST STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201B	FIRST STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201C	FIRST STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201D	FIRST STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201E	FIRST STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201F	FIRST STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201G	FIRST STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	F-201A	MAGNET SEPARATOR NO. 1	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201B	MAGNET SEPARATOR NO. 2	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201C	MAGNET SEPARATOR NO. 3	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201D	MAGNET SEPARATOR NO. 4	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201E	MAGNET SEPARATOR NO. 5	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201F	MAGNET SEPARATOR NO. 6	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201G	MAGNET SEPARATOR NO. 7	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	L-202A	SECOND STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202B	SECOND STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202C	SECOND STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202D	SECOND STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202E	SECOND STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202F	SECOND STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202G	SECOND STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	M-203	DRAG CHAIN CONVEYOR	200									CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-202A	LIVE BOTTOM BIN NO. 1	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202B	LIVE BOTTOM BIN NO. 2	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202C	LIVE BOTTOM BIN NO. 3	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202D	LIVE BOTTOM BIN NO. 4	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	M-204A	DILUTION CONVEYOR NO. 1	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204B	DILUTION CONVEYOR NO. 2	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204C	DILUTION CONVEYOR NO. 3	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204D	DILUTION CONVEYOR NO. 4	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-205A	TWIN SCREW FEEDER NO. 1	200				190gpm		9200		460	Chrome lined	add 5% for 316L	USD 4,376,400	2011	Pump Feed	2300	gpm	0.8	2.3	2300	2300	$ 4,376,400	$ 4,376,400	$ 10,065,720
	M-205B	TWIN SCREW FEEDER NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205C	TWIN SCREW FEEDER NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205D	TWIN SCREW FEEDER NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205E	TWIN SCREW FEEDER NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205F	TWIN SCREW FEEDER NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205G	TWIN SCREW FEEDER NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205H	TWIN SCREW FEEDER NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205I	TWIN SCREW FEEDER NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205J	TWIN SCREW FEEDER NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205K	TWIN SCREW FEEDER NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205L	TWIN SCREW FEEDER NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203A	BIOMASS FEED PUMP NO. 1	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203B	BIOMASS FEED PUMP NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203C	BIOMASS FEED PUMP NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203D	BIOMASS FEED PUMP NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203E	BIOMASS FEED PUMP NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203F	BIOMASS FEED PUMP NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203G	BIOMASS FEED PUMP NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203H	BIOMASS FEED PUMP NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203I	BIOMASS FEED PUMP NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203J	BIOMASS FEED PUMP NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203K	BIOMASS FEED PUMP NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203L	BIOMASS FEED PUMP NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-201	MAKEUP WATER PUMP	200				10gpm	150ft	5			316L		USD 8,700	2013	pump feed	10	gpm	0.8	2.3	10	1.00	$ 8,700	$ 8,856	$ 20,368
	A-201	NA2CO3 SOLUTION AGITATOR	200			8'ϕ			30			316L		USD 40,628	2013	N/A	N/A	N/A	0.5	1.5	10	N/A	$ 40,628	$ 41,355	$ 62,033
	T-204	NA2CO3 SOLUTION MAKEUP TANK	200			12'ϕ ⊥ 11'	9500gal					316L		USD 90,460	2012	capacity	15000	gal	0.7	1.5	9500	0.63	$ 65,705	$ 66,881	$ 100,322
	P-202	NA2CO3 SOLUTION PUMP	200				300gpm	150ft	20			Duplex SS		USD 10,930	2013	pump feed	300	gpm	0.8	2.3	300	1.00	$ 10,930	$ 11,126	$ 25,589
	A-202	STATIC MIXER	200			10"x29"								USD 3,696	2013	Flow	N/A	gpm	0.5	1	N/A	1	$3,696	$3,762	$3,762
	M-206	NA2CO3 SUPER SACK FEEDER	200						5					USD 54,600	2013	N/A	N/A	N/A	N/A	1.7	N/A	N/A	$ 54,600	$ 55,577	$ 94,482
		HTL REACTION SECTION																							
	A-301A	STATIC MIXER NO. 1	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	1800	2.40	$ 26,553	$ 27,028	$ 27,028
	A-301B	STATIC MIXER NO. 2	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	1800	2.40	$ 26,553	$ 27,028	$ 27,028
	A-301C	STATIC MIXER NO. 3	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	1800	2.40	$ 26,553	$ 27,028	$ 27,028
	A-301D	STATIC MIXER NO. 4	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	1800	2.40	$ 26,553	$ 27,028	$ 27,028
	E-301A	PURGE/REACTOR EXCHANGER NO. 1	300				60 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 4,913,333	2013	Area	7500	ft2	0.7	2.2	7720	1.03	$ 5,013,647	$ 5,103,394	$ 11,227,468
	E-301B	PURGE/REACTOR EXCHANGER NO. 2	300				60 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 4,913,333	2013	Area	7500	ft2	0.7	2.2	7720	1.03	$ 5,013,647	$ 5,103,394	$ 11,227,468
	E-301C	PURGE/REACTOR EXCHANGER NO. 3	300				60 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 4,913,333	2013	Area	7500	ft2	0.7	2.2	7720	1.03	$ 5,013,647	$ 5,103,394	$ 11,227,468
	E-301D	PURGE/REACTOR EXCHANGER NO. 4	300				60 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 4,913,333	2013	Area	7500	ft2	0.7	2.2	7720	1.03	$ 5,013,647	$ 5,103,394	$ 11,227,468
	E-302A	REACTOR HEATER NO. 1	300				114.50 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	9496 ft2	1.57	$ 1,372,282	$ 1,396,847	$ 3,073,063
	E-302B	REACTOR HEATER NO. 2	300				114.50 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	9496 ft2	1.57	$ 1,372,282	$ 1,396,847	$ 3,073,063
	E-302C	REACTOR HEATER NO. 3	300				114.50 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	9496 ft2	1.57	$ 1,372,282	$ 1,396,847	$ 3,073,063
	E-302D	REACTOR HEATER NO. 4	300				114.50 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	9496 ft2	1.57	$ 1,372,282	$ 1,396,847	$ 3,073,063
	R-301A	HTL REACTOR NO. 1	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301B	HTL REACTOR NO. 2	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301C	HTL REACTOR NO. 3	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301D	HTL REACTOR NO. 4	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	V-301	REACTOR GAS KO DRUM	300				4x4230 gal					316	316L cladded CS shell	USD 5,600,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 5,600,000	$ 5,700,243	$ 11,400,487
	V-302A	RECYCLE GAS KO DRUM NO. 1	300				4230 gal					316	316L cladded CS shell	USD 1,400,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 1,400,000	$ 1,425,061	$ 2,850,122
	V-302B	RECYCLE GAS KO DRUM NO. 2	300				4230 gal					316	316L cladded CS shell	USD 1,400,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 1,400,000	$ 1,425,061	$ 2,850,122
	V-302C	RECYCLE GAS KO DRUM NO. 3	300				4230 gal					316	316L cladded CS shell	USD 1,400,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 1,400,000	$ 1,425,061	$ 2,850,122
	V-302D	RECYCLE GAS KO DRUM NO. 4	300				4230 gal					316	316L cladded CS shell	USD 1,400,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 1,400,000	$ 1,425,061	$ 2,850,122
	F-301	SOLIDS FILTER	300				3894gpm					316L		USD 1,311,000	2011	Filter Feed	3689	gpm	0.6	1.7	2420	0.66	$ 1,017,998	$ 1,017,998	$ 1,730,596
	C-301	SEPARATOR	300				3894gpm					316L		USD 3,565,000	2011	SEPARATOR Feed	3689	gpm	0.7	2.0	2420	0.66	$ 2,653,959	$ 2,653,959	$ 5,307,918
	P-301A	WATER RECYCLE PUMP NO. 1	300				1400gpm	750ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	1400	1.17	$ 433,041	$ 440,793	$ 1,013,824
	P-301B	WATER RECYCLE PUMP NO. 2	300				1400gpm	750ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	1400	1.17	$ 433,041	$ 440,793	$ 1,013,824
	P-301C	WATER RECYCLE PUMP NO. 3	300				1400gpm	750ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	1400	1.17	$ 433,041	$ 440,793	$ 1,013,824
	P-301D	WATER RECYCLE PUMP NO. 4	300				1400gpm	750ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	1400	1.17	$ 433,041	$ 440,793	$ 1,013,824

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE A

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS
	E-303	BIO-OIL HEAT RECOVERY STEAM GENERATOR	300				17.1 MMBTU/hr					316L	95 BTU/hr/ft2/F
	E-304	PURGE HEAT RECOVERY STEAM GENERATOR	300				135.3 MMBTU/hr					347	100 BTU/hr/ft2/F
	E-305	PURGE WATER COOLER	300			13863ft 2	229.3 MMBTU/hr					316L/CS	
		HOT OIL SYSTEM											
	H-401A	PACKAGE HOT OIL SYSTEM NO. 1	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401B	PACKAGE HOT OIL SYSTEM NO. 2	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401C	PACKAGE HOT OIL SYSTEM NO. 3	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401D	PACKAGE HOT OIL SYSTEM NO. 4	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401E	PACKAGE HOT OIL SYSTEM NO. 5	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401F	PACKAGE HOT OIL SYSTEM NO. 6	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401G	PACKAGE HOT OIL SYSTEM NO. 7	400				63.6 MMBTU/hr		150				90% Efficiency
	H-401H	PACKAGE HOT OIL SYSTEM NO. 8	400				63.6 MMBTU/hr		150				90% Efficiency
		HOT OIL	400				63400 gal						
		TOTALS							20,221				

DESCRIPTION	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
BIO-OIL HEAT RECOVERY STEAM GENERATOR	USD 102,000	2012	Area	868	ft2	0.7	2.2	868 ft2	1.00	$ 101,991	$ 101,991	$ 224,380
PURGE HEAT RECOVERY STEAM GENERATOR	USD 8,305,320	2013	Area	25500	ft2	0.7	2.2	25722 ft2	1.01	$ 8,355,966	$ 8,505,543	$ 18,712,195
PURGE WATER COOLER	USD 255,600	2013	area	13020	ft	0.8	2.3	13863	1.06	$ 268,756	$ 273,567	$ 629,203
HOT OIL SYSTEM												
PACKAGE HOT OIL SYSTEM NO. 1	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 2	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 3	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 4	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 5	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 6	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 7	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
PACKAGE HOT OIL SYSTEM NO. 8	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	63.6 MMBTU/hr	1.06	$ 1,243,344	$ 1,265,600	$ 2,278,081
HOT OIL	USD 2,101,710	USD 2,012	N/A	N/A	N/A	N/A	USD 1	N/A	N/A	$ 2,101,710	$ 2,139,332	$ 2,139,332
TOTALS										**$ 88,844,000**	**$ 90,289,000**	**$ 183,726,000**

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE: 3/18/13

Harris Group - NREL

Mechanical Equipment List CASE B

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATI FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
		FEED HANDLING																							
	M-101A	TRUCK SCALE NO. 1	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-101B	TRUCK SCALE NO. 2	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-102A	TRUCK TIPPER NO. 1	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102B	TRUCK TIPPER NO. 2	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102C	TRUCK TIPPER NO. 3	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102D	TRUCK TIPPER NO. 4	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-103	OFFLOAD CONVEYOR	100						2			CS		USD 250,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 250,000	$ 254,475	$ 432,608
	M-104	STACKER/RECLAIMER	100				350,000lb/hr		50			CS		USD 4,000,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 4,000,000	$ 4,071,602	$ 6,921,724
	F-101	CHIP SCREEN	100			10x18ft			30			CS		USD 173,820	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 173,820	$ 176,931	$ 300,784
	M-105	CHIP TRANSFER CONVEYOR	100			200ft			2			CS		USD 225,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 225,000	$ 229,028	$ 389,347
		FEED PREPARATION																							
	B-201	MILL AIR BLOWER	200			55000cfm			150			CS		USD 40,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 40,000	$ 40,716	$ 65,146
	N-201	CYCLONIC FILTER	200			9300ft3						CS		USD 125,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 125,000	$ 127,238	$ 203,580
	N-202	ROTARY AIR LOCK	200						5			CS		USD 10,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 10,000	$ 10,179	$ 16,286
	M-201	CHIP ELEVATOR	200			50ft			5			CS		USD 100,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 100,000	$ 101,790	$ 173,043
	M-202	DRAG CHAIN CONVEYOR	200			200ft			5			CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-201A	FEEDSTOCK FEED BIN NO. 1	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201B	FEEDSTOCK FEED BIN NO. 2	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201C	FEEDSTOCK FEED BIN NO. 3	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201D	FEEDSTOCK FEED BIN NO. 4	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201E	FEEDSTOCK FEED BIN NO. 5	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201F	FEEDSTOCK FEED BIN NO. 6	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201G	FEEDSTOCK FEED BIN NO. 7	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	L-201A	FIRST STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201B	FIRST STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201C	FIRST STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201D	FIRST STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201E	FIRST STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201F	FIRST STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201G	FIRST STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	F-201A	MAGNET SEPARATOR NO. 1	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201B	MAGNET SEPARATOR NO. 2	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201C	MAGNET SEPARATOR NO. 3	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201D	MAGNET SEPARATOR NO. 4	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201E	MAGNET SEPARATOR NO. 5	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201F	MAGNET SEPARATOR NO. 6	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201G	MAGNET SEPARATOR NO. 7	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	L-202A	SECOND STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202B	SECOND STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202C	SECOND STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202D	SECOND STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202E	SECOND STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202F	SECOND STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202G	SECOND STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	M-203	DRAG CHAIN CONVEYOR	200									CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-202A	LIVE BOTTOM BIN NO. 1	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202B	LIVE BOTTOM BIN NO. 2	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202C	LIVE BOTTOM BIN NO. 3	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202D	LIVE BOTTOM BIN NO. 4	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	M-204A	DILUTION CONVEYOR NO. 1	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204B	DILUTION CONVEYOR NO. 2	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204C	DILUTION CONVEYOR NO. 3	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204D	DILUTION CONVEYOR NO. 4	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-205A	TWIN SCREW FEEDER NO. 1	200				190gpm		9200		460	Chrome lined	add 5% for 316L	USD 4,376,400	2011	Pump Feed	2300	gpm	0.8	2.3	2300	2300	$ 4,376,400	$ 4,376,400	$ 10,065,720
	M-205B	TWIN SCREW FEEDER NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205C	TWIN SCREW FEEDER NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205D	TWIN SCREW FEEDER NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205E	TWIN SCREW FEEDER NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205F	TWIN SCREW FEEDER NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205G	TWIN SCREW FEEDER NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205H	TWIN SCREW FEEDER NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205I	TWIN SCREW FEEDER NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205J	TWIN SCREW FEEDER NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205K	TWIN SCREW FEEDER NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205L	TWIN SCREW FEEDER NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203A	BIOMASS FEED PUMP NO. 1	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203B	BIOMASS FEED PUMP NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203C	BIOMASS FEED PUMP NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203D	BIOMASS FEED PUMP NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203E	BIOMASS FEED PUMP NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203F	BIOMASS FEED PUMP NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203G	BIOMASS FEED PUMP NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203H	BIOMASS FEED PUMP NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203I	BIOMASS FEED PUMP NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203J	BIOMASS FEED PUMP NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203K	BIOMASS FEED PUMP NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203L	BIOMASS FEED PUMP NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-201	MAKEUP WATER PUMP	200				10gpm	150ft	5			316L		USD 8,700	2013	pump feed	10	gpm	0.8	2.3	10	1.00	$ 8,700	$ 8,856	$ 20,368
	A-201	NA2CO3 SOLUTION AGITATOR	200			8'ϕ			30			316L		USD 40,628	2013	N/A	N/A	N/A	0.5	1.5	10	N/A	$ 40,628	$ 41,355	$ 62,033
	T-204	NA2CO3 SOLUTION MAKEUP TANK	200			12'ϕ 11'	9500gal					316L		USD 90,460	2012	capacity	15000	gal	0.7	1.5	9500	0.63	$ 65,705	$ 66,881	$ 100,322
	P-202	NA2CO3 SOLUTION PUMP	200				300gpm	150ft	20			Duplex SS		USD 10,930	2013	pump feed	300	gpm	0.8	2.3	300	1.00	$ 10,930	$ 11,126	$ 25,589
	A-202	STATIC MIXER	200			10"x29"								USD 3,696	2013	Flow	N/A	gpm	0.5	1.0	N/A	1.00	$ 3,696	$ 3,762	$ 3,762
	M-206	NA2CO3 SUPER SACK FEEDER	200						5					USD 54,600	2013	N/A	N/A	N/A	N/A	1.7	N/A	N/A	$ 54,600	$ 55,577	$ 94,482
		HTL REACTION SECTION																							
	E-301A	FIRST FEED PREHEATER NO. 1	300				46.0 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 44,604,000	2012	Area	49756	ft2	0.7	2.2	52942 ft2	1.06	$ 46,584,539	$ 47,418,430	$ 104,320,545
	E-301B	FIRST FEED PREHEATER NO. 2	300				46.0 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 44,604,000	2012	Area	49756	ft2	0.7	2.2	52942 ft2	1.06	$ 46,584,539	$ 47,418,430	$ 104,320,545
	E-301C	FIRST FEED PREHEATER NO. 3	300				46.0 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 44,604,000	2012	Area	49756	ft2	0.7	2.2	52942 ft2	1.06	$ 46,584,539	$ 47,418,430	$ 104,320,545
	E-301D	FIRST FEED PREHEATER NO. 4	300				46.0 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 44,604,000	2012	Area	49756	ft2	0.7	2.2	52942 ft2	1.06	$ 46,584,539	$ 47,418,430	$ 104,320,545
	E-302A	SECOND FEED PREHEATER NO. 1	300				35.3 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 31,860,000	2012	Area	35540	ft2	0.7	2.2	37216 ft2	1.05	$ 32,904,232	$ 33,493,238	$ 73,685,123
	E-302B	SECOND FEED PREHEATER NO. 2	300				35.3 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 31,860,000	2012	Area	35540	ft2	0.7	2.2	37216 ft2	1.05	$ 32,904,232	$ 33,493,238	$ 73,685,123
	E-302C	SECOND FEED PREHEATER NO. 3	300				35.3 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 31,860,000	2012	Area	35540	ft2	0.7	2.2	37216 ft2	1.05	$ 32,904,232	$ 33,493,238	$ 73,685,123
	E-302D	SECOND FEED PREHEATER NO. 4	300				35.3 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 31,860,000	2012	Area	35540	ft2	0.7	2.2	37216 ft2	1.05	$ 32,904,232	$ 33,493,238	$ 73,685,123
	E-303A	FEED/RECYCLE EXCHANGER NO. 1	300				65.6 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2012	Area	4500	ft2	0.7	2.2	5511 ft2	1.22	$ 3,397,443	$ 3,458,259	$ 7,608,169
	E-303B	FEED/RECYCLE EXCHANGER NO. 2	300				65.6 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2012	Area	4500	ft2	0.7	2.2	5511 ft2	1.22	$ 3,397,443	$ 3,458,259	$ 7,608,169

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE: 3/18/13

Harris Group - NREL

Mechanical Equipment List CASE B

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE
	E-303C	FEED/RECYCLE EXCHANGER NO. 3	300				65.6 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2012
	E-303D	FEED/RECYCLE EXCHANGER NO. 4	300				65.6 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2012
	E-304A	FINAL FEED HEATER NO. 1	300				32.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012
	E-304B	FINAL FEED HEATER NO. 2	300				32.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012
	E-304C	FINAL FEED HEATER NO. 3	300				32.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012
	E-304D	FINAL FEED HEATER NO. 4	300				32.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012
	R-301A	HTL REACTOR NO. 1	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013
	R-301B	HTL REACTOR NO. 2	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013
	R-301C	HTL REACTOR NO. 3	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013
	R-301D	HTL REACTOR NO. 4	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013
	V-301	REACTOR GAS KO DRUM	300				4x4230 gal					316	316L cladded CS shell	USD 5,600,000	2012
	F-301	SOLIDS FILTER	300				3894gpm					316L		USD 1,311,000	2011
	C-301	SEPARATOR	300				3894gpm					316L		USD 3,565,000	2011
	E-305	BIO-OIL HEAT RECOVERY STEAM GENERATOR	300				17.1 MMBTU/hr					316L	95 BTU/hr/ft2/F	USD 102,000	2012
	E-306	RECYCLE WATER COOLER	300				30.6 MMBTU/hr					316L	100 BTU/hr/ft2/F	USD 63,900	2012
		HOT OIL SYSTEM													
	H-401A	PACKAGE HOT OIL SYSTEM NO. 1	400				71.2 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
	H-401B	PACKAGE HOT OIL SYSTEM NO. 2	400				71.2 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
		HOT OIL	400				23200 gal							USD 769,080	USD 2,012
		TOTALS							18,521						

EQPT NO.	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATI FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
E-303C	Area	4500	ft2	0.7	2.2	5511 ft2	1.22	$ 3,397,443	$ 3,458,259	$ 7,608,169
E-303D	Area	4500	ft2	0.7	2.2	5511 ft2	1.22	$ 3,397,443	$ 3,458,259	$ 7,608,169
E-304A	Area	6032	ft2	0.7	2.2	3412 ft2	0.57	$ 670,361	$ 682,361	$ 1,501,195
E-304B	Area	6032	ft2	0.7	2.2	3412 ft2	0.57	$ 670,361	$ 682,361	$ 1,501,195
E-304C	Area	6032	ft2	0.7	2.2	3412 ft2	0.57	$ 670,361	$ 682,361	$ 1,501,195
E-304D	Area	6032	ft2	0.7	2.2	3412 ft2	0.57	$ 670,361	$ 682,361	$ 1,501,195
R-301A	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
R-301B	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
R-301C	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
R-301D	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
V-301	Volume	1	ft2	0.7	2.0	1	1.00	$ 5,600,000	$ 5,700,243	$ 11,400,487
F-301	Filter Feed	3689	gpm	0.6	1.7	2420	0.66	$ 1,017,998	$ 1,017,998	$ 1,730,596
C-301	SEPARATOR	3689	gpm	0.7	2.0	2420	0.66	$ 2,653,959	$ 2,653,959	$ 5,307,918
E-305	Area	868	ft2	0.7	2.2	868 ft2	1.00	$ 101,991	$ 101,991	$ 224,380
E-306	Area	3255	ft2	0.7	2.2	3238 ft2	0.99	$ 63,668	$ 64,807	$ 142,576
HOT OIL SYSTEM										
H-401A	Duty	60	MMBTU/hr	0.6	1.8	71.23	1.19	$ 1,330,704	$ 1,354,524	$ 2,438,143
H-401B	Duty	60	MMBTU/hr	0.6	1.8	71.23	1.19	$ 1,330,704	$ 1,354,524	$ 2,438,143
HOT OIL	N/A	N/A	N/A	N/A	USD 1	N/A	N/A	$ 769,080	$ 782,847	$ 782,847
TOTALS								**$ 379,448,000**	**$ 386,095,000**	**$ 836,831,000**

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL

REV D | PROJECT: 30352.00 | DATE: 4/3/13

Harris Group - NREL

Mechanical Equipment List CASE B-L

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
		FEED HANDLING																							
	M-101A	TRUCK SCALE NO. 1	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-101B	TRUCK SCALE NO. 2	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-102A	TRUCK TIPPER NO. 1	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102B	TRUCK TIPPER NO. 2	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102C	TRUCK TIPPER NO. 3	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102D	TRUCK TIPPER NO. 4	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-103	OFFLOAD CONVEYOR	100						2			CS		USD 250,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 250,000	$ 254,475	$ 432,608
	M-104	STACKER/RECLAIMER	100				350,000lb/hr		50			CS		USD 4,000,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 4,000,000	$ 4,071,602	$ 6,921,724
	F-101	CHIP SCREEN	100			10x18ft			30			CS		USD 173,820	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 173,820	$ 176,931	$ 300,784
	M-105	CHIP TRANSFER CONVEYOR	100			200ft			2			CS		USD 225,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 225,000	$ 229,028	$ 389,347
		FEED PREPARATION																							
	B-201	MILL AIR BLOWER	200			55000cfm			150			CS		USD 40,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 40,000	$ 40,716	$ 65,146
	N-201	CYCLONIC FILTER	200			9300ft3						CS		USD 125,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 125,000	$ 127,238	$ 203,580
	N-202	ROTARY AIR LOCK	200						5			CS		USD 10,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 10,000	$ 10,179	$ 16,286
	M-201	CHIP ELEVATOR	200			50ft			5			CS		USD 100,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 100,000	$ 101,790	$ 173,043
	M-202	DRAG CHAIN CONVEYOR	200			200ft			5			CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-201A	FEEDSTOCK FEED BIN NO. 1	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201B	FEEDSTOCK FEED BIN NO. 2	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201C	FEEDSTOCK FEED BIN NO. 3	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201D	FEEDSTOCK FEED BIN NO. 4	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201E	FEEDSTOCK FEED BIN NO. 5	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201F	FEEDSTOCK FEED BIN NO. 6	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201G	FEEDSTOCK FEED BIN NO. 7	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	L-201A	FIRST STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201B	FIRST STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201C	FIRST STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201D	FIRST STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201E	FIRST STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201F	FIRST STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201G	FIRST STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	F-201A	MAGNET SEPARATOR NO. 1	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201B	MAGNET SEPARATOR NO. 2	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201C	MAGNET SEPARATOR NO. 3	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201D	MAGNET SEPARATOR NO. 4	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201E	MAGNET SEPARATOR NO. 5	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201F	MAGNET SEPARATOR NO. 6	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201G	MAGNET SEPARATOR NO. 7	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	L-202A	SECOND STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202B	SECOND STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202C	SECOND STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202D	SECOND STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202E	SECOND STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202F	SECOND STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202G	SECOND STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	M-203	DRAG CHAIN CONVEYOR	200									CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-202A	LIVE BOTTOM BIN NO. 1	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202B	LIVE BOTTOM BIN NO. 2	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202C	LIVE BOTTOM BIN NO. 3	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202D	LIVE BOTTOM BIN NO. 4	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	M-204A	DILUTION CONVEYOR NO. 1	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204B	DILUTION CONVEYOR NO. 2	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204C	DILUTION CONVEYOR NO. 3	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204D	DILUTION CONVEYOR NO. 4	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-205A	TWIN SCREW FEEDER NO. 1	200				190gpm		9200		460	Chrome lined	add 5% for 316L	USD 4,376,400	2011	Pump Feed	2300	gpm	0.8	2.3	2300	2300	$ 4,376,400	$ 4,376,400	$ 10,065,720
	M-205B	TWIN SCREW FEEDER NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205C	TWIN SCREW FEEDER NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205D	TWIN SCREW FEEDER NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205E	TWIN SCREW FEEDER NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205F	TWIN SCREW FEEDER NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205G	TWIN SCREW FEEDER NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205H	TWIN SCREW FEEDER NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205I	TWIN SCREW FEEDER NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205J	TWIN SCREW FEEDER NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205K	TWIN SCREW FEEDER NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	M-205L	TWIN SCREW FEEDER NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203A	BIOMASS FEED PUMP NO. 1	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203B	BIOMASS FEED PUMP NO. 2	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203C	BIOMASS FEED PUMP NO. 3	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203D	BIOMASS FEED PUMP NO. 4	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203E	BIOMASS FEED PUMP NO. 5	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203F	BIOMASS FEED PUMP NO. 6	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203G	BIOMASS FEED PUMP NO. 7	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203H	BIOMASS FEED PUMP NO. 8	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203I	BIOMASS FEED PUMP NO. 9	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203J	BIOMASS FEED PUMP NO. 10	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203K	BIOMASS FEED PUMP NO. 11	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-203L	BIOMASS FEED PUMP NO. 12	200				190gpm				460	Chrome lined	add 5% for 316L												
	P-201	MAKEUP WATER PUMP	200				10gpm	150ft	5			316L		USD 8,700	2013	pump feed	10	gpm	0.8	2.3	10	1.00	$ 8,700	$ 8,856	$ 20,368
	A-201	NA2CO3 SOLUTION AGITATOR	200			8'ϕ			30			316L		USD 40,628	2013	N/A	N/A	N/A	0.5	1.5	10	N/A	$ 40,628	$ 41,355	$ 62,033
	T-204	NA2CO3 SOLUTION MAKEUP TANK	200			12'ϕ♧ 11'	15000					316L		USD 118,990	2012	capacity	15000	gal	0.7	1.5	9500	0.63	$ 86,428	$ 87,975	$ 131,962
	P-202	NA2CO3 SOLUTION PUMP	200				300gpm	150ft	20			Duplex SS		USD 10,930	2013	pump feed	300	gpm	0.8	2.3	300	1.00	$ 10,930	$ 11,126	$ 25,589
	A-202	STATIC MIXER	200			10"x29"								USD 3,696	2013	Flow	N/A	gpm	0.5	1	N/A	1	$3,696	$3,762	$3,762
	M-206	NA2CO3 SUPER SACK FEEDER	200						5					USD 54,600	2013	N/A	N/A	N/A	N/A	1.7	N/A	N/A	$ 54,600	$ 55,577	$ 94,482
		HTL REACTION SECTION																							
	E-301A	FIRST FEED PREHEATER NO. 1	300				52.4 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 50,976,000	2012	Area	56864	ft2	0.7	2.2	56133 ft2	0.99	$ 50,516,523	$ 50,516,523	$ 111,136,351
	E-301B	FIRST FEED PREHEATER NO. 2	300				52.4 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 50,976,000	2012	Area	56864	ft2	0.7	2.2	56133 ft2	0.99	$ 50,516,523	$ 50,516,523	$ 111,136,351
	E-301C	FIRST FEED PREHEATER NO. 3	300				52.4 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 50,976,000	2012	Area	56864	ft2	0.7	2.2	56133 ft2	0.99	$ 50,516,523	$ 50,516,523	$ 111,136,351
	E-301D	FIRST FEED PREHEATER NO. 4	300				52.4 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 50,976,000	2012	Area	56864	ft2	0.7	2.2	56133 ft2	0.99	$ 50,516,523	$ 50,516,523	$ 111,136,351
	E-302A	SECOND FEED PREHEATER NO. 1	300				37.6 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 35,046,000	2012	Area	39094	ft2	0.7	2.2	39701 ft2	1.02	$ 35,426,165	$ 35,426,165	$ 77,937,564
	E-302B	SECOND FEED PREHEATER NO. 2	300				37.6 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 35,046,000	2012	Area	39094	ft2	0.7	2.2	39701 ft2	1.02	$ 35,426,165	$ 35,426,165	$ 77,937,564
	E-302C	SECOND FEED PREHEATER NO. 3	300				37.6 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 35,046,000	2012	Area	39094	ft2	0.7	2.2	39701 ft2	1.02	$ 35,426,165	$ 35,426,165	$ 77,937,564
	E-302D	SECOND FEED PREHEATER NO. 4	300				37.6 MMBTU/hr					316L	14 BTU/hr/ft2/F	USD 35,046,000	2012	Area	39094	ft2	0.7	2.2	39701 ft2	1.02	$ 35,426,165	$ 35,426,165	$ 77,937,564
	E-303A	FEED/RECYCLE EXCHANGER NO. 1	300				59.7 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 1,965,333	2012	Area	3000	ft2	0.7	2.2	5734 ft2	1.91	$ 3,092,782	$ 3,092,782	$ 6,804,120
	E-303B	FEED/RECYCLE EXCHANGER NO. 2	300				59.7 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 1,965,333	2012	Area	3000	ft2	0.7	2.2	5734 ft2	1.91	$ 3,092,782	$ 3,092,782	$ 6,804,120

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE: 4/3/13

Harris Group - NREL

Mechanical Equipment List CASE B-L

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN			ELECTRICAL			MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
						SIZE	CAPACITY	HEAD/PRESS	HP	RPM	VOLTS														
	E-303C	FEED/RECYCLE EXCHANGER NO. 3	300				59.7 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 1,965,333	2012	Area	3000	ft2	0.7	2.2	5734 ft2	1.91	$ 3,092,782	$ 3,092,782	$ 6,804,120
	E-303D	FEED/RECYCLE EXCHANGER NO. 4	300				59.7 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 1,965,333	2012	Area	3000	ft2	0.7	2.2	5734 ft2	1.91	$ 3,092,782	$ 3,092,782	$ 6,804,120
	E-304A	FINAL FEED HEATER NO. 1	300				27.2 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012	Area	6032	ft2	0.7	2.2	3177 ft2	0.53	$ 637,592	$ 637,592	$ 1,402,702
	E-304B	FINAL FEED HEATER NO. 2	300				27.2 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012	Area	6032	ft2	0.7	2.2	3177 ft2	0.53	$ 637,592	$ 637,592	$ 1,402,702
	E-304C	FINAL FEED HEATER NO. 3	300				27.2 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012	Area	6032	ft2	0.7	2.2	3177 ft2	0.53	$ 637,592	$ 637,592	$ 1,402,702
	E-304D	FINAL FEED HEATER NO. 4	300				27.2 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2012	Area	6032	ft2	0.7	2.2	3177 ft2	0.53	$ 637,592	$ 637,592	$ 1,402,702
	R-301A	HTL REACTOR NO. 1	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301B	HTL REACTOR NO. 2	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301C	HTL REACTOR NO. 3	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301D	HTL REACTOR NO. 4	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	V-301	REACTOR GAS KO DRUM	300				4x4230 gal					316	316L cladded CS shell	USD 5,600,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 5,600,000	$ 5,700,243	$ 11,400,487
	F-301	SOLIDS FILTER	300				3689gpm					316L		USD 1,311,000	2011	Filter Feed	3689	gpm	0.6	1.7	2420	0.66	$ 1,017,998	$ 1,017,998	$ 1,730,596
	C-301	SEPARATOR	300				3689gpm					316L		USD 3,565,000	2011	SEPARATOR	3689	gpm	0.7	2.0	2420	0.66	$ 2,653,959	$ 2,653,959	$ 5,307,918
	E-305	FILTER PURGE HEATER	300				1.7 MMBTU/hr					316L	150 BTU/hr/ft2/F	USD 1,384,220	2012	Area	4250	ft2	0.7	2.2	58 ft2	0.01	$ 68,117	$ 68,117	$ 149,858
	E-306	SEPARATOR FEED COOLER	300				46.9 MMBTU/hr					316L	100 BTU/hr/ft2/F	USD 63,900	2012	Area	3255	ft2	0.7	2.2	4662 ft2	1.43	$ 82,171	$ 82,171	$ 180,776
		HOT OIL SYSTEM																							
	H-401A	PACKAGE HOT OIL SYSTEM	400				60.6 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	61 MMBTU/hr	1.01	$ 1,207,091	$ 1,228,698	$ 2,211,657
	H-401B	PACKAGE HOT OIL SYSTEM	400				60.6 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	61 MMBTU/hr	1.01	$ 1,207,091	$ 1,228,698	$ 2,211,657
		HOT OIL	400				23200 gal							USD 769,080	USD 2,012	N/A	N/A	N/A	N/A	USD 1	N/A	N/A	$ 769,080	$ 782,847	$ 782,847
		TOTALS							18,521														**$ 403,672,000**	**$ 404,331,000**	**$ 877,036,000**

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE D

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN			ELECTRICAL			MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATI FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
						SIZE	CAPACITY	HEAD/PRESS	HP	RPM	VOLTS														
		FEED HANDLING																							
	M-101A	TRUCK SCALE NO. 1	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-101B	TRUCK SCALE NO. 2	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-102A	TRUCK TIPPER NO. 1	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102B	TRUCK TIPPER NO. 2	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102C	TRUCK TIPPER NO. 3	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102D	TRUCK TIPPER NO. 4	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-103	OFFLOAD CONVEYOR	100						2			CS		USD 250,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 250,000	$ 254,475	$ 432,608
	M-104	STACKER/RECLAIMER	100				350,000lb/hr		50			CS		USD 4,000,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 4,000,000	$ 4,071,602	$ 6,921,724
	F-101	CHIP SCREEN	100			10x18ft			30			CS		USD 173,820	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 173,820	$ 176,931	$ 300,784
	M-105	CHIP TRANSFER CONVEYOR	100			200ft			2			CS		USD 225,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 225,000	$ 229,028	$ 389,347
		FEED PREPARATION																							
	B-201	MILL AIR BLOWER	200			55000cfm			150			CS		USD 40,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 40,000	$ 40,716	$ 65,146
	N-201	CYCLONIC FILTER	200			9300ft3						CS		USD 125,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 125,000	$ 127,238	$ 203,580
	N-202	ROTARY AIR LOCK	200						5			CS		USD 10,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 10,000	$ 10,179	$ 16,286
	M-201	CHIP ELEVATOR	200			50ft			5			CS		USD 100,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 100,000	$ 101,790	$ 173,043
	M-202	DRAG CHAIN CONVEYOR	200			200ft			5			CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-201A	FEEDSTOCK FEED BIN NO. 1	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201B	FEEDSTOCK FEED BIN NO. 2	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201C	FEEDSTOCK FEED BIN NO. 3	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201D	FEEDSTOCK FEED BIN NO. 4	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201E	FEEDSTOCK FEED BIN NO. 5	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201F	FEEDSTOCK FEED BIN NO. 6	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201G	FEEDSTOCK FEED BIN NO. 7	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	L-201A	FIRST STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201B	FIRST STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201C	FIRST STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201D	FIRST STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201E	FIRST STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201F	FIRST STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201G	FIRST STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	F-201A	MAGNET SEPARATOR NO. 1	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201B	MAGNET SEPARATOR NO. 2	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201C	MAGNET SEPARATOR NO. 3	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201D	MAGNET SEPARATOR NO. 4	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201E	MAGNET SEPARATOR NO. 5	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201F	MAGNET SEPARATOR NO. 6	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201G	MAGNET SEPARATOR NO. 7	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	L-202A	SECOND STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202B	SECOND STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202C	SECOND STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202D	SECOND STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202E	SECOND STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202F	SECOND STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202G	SECOND STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	M-203	DRAG CHAIN CONVEYOR	200									CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-202A	LIVE BOTTOM BIN NO. 1	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202B	LIVE BOTTOM BIN NO. 2	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202C	LIVE BOTTOM BIN NO. 3	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202D	LIVE BOTTOM BIN NO. 4	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	M-204A	DILUTION CONVEYOR NO. 1	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204B	DILUTION CONVEYOR NO. 2	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204C	DILUTION CONVEYOR NO. 3	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204D	DILUTION CONVEYOR NO. 4	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-205A	TWIN SCREW FEEDER NO. 1	200				190 gpm		4600		460	Chrome lined	add 5% for 316L	USD 2,188,200	2011	pump feed	1140	gpm	0.8	2.3	1140	1.00	$ 2,188,200	$ 2,188,200	$ 5,032,860
	M-205B	TWIN SCREW FEEDER NO. 2	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205C	TWIN SCREW FEEDER NO. 3	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205D	TWIN SCREW FEEDER NO. 4	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205E	TWIN SCREW FEEDER NO. 5	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205F	TWIN SCREW FEEDER NO. 6	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203A	BIOMASS FEED PUMP NO. 1	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203B	BIOMASS FEED PUMP NO. 2	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203C	BIOMASS FEED PUMP NO. 3	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203D	BIOMASS FEED PUMP NO. 4	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203E	BIOMASS FEED PUMP NO. 5	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203F	BIOMASS FEED PUMP NO. 6	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-201	MAKEUP WATER PUMP	200				10gpm	150ft	5			316L		USD 8,700	2013	pump feed	10	gpm	0.8	2.3	10	1.00	$ 8,700	$ 8,856	$ 20,368
	A-201	NA2CO3 SOLUTION AGITATOR	200			8'ϕ			30			316L		USD 40,628	2013	N/A	N/A	N/A	0.5	1.5	10	N/A	$ 40,628	$ 41,355	$ 62,033
	T-204	NA2CO3 SOLUTION MAKEUP TANK	200			12'ϕ♧ 11'	9500gal					316L		USD 90,460	2012	capacity	15000	gal	0.7	1.5	9500	0.63	$ 65,705	$ 66,881	$ 100,322
	P-202	NA2CO3 SOLUTION PUMP	200				300gpm	150ft	20			Duplex SS		USD 10,930	2013	pump feed	300	gpm	0.8	2.3	300	1.00	$ 10,930	$ 11,126	$ 25,589
	A-202	STATIC MIXER	200			10"x29"								USD 3,696	2013	Flow	N/A	gpm	0.5	1.0	N/A	1.00	$ 3,696	$ 3,762	$ 3,762
	M-206	NA2CO3 SUPER SACK FEEDER	200						5					USD 54,600	2013	N/A	N/A	N/A	N/A	1.7	N/A	N/A	$ 54,600	$ 55,577	$ 94,482
		HTL REACTION SECTION																							
	A-301A	STATIC MIXER NO. 1	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301B	STATIC MIXER NO. 2	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301C	STATIC MIXER NO. 3	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301D	STATIC MIXER NO. 4	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	E-301A	PURGE/REACTOR EXCHANGER NO. 1	300				23.7 MMBTU/hr					347	170 BTU/hr/ft2/F	USD 1,965,333	2013	Area	3000	ft2	0.7	2.2	2587 ft2	0.86	$ 1,771,859	$ 1,803,577	$ 3,967,868
	E-301B	PURGE/REACTOR EXCHANGER NO. 2	300				23.7 MMBTU/hr					347	170 BTU/hr/ft2/F	USD 1,965,333	2013	Area	3000	ft2	0.7	2.2	2587 ft2	0.86	$ 1,771,859	$ 1,803,577	$ 3,967,868
	E-301C	PURGE/REACTOR EXCHANGER NO. 3	300				23.7 MMBTU/hr					347	170 BTU/hr/ft2/F	USD 1,965,333	2013	Area	3000	ft2	0.7	2.2	2587 ft2	0.86	$ 1,771,859	$ 1,803,577	$ 3,967,868
	E-301D	PURGE/REACTOR EXCHANGER NO. 4	300				23.7 MMBTU/hr					347	170 BTU/hr/ft2/F	USD 1,965,333	2013	Area	3000	ft2	0.7	2.2	2587 ft2	0.86	$ 1,771,859	$ 1,803,577	$ 3,967,868
	E-302A	REACTOR HEATER NO. 1	300				57.6 MMBTU/hr					347	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4366 ft2	0.72	$ 796,625	$ 810,885	$ 1,783,947
	E-302B	REACTOR HEATER NO. 2	300				57.6 MMBTU/hr					347	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4366 ft2	0.72	$ 796,625	$ 810,885	$ 1,783,947
	E-302C	REACTOR HEATER NO. 3	300				57.6 MMBTU/hr					347	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4366 ft2	0.72	$ 796,625	$ 810,885	$ 1,783,947
	E-302D	REACTOR HEATER NO. 4	300				57.6 MMBTU/hr					347	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4366 ft2	0.72	$ 796,625	$ 810,885	$ 1,783,947
	R-301A	HTL REACTOR NO. 1	300			8"	480					316L	XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301B	HTL REACTOR NO. 2	300			8"	480					316L	XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301C	HTL REACTOR NO. 3	300			8"	480					316L	XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301D	HTL REACTOR NO. 4	300			8"	480					316L	XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	V-301	REACTOR GAS KO DRUM	300				4x4230 gal					316	316L cladded CS shell	USD 5,600,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 5,600,000	$ 5,700,243	$ 11,400,487
	F-301	SOLIDS FILTER	300				3894gpm					316L		USD 1,311,000	2011	Filter Feed	3689	gpm	0.6	1.7	2420	0.66	$ 1,017,998	$ 1,017,998	$ 1,730,596
	C-301	SEPARATOR	300				3894gpm					316L		USD 3,565,000	2011	SEPARATOR	3689	gpm	0.7	2.0	2420	0.66	$ 2,653,959	$ 2,653,959	$ 5,307,918
	P-301A	WATER RECYCLE PUMP NO. 1	300				600 gpm	800ft	150			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	600	0.50	$ 219,861	$ 223,797	$ 514,732
	P-301B	WATER RECYCLE PUMP NO. 2	300				600 gpm	800ft	150			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	600	0.50	$ 219,861	$ 223,797	$ 514,732
	P-301C	WATER RECYCLE PUMP NO. 3	300				600 gpm	800ft	150			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	600	0.50	$ 219,861	$ 223,797	$ 514,732
	P-301D	WATER RECYCLE PUMP NO. 3	300				600 gpm	800ft	150			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	600	0.50	$ 219,861	$ 223,797	$ 514,732
	E-303	BIO-OIL HEAT RECOVERY STEAM GENERATOR	300				17.1 MMBTU/hr					316L	95 BTU/hr/ft2/F	USD 102,000	2012	Area	868	ft2	0.7	2.2	868 ft2	1.00	$ 101,991	$ 101,991	$ 224,380
	E-304	PURGE HEAT RECOVERY STEAM GENERATOR	300				45.9 MMBTU/hr					347	100 BTU/hr/ft2/F	USD 2,768,440	2013	Area	8500	ft2	0.7	2.2	9217 ft2	1.08	$ 2,929,883	$ 2,982,329	$ 6,561,124

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE D

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE
	E-305	PURGE WATER COOLER	300				86.1 MMBTU/hr					316L	100 BTU/hr/ft2/F	USD 127,800	2013
		HOT OIL SYSTEM													
	H-401A	PACKAGE HOT OIL SYSTEM NO. 1	400				64.03 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
	H-401B	PACKAGE HOT OIL SYSTEM NO. 2	400				64.03 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
	H-401C	PACKAGE HOT OIL SYSTEM NO. 3	400				64.03 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
	H-401D	PACKAGE HOT OIL SYSTEM NO. 4	400				64.03 MMBTU/hr		150				90% Efficiency	USD 1,200,500	2012
		HOT OIL	400				34200 gal							USD 1,133,730	USD 2,012
		TOTALS							14,821						

EQPT NO.	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATI FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
E-305	Area	6470	ft2	0.7	2.2	5199 ft2	0.80	$ 109,662	$ 111,625	$ 245,576
HOT OIL SYSTEM										
H-401A	Duty	60	MMBTU/hr	0.6	1.8	64 MMBTU/hr	1.07	$ 1,248,224	$ 1,270,568	$ 2,287,022
H-401B	Duty	60	MMBTU/hr	0.6	1.8	64 MMBTU/hr	1.07	$ 1,248,224	$ 1,270,568	$ 2,287,022
H-401C	Duty	60	MMBTU/hr	0.6	1.8	64 MMBTU/hr	1.07	$ 1,248,224	$ 1,270,568	$ 2,287,022
H-401D	Duty	60	MMBTU/hr	0.6	1.8	64 MMBTU/hr	1.07	$ 1,248,224	$ 1,270,568	$ 2,287,022
HOT OIL	N/A	N/A	N/A	N/A	USD 1	N/A	N/A	$ 1,133,730	$ 1,154,024	$ 1,154,024
TOTALS								USD 59,928,000	USD 60,894,000	USD 119,781,000

Harris Group Inc.	REV	DATE	BY	HTL REACTOR DESIGN
	A	3/1/2013	DBK	
	B	3/14/2013	DBK	
	C	3/18/2013	DBK	
	D	4/3/2013	DBK	

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE D-L

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
		FEED HANDLING																							
	M-101A	TRUCK SCALE NO. 1	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-101B	TRUCK SCALE NO. 2	100									CS		USD 44,900	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 44,900	$ 45,704	$ 77,696
	M-102A	TRUCK TIPPER NO. 1	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102B	TRUCK TIPPER NO. 2	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102C	TRUCK TIPPER NO. 3	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-102D	TRUCK TIPPER NO. 4	100						60			CS	Includes receiving hopper	USD 450,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 450,000	$ 458,055	$ 778,694
	M-103	OFFLOAD CONVEYOR	100						2			CS		USD 250,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 250,000	$ 254,475	$ 432,608
	M-104	STACKER/RECLAIMER	100				350,000lb/hr		50			CS		USD 4,000,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 4,000,000	$ 4,071,602	$ 6,921,724
	F-101	CHIP SCREEN	100			10x18ft			30			CS		USD 173,820	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 173,820	$ 176,931	$ 300,784
	M-105	CHIP TRANSFER CONVEYOR	100			200ft			2			CS		USD 225,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 225,000	$ 229,028	$ 389,347
		FEED PREPARATION																							
	B-201	MILL AIR BLOWER	200			55000cfm			150			CS		USD 40,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 40,000	$ 40,716	$ 65,146
	N-201	CYCLONIC FILTER	200			9300ft3						CS		USD 125,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 125,000	$ 127,238	$ 203,580
	N-202	ROTARY AIR LOCK	200						5			CS		USD 10,000	2012	Air Flow	4488	lb/hr	0.6	1.6	4488	1.00	$ 10,000	$ 10,179	$ 16,286
	M-201	CHIP ELEVATOR	200			50ft			5			CS		USD 100,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 100,000	$ 101,790	$ 173,043
	M-202	DRAG CHAIN CONVEYOR	200			200ft			5			CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-201A	FEEDSTOCK FEED BIN NO. 1	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201B	FEEDSTOCK FEED BIN NO. 2	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201C	FEEDSTOCK FEED BIN NO. 3	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201D	FEEDSTOCK FEED BIN NO. 4	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201E	FEEDSTOCK FEED BIN NO. 5	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201F	FEEDSTOCK FEED BIN NO. 6	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	T-201G	FEEDSTOCK FEED BIN NO. 7	200									CS		USD 45,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 45,000	$ 45,806	$ 77,869
	L-201A	FIRST STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201B	FIRST STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201C	FIRST STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201D	FIRST STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201E	FIRST STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201F	FIRST STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-201G	FIRST STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	F-201A	MAGNET SEPARATOR NO. 1	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201B	MAGNET SEPARATOR NO. 2	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201C	MAGNET SEPARATOR NO. 3	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201D	MAGNET SEPARATOR NO. 4	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201E	MAGNET SEPARATOR NO. 5	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201F	MAGNET SEPARATOR NO. 6	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	F-201G	MAGNET SEPARATOR NO. 7	200									CS		USD 23,700	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 23,700	$ 24,124	$ 41,011
	L-202A	SECOND STAGE HAMMER MILL NO. 1	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202B	SECOND STAGE HAMMER MILL NO. 2	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202C	SECOND STAGE HAMMER MILL NO. 3	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202D	SECOND STAGE HAMMER MILL NO. 4	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202E	SECOND STAGE HAMMER MILL NO. 5	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202F	SECOND STAGE HAMMER MILL NO. 6	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	L-202G	SECOND STAGE HAMMER MILL NO. 7	200						600			CS		USD 108,070	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 108,070	$ 110,005	$ 187,008
	M-203	DRAG CHAIN CONVEYOR	200									CS		USD 325,000	2012	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 325,000	$ 330,818	$ 562,390
	T-202A	LIVE BOTTOM BIN NO. 1	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202B	LIVE BOTTOM BIN NO. 2	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202C	LIVE BOTTOM BIN NO. 3	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	T-202D	LIVE BOTTOM BIN NO. 4	200			15' dia x 13'	3200ft3		3		460	CS		USD 21,535	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 21,535	$ 21,920	$ 37,265
	M-204A	DILUTION CONVEYOR NO. 1	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204B	DILUTION CONVEYOR NO. 2	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204C	DILUTION CONVEYOR NO. 3	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-204D	DILUTION CONVEYOR NO. 4	200			20ft long	<600 ton/h		15			316SS		USD 94,300	2013	Feed Rate	353304	lb/hr	0.8	1.7	353304	1.00	$ 94,300	$ 95,988	$ 163,180
	M-205A	TWIN SCREW FEEDER NO. 1	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205B	TWIN SCREW FEEDER NO. 2	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205C	TWIN SCREW FEEDER NO. 3	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205D	TWIN SCREW FEEDER NO. 4	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205E	TWIN SCREW FEEDER NO. 5	200				190 gpm				460	Chrome lined	add 5% for 316L												
	M-205F	TWIN SCREW FEEDER NO. 6	200				190 gpm		4600		460	Chrome lined	add 5% for 316L	USD 2,188,200	2011	pump feed	1140	gpm	0.8	2.3	1140	1.00	$ 2,188,200	$ 2,188,200	$ 5,032,860
	P-203A	BIOMASS FEED PUMP NO. 1	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203B	BIOMASS FEED PUMP NO. 2	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203C	BIOMASS FEED PUMP NO. 3	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203D	BIOMASS FEED PUMP NO. 4	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203E	BIOMASS FEED PUMP NO. 5	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-203F	BIOMASS FEED PUMP NO. 6	200				190 gpm				460	Chrome lined	add 5% for 316L												
	P-201	MAKEUP WATER PUMP	200				10gpm	150ft	5			316L		USD 8,700	2013	pump feed	10	gpm	0.8	2.3	10	1.00	$ 8,700	$ 8,856	$ 20,368
	A-201	NA2CO3 SOLUTION AGITATOR	200			8'ϕ			30			316L		USD 40,628	2013	N/A	N/A	N/A	0.5	1.5	10	N/A	$ 40,628	$ 41,355	$ 62,033
	T-204	NA2CO3 SOLUTION MAKEUP TANK	200			12'ϕ♧ 11'	9500gal					316L		USD 90,460	2012	capacity	15000	gal	0.7	1.5	9500	0.63	$ 65,705	$ 66,881	$ 100,322
	P-202	NA2CO3 SOLUTION PUMP	200				300gpm	150ft	20			Duplex SS		USD 10,930	2013	pump feed	300	gpm	0.8	2.3	300	1.00	$ 10,930	$ 11,126	$ 25,589
	A-202	STATIC MIXER	200			10"x29"								USD 3,696	2013	Flow	N/A	gpm	0.5	1.0	N/A	1.00	$ 3,696	$ 3,762	$ 3,762
	M-206	NA2CO3 SUPER SACK FEEDER	200						5					USD 54,600	2013	N/A	N/A	N/A	N/A	1.7	N/A	N/A	$ 54,600	$ 55,577	$ 94,482
		HTL REACTION SECTION																							
	A-301A	STATIC MIXER NO. 1	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301B	STATIC MIXER NO. 2	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301C	STATIC MIXER NO. 3	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	A-301D	STATIC MIXER NO. 4	300			10" x 116"	750gpm					316L		USD 17,140	2013	Flow	750	gpm	0.5	1.0	750	1.00	$ 17,140	$ 17,447	$ 17,447
	E-301A	REACTOR HEATER NO. 1	300				81.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4840 ft2	0.80	$ 856,131	$ 871,457	$ 1,917,204
	E-301B	REACTOR HEATER NO. 2	300				81.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4840 ft2	0.80	$ 856,131	$ 871,457	$ 1,917,204
	E-301C	REACTOR HEATER NO. 3	300				81.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4840 ft2	0.80	$ 856,131	$ 871,457	$ 1,917,204
	E-301D	REACTOR HEATER NO. 4	300				81.1 MMBTU/hr					316L	154 BTU/hr/ft2/F	USD 998,850	2013	Area	6032	ft2	0.7	2.2	4840 ft2	0.80	$ 856,131	$ 871,457	$ 1,917,204
	E-302A	SEPARATOR /EFFLUENT HEX TRAIN A NO.1	300				13 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2013	Area	4500	ft2	0.7	2.2	3978	0.88	$ 2,704,328	$ 2,752,737	$ 6,056,021
	E-302B	SEPARATOR /EFFLUENT HEX TRAIN A NO.2	300				13 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2013	Area	4500	ft2	0.7	2.2	3978	0.88	$ 2,704,328	$ 2,752,737	$ 6,056,021
	E-302C	SEPARATOR /EFFLUENT HEX TRAIN A NO.3	300				13 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2013	Area	4500	ft2	0.7	2.2	3978	0.88	$ 2,704,328	$ 2,752,737	$ 6,056,021
	E-302D	SEPARATOR /EFFLUENT HEX TRAIN A NO.4	300				13 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 2,948,000	2013	Area	4500	ft2	0.7	2.2	3978	0.88	$ 2,704,328	$ 2,752,737	$ 6,056,021
	E-303B	SEPARATOR/EFFLUENT HEX TRAIN B NO. 1	300				91 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 3,930,667	2013	Area	6000	ft2	0.7	2.2	5983	1.00	$ 3,922,864	$ 3,993,085	$ 8,784,788
	E-303B	SEPARATOR/EFFLUENT HEX TRAIN B NO. 2	300				91 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 3,930,667	2013	Area	6000	ft2	0.7	2.2	5983	1.00	$ 3,922,864	$ 3,993,085	$ 8,784,788
	E-303B	SEPARATOR/EFFLUENT HEX TRAIN B NO. 3	300				91 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 3,930,667	2013	Area	6000	ft2	0.7	2.2	5983	1.00	$ 3,922,864	$ 3,993,085	$ 8,784,788
	E-303B	SEPARATOR/EFFLUENT HEX TRAIN B NO. 4	300				91 MMBTU/hr					316L	170 BTU/hr/ft2/F	USD 3,930,667	2013	Area	6000	ft2	0.7	2.2	5983	1.00	$ 3,922,864	$ 3,993,085	$ 8,784,788
	R-301A	HTL REACTOR NO. 1	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301B	HTL REACTOR NO. 2	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301C	HTL REACTOR NO. 3	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	R-301D	HTL REACTOR NO. 4	300			8"	480 ft					316L	LHSV=4 XXHpipe	USD 272,788	2013	length	480	ft	1	2.0	7862	16.38	$ 4,468,040	$ 4,548,021	$ 9,096,041
	V-301	REACTOR GAS KO DRUM	300				4x4230 gal					316	316L cladded CS shell	USD 5,600,000	2012	Volume	1	ft2	0.7	2.0	1	1.00	$ 5,600,000	$ 5,700,243	$ 11,400,487
	F-301	SOLIDS FILTER	300				2420gpm					316L		USD 2,769,000	2011	Filter Feed	3689	gpm	0.6	1.7	2420	0.66	$ 2,150,141	$ 2,150,141	$ 3,655,240
	C-301	SEPARATOR	300				2420gpm					316L		USD 1,018,000	2011	SEPARATOR Feed	3689	gpm	0.7	2.0	2420	0.66	$ 757,849	$ 757,849	$ 1,515,697
	P-301A	WATER RECYCLE PUMP NO. 1	300				740gpm	800ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	740	0.62	$ 260,023	$ 264,678	$ 608,759
	P-301B	WATER RECYCLE PUMP NO. 2	300				740gpm	800ft	200			316L		USD 382,800	2012	Flow	1200	gpm	0.8	2.3	740	0.62	$ 260,023	$ 264,678	$ 608,759

Harris Group Inc.

REV	DATE	BY
A	3/1/2013	DBK
B	3/14/2013	DBK
C	3/18/2013	DBK
D	4/3/2013	DBK

HTL REACTOR DESIGN

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REV D PROJECT: 30352.00
DATE:

Harris Group - NREL

Mechanical Equipment List CASE D-L

REV	EQPT NO.	DESCRIPTION	PFD	VENDOR	MODEL	DESIGN SIZE	DESIGN CAPACITY	DESIGN HEAD/PRESS	ELECTRICAL HP	ELECTRICAL RPM	ELECTRICAL VOLTS	MATERIAL	REMARKS
	P-301C	WATER RECYCLE PUMP NO. 3	300				740gpm	800ft	200			316L	
	P-301D	WATER RECYCLE PUMP NO. 4	300				740gpm	800ft	200			316L	
	E-304	SEPARATOR FEED/BIO-OIL EXCHANGER	300				13 MMBTU/hr					316L	170 BTU/hr/ft2/F
	E-305	SEPARATOR FEED COOLER	300				255 MMBTU/hr					347	100 BTU/hr/ft2/F
	E-306	RECYCLE HEATER	300				20 MMBTU/hr					316L	154 BTU/hr/ft2/F
		HOT OIL SYSTEM											
	H-401A	PACKAGE HOT OIL SYSTEM NO. 1	400				60.07 MMBTU/hr		150				90% Efficiency
	H-401B	PACKAGE HOT OIL SYSTEM NO. 2	400				60.07 MMBTU/hr		150				90% Efficiency
	H-401C	PACKAGE HOT OIL SYSTEM NO. 3	400				60.07 MMBTU/hr		150				90% Efficiency
	H-401D	PACKAGE HOT OIL SYSTEM NO. 4	400				60.07 MMBTU/hr		150				90% Efficiency
	H-401E	PACKAGE HOT OIL SYSTEM NO. 5	400				60.07 MMBTU/hr		150				90% Efficiency
	H-401F	PACKAGE HOT OIL SYSTEM NO. 6	400				60.07 MMBTU/hr		150				90% Efficiency
		HOT OIL	400				52400 gal						
		TOTALS							15,321				

DESCRIPTION	PRICE	YEAR OF QUOTE	SCALING VARIABLE	SCALING VALUE	UNITS	SCALING EXPONENT	INSTALLATION FACTOR	NEW VALUE	SIZE RATIO	SCALED PURCH COST	PURCH COST IN PROJ YEAR	INSTALL COST IN PROJ YEAR
WATER RECYCLE PUMP NO. 3	USD 382,800	2012	Flow	1200	gpm	0.8	2.3	740	0.62	$ 260,023	$ 264,678	$ 608,759
WATER RECYCLE PUMP NO. 4	USD 382,800	2012	Flow	1200	gpm	0.8	2.3	740	0.62	$ 260,023	$ 264,678	$ 608,759
SEPARATOR FEED/BIO-OIL EXCHANGER	USD 1,061,280	2013	Area	1500	ft2	0.7	2.2	1008	0.67	$ 803,485	$ 817,867	$ 1,799,308
SEPARATOR FEED COOLER	USD 5,536,880	2013	Area	17000	ft2	0.7	2.2	15257 ft2	0.90	$ 5,133,209	$ 5,225,096	$ 11,495,212
RECYCLE HEATER	USD 1,384,220	2013	Area	4250	ft2	0.7	2.2	4286 ft2	1.01	$ 1,392,352	$ 1,417,276	$ 3,118,008
HOT OIL SYSTEM												
PACKAGE HOT OIL SYSTEM NO. 1	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
PACKAGE HOT OIL SYSTEM NO. 2	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
PACKAGE HOT OIL SYSTEM NO. 3	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
PACKAGE HOT OIL SYSTEM NO. 4	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
PACKAGE HOT OIL SYSTEM NO. 5	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
PACKAGE HOT OIL SYSTEM NO. 6	USD 1,200,500	2012	Duty	60	MMBTU/hr	0.6	1.8	57.25	0.95	$ 1,167,177	$ 1,188,070	$ 2,138,526
HOT OIL	USD 1,737,060	USD 2,012	N/A	N/A	N/A	N/A	USD 1	N/A	N/A	$ 1,737,060	$ 1,768,154	$ 1,768,154
TOTALS										$ 85,785,000	$ 87,229,000	$ 175,993,000

APPENDIX D

CAPITAL COST INFORMATION

Harris Group Inc.	By: DBK	CASE A
	Checked:	HYDROTHERMAL LIQUEFACTION

PROJECT NO.	**30352.00**	**Order of Magnitude Cost Estimate**			
Rev. C	DATE: 18-Mar-13	**Capital Cost Summary**			
Process Area					
		Purchased Cost			Installed Cost
Area 100: FEED HANDLING		$	6,656,000	$	11,315,000
Area 200: FEED PREPARATION		$	8,007,000	$	16,207,000
Area 300: HTL REACTION SECTION		$	70,018,000	$	147,155,000
Area 400: HOT OIL SYSTEM		$	12,264,000	$	20,364,000
	Totals:	$	96,945,000	$	195,041,000
Warehouse	4%	of ISBL		$	7,349,000
Site Development	9%	of ISBL		$	16,535,000
Additional Piping	4.50%	of ISBL		$	8,268,000
Total Direct Costs (TDC)				$	227,193,000
Indirect Costs					
Proratable expenses	10%	of TDC		$	22,719,000
Field Expenses	10%	of TDC		$	22,719,000
Home office and Constr. Feed	20%	of TDC		$	45,439,000
Project Contingency	10%	of TDC		$	22,719,000
Other costs (start-up, permits, etc.)	10%	of TDC		$	22,719,000
TOTAL INDIRECT COSTS				$	136,315,000
FIXED CAPITAL INVESTMENT (FCI)				$	363,508,000
Working Capital	5%	of FCI		$	18,175,000
TOTAL CAPITAL INVESTMENT (TCI)				**$**	**381,683,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 534,356,000**	**$ 267,178,000**

Harris Group Inc.®	By: DBK	CASE B
	Checked:	HYDROTHERMAL LIQUEFACTION

PROJECT NO.		**30352.00**	**Order of Magnitude Cost Estimate**			
Rev. C		DATE: 18-Mar-13	**Capital Cost Summary**			
Process Area						
			Purchased Cost			Installed Cost
	Area 100: FEED HANDLING		$ 6,656,000			$ 11,315,000
	Area 200: FEED PREPARATION		$ 8,007,000			$ 16,207,000
	Area 300: HTL REACTION SECTION		$ 367,940,000			$ 803,650,000
	Area 400: HOT OIL SYSTEM		$ 3,492,000			$ 5,659,000
		Totals:	$ 386,095,000			$ 836,831,000
	Warehouse	4%	of ISBL			$ 33,021,000
	Site Development	9%	of ISBL			$ 74,296,000
	Additional Piping	4.50%	of ISBL			$ 37,148,000
	Total Direct Costs (TDC)					$ 981,296,000
Indirect Costs						
	Proratable expenses	10%	of TDC			$ 98,130,000
	Field Expenses	10%	of TDC			$ 98,130,000
	Home office and Constr. Feed	20%	of TDC			$ 196,259,000
	Project Contingency	10%	of TDC			$ 98,130,000
	Other costs (start-up, permits, etc.)	10%	of TDC			$ 98,130,000
	TOTAL INDIRECT COSTS					$ 588,779,000
	FIXED CAPITAL INVESTMENT (FCI)					$ 1,570,075,000
	Working Capital	5%	of FCI			$ 78,504,000
	TOTAL CAPITAL INVESTMENT (TCI)					**$ 1,648,579,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 2,308,011,000**	**$ 1,154,005,000**

Harris Group Inc.	By: DBK	CASE B-L
	Checked:	HYDROTHERMAL LIQUEFACTION

PROJECT NO.	**30352.00**	**Order of Magnitude Cost Estimate**			
Rev. C	DATE: 18-Mar-13	**Capital Cost Summary**			
Process Area					
		Purchased Cost		Installed Cost	
Area 100: FEED HANDLING		$ 6,656,000		$ 11,315,000	
Area 200: FEED PREPARATION		$ 8,028,000		$ 16,239,000	
Area 300: HTL REACTION SECTION		$ 386,407,000		$ 844,277,000	
Area 400: HOT OIL SYSTEM		$ 3,240,000		$ 5,206,000	
	Totals:	$ 404,331,000		$ 877,037,000	
Warehouse	4%	of ISBL		$ 34,629,000	
Site Development	9%	of ISBL		$ 77,915,000	
Additional Piping	4.50%	of ISBL		$ 38,957,000	
Total Direct Costs (TDC)				$ 1,028,538,000	
Indirect Costs					
Proratable expenses	10%	of TDC		$ 102,854,000	
Field Expenses	10%	of TDC		$ 102,854,000	
Home office and Constr. Feed	20%	of TDC		$ 205,708,000	
Project Contingency	10%	of TDC		$ 102,854,000	
Other costs (start-up, permits, etc.)	10%	of TDC		$ 102,854,000	
TOTAL INDIRECT COSTS				$ 617,124,000	
FIXED CAPITAL INVESTMENT (FCI)				$ 1,645,662,000	
Working Capital	5%	of FCI		$ 82,283,000	
TOTAL CAPITAL INVESTMENT (TCI)				**$ 1,727,945,000**	

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 2,419,123,000**	**$ 1,209,562,000**

Harris Group Inc.	By: DBK	CASE D
	Checked:	HYDROTHERMAL LIQUEFACTION

PROJECT NO.		**30352.00**	**Order of Magnitude Cost Estimate**			
Rev. C		DATE: 18-Mar-13	**Capital Cost Summary**			
	Process Area					
			Purchased Cost			Installed Cost
	Area 100: FEED HANDLING		$	6,656,000	$	11,315,000
	Area 200: FEED PREPARATION		$	5,819,000	$	11,174,000
	Area 300: HTL REACTION SECTION		$	42,183,000	$	86,990,000
	Area 400: HOT OIL SYSTEM		$	6,236,000	$	10,302,000
		Totals:	$	60,894,000	$	119,781,000
	Warehouse	4%	of ISBL		$	4,339,000
	Site Development	9%	of ISBL		$	9,762,000
	Additional Piping	4.50%	of ISBL		$	4,881,000
	Total Direct Costs (TDC)				$	138,763,000
Indirect Costs						
	Proratable expenses	10%	of TDC		$	13,876,000
	Field Expenses	10%	of TDC		$	13,876,000
	Home office and Constr. Feed	20%	of TDC		$	27,753,000
	Project Contingency	10%	of TDC		$	13,876,000
	Other costs (start-up, permits, etc.)	10%	of TDC		$	13,876,000
	TOTAL INDIRECT COSTS				$	83,257,000
	FIXED CAPITAL INVESTMENT (FCI)				$	222,020,000
	Working Capital	5%	of FCI		$	11,101,000
	TOTAL CAPITAL INVESTMENT (TCI)				**$**	**233,121,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 326,369,000**	**$ 163,185,000**

Harris Group Inc.	By: DBK	**CASE D-L**		
	Checked:	**HYDROTHERMAL LIQUEFACTION**		
PROJECT NO.	**30352.00**	**Order of Magnitude Cost Estimate**		
Rev. C	DATE: 14-Mar-13	**Capital Cost Summary**		

Process Area				
		Purchased Cost		Installed Cost
Area 100: FEED HANDLING		$ 6,427,000		$ 11,315,000
Area 200: FEED PREPARATION		$ 5,819,000		$ 11,174,000
Area 300: HTL REACTION SECTION		$ 65,858,000		$ 138,905,000
Area 400: HOT OIL SYSTEM		$ 8,897,000		$ 14,599,000
	Totals:	$ 87,001,000		$ 175,993,000
Warehouse	4%	of ISBL		$ 6,587,000
Site Development	9%	of ISBL		$ 14,821,000
Additional Piping	4.50%	of ISBL		$ 7,411,000
Total Direct Costs (TDC)				$ 204,812,000
Indirect Costs				
Proratable expenses	10%	of TDC		$ 20,481,000
Field Expenses	10%	of TDC		$ 20,481,000
Home office and Constr. Feed	20%	of TDC		$ 40,962,000
Project Contingency	10%	of TDC		$ 20,481,000
Other costs (start-up, permits, etc.)	10%	of TDC		$ 20,481,000
TOTAL INDIRECT COSTS				$ 122,886,000
FIXED CAPITAL INVESTMENT (FCI)				$ 327,698,000
Working Capital	5%	of FCI		$ 16,385,000
TOTAL CAPITAL INVESTMENT (TCI)				**$ 344,083,000**

	Estimate Range	
	Upper Limit (+40%)	**Lower Limit (-30%)**
Total Project Cost:	**$ 481,716,000**	**$ 240,858,000**

APPENDIX E

RECOMMENDED EXPERIMENTS

Harris Group Inc.
Engineering Solutions for a Better World.®

NATIONAL RENEWABLE ENERGY LABORATORY

HTL REACTOR DESIGN

Project: 30352.00

March 14, 2013

	PFD	RECOMMENDED TESTING
1	PFD-200	Determine expected volatility of organics in the water recycle stream to determine if head space purges on tanks are necessary
2	PFD-200	Test ability of hammer mills to achieve ~3mm sized wood particles suitable for further processing
3	PFD-300 A	Determine if centrifugal pump can handle solids in recycle loop
4	PFD-300 B	Determine pumpability of slurry in high viscosity range in large diameter pipe
5	PFD-200D	Confirm that pumping ~36.6wt% wood solids can be accomplished with piston pump
6	PFD-300A/B/D	Confirm bio-oil water separator operation at high temperature is possible
7	PFD-300 (all)	Determine heat transfer coefficients
8	PFD-300 (all)	Determine maximum acceptable LHSV for the system
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		