

Equipment Design and Cost Estimation for Small Modular Biomass Systems, Synthesis Gas Cleanup, and Oxygen Separation Equipment

Task 2: Gas Cleanup Design and Cost Estimates – Wood Feedstock

Nexant Inc.
San Francisco, California

Subcontract Report
NREL/SR-510-39945
May 2006

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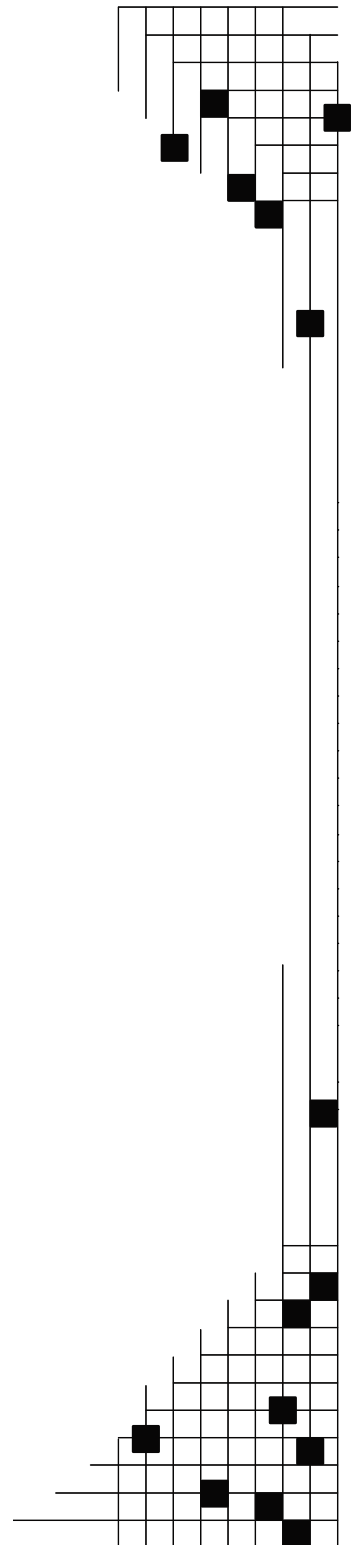
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Prepared under Subcontract No. ACO-5-44027

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National Renewable Energy Laboratory
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Executive Summary

As part of Task 2, Gas Cleanup and Cost Estimates, the team investigated the appropriate process scheme for treatment of wood derived syngas for use in the synthesis of liquid fuels. Two different 2,000 metric tonne per day gasification schemes, a low-pressure, indirect system using the BCL gasifier, and a high-pressure, direct system using GTI gasification technology, were evaluated. Initial syngas conditions from each of the gasifiers was provided to the team by NREL. Nexant was the prime contractor and principal investigator during this task; technical assistance was provided by both GTI and Emery Energy.

The first task explored the different process options available for the removal of the main process impurities, including particulates, sulfur, carbon dioxide, tar, ammonia, and metals. From this list, selection of commercial technologies appropriate for syngas clean-up was made based on the criteria of cost and the ability to meet the final specifications. Preliminary flow schemes were established and presented to NREL; after discussion and modification, final designs, including unit sizes, energy use, capital and operating costs, and labor requirements, were developed. Finally, Nexant performed an analysis to determine how changes in syngas flowrates and compositions would impact the designs, for future reference as the plant size changes.

The technologies chosen for both cases did not differ considerably. Each case possesses the following pieces of equipment:

- Cyclones for particulate removal
- Tar cracking for the removal of heavy and light hydrocarbons. Steam is injected in varying amounts into the tar cracker to set the appropriate hydrogen to carbon monoxide ratio.
- Syngas cooling, necessary for downstream sulfur treatment, and a water quench/venturi scrubber for ammonia and trace contaminant removal
- Amine treatment for sulfur and carbon dioxide removal
- Zinc oxide beds for additional sulfur removal down to the low levels required for fuels synthesis
- Liquid phase oxidation of acid gas for sulfur recovery

The low-pressure gasifier case required the use of a process gas compressor to raise the gas pressure to the level appropriate for downstream treatment and product synthesis. Information was also provided for the level of clean syngas compression necessary to prepare both cases for methanol synthesis.

The results of the analysis for both cases can be seen in Table A below, with information on the capital and operating costs:

TABLE A SYNGAS CLEAN-UP CASE SUMMARY

| | Low-Pressure BCL Gasifier | High-Pressure GTI Gasifier |
|----------------------------------|------------------------------|-------------------------------|
| Wood Feedrate (MTPD) | 2,000 | 2,000 |
| Syngas Rate (lb/hr) | 316,369 | 418,416 |
| Total Installed Cost (\$MM) | 109.4 | 76.5 |
| Power Required (MW) | 18.5 | (5.2) |
| Net Steam Required (lb/hr) | 44,000 | 114,000 |
| Water Required (GPM) | 37,806 | 25,454 |
| Natural Gas (MMSCFD) | 7 | 8 |
| Catalysts and Chemicals (\$/day) | 1,931 | 1,457 |

The bulk of the cost difference between the two cases is due to the process gas compressor required in the low-pressure case. The two cases use similar equipment for all other steps of the process; although the cases had different gas flowrates and compositions, the equipment impact is small relative to that of the process gas compressor. While these results imply that direct gasification is preferred, this study did not take into account other differences in the two process schemes, such as the potential need for an oxygen plant in the high-pressure to chemicals case.

The team also compared the clean-up system design and costs versus the design developed by NREL for a recent biomass to hydrogen study. The cost for the clean-up section of the biomass to chemicals designs is more expensive due to three main reasons: more equipment necessary in the chemical production designs, the increase in steel prices from 2002 to 2005, and different engineering assumptions made in the chemicals production case. The main engineering difference is the cost assumed for the process gas compressor in the low pressure case; a larger compressor and selection of a different design type increases the installed cost by \$25MM versus the NREL design. In addition, gas clean-up cost assumptions made by NREL from previous studies likely underestimated the cost of the tar cracker and heat exchange equipment.

This study updates previous NREL investigations by providing the most up-to-date information for appropriate technologies and their respective costs. Future studies should focus on the following areas to further define suitable technologies and confirm costs:

- **Alternatives for Tar Removal:** Further study and analysis should be performed to validate the methods used by the team. In addition, alternative tar removal technology should be considered, including cracking within the gasifier.
- **Process Integration, Gasification Systems and Biorefinery:** Integration of the clean-up section with the other parts of the gasification plant will provide a better picture of the overall plant costs.
- **Alternate CO₂/Sulfur Removal Steps:** A cost comparison of amine versus physical solvents would provide additional data to confirm the appropriate use of amine in this design. Advanced technologies for acid gas removal, such as warm gas clean-up, should also be considered.

- ***Other Impurities in the Syngas:*** If it is deemed that the level of items such as metals and halides entering the scrubber will not adversely impact the FT or methanol catalysts, this step could be removed.

Introduction and Methodology

This study provides designs and costs for cleaning wood derived syngas in preparation for feed to liquid fuel synthesis units. Two different starting conditions, one with syngas derived from a low-pressure, indirect gasifier, and one from a high-pressure, direct gasifier, were evaluated. The goal was to provide NREL with a complete design package, including process flow diagrams, equipment specification sheets, mass and energy balances, capital and operating costs, and labor requirements, that can be used to evaluate the feasibility of biomass to chemicals technologies. The study also addressed how the designs would be impacted by changing flowrates and syngas compositions, so that the designs could be adapted to other process conditions.

The work was divided into three main task areas. The first Subtask (2.1) presented a list of possible gas clean-up technologies, with recommendations provided for the most suitable ones for additional analysis. The results of this study can be seen in Appendix D. Next, preliminary process flow diagrams were developed, along with an initial material balance (Subtasks 2.2.1 and 2.2.2). This was reviewed with NREL, and modifications made before the final design work began. The final phase consisted of performing equipment sizing, development of costs, and scaling analysis (Subtasks 2.2.3 through 2.2.7).

A variety of resources were used throughout the project to produce the final designs. In gathering the initial technology data, previous team studies, literature reviews, vendor information, and NREL input were all used to establish the items for consideration. Vendors and R&D facilities were especially helpful in providing data for novel technologies, such as tar cracking and liquid phase sulfur oxidation. Team members involved in biomass gasification, GTI and Emery Energy, provided valuable insight on reliability and feasibility issues.

HYSYS was used for modeling the overall process, with vendor input for specialty equipment. Design and performance of the amine system, LO-CATTM unit, tar cracker, and process gas compressor were provided by vendors and estimated through other modeling work. All other process equipment was sized by the HYSYS program. Since the basis for the tar cracker, the NREL TCPDU, is not commercial, data from NREL was used, along with assumptions for bed fluidization needs and heat transfer requirements to produce a size estimate. Greater detail for the assumptions made can be found in Section 2.

Costing was performed in a similar fashion as design, with commercially available software, ICARUS, used for much of the equipment sized using HYSYS. All cost estimates use a second quarter 2005 basis. Quotes were obtained from vendors for unique and capital intensive items, such as the process gas compressor, cyclones, ZnO beds, and LO-CATTM unit. Industry derived cost curves were used for the amine system and as a check on other process items. Operating costs were developed from vendor supplied information and the energy balance. Finally, labor requirements are derived from a scale-up of a detailed study by Emery Energy specific to biomass gasification. For all results, comparisons were made throughout the study to results from previously developed NREL reports.

1.1 INTRODUCTION

The initial task for the Nexant team was to identify and evaluate all commercially available technology for clean-up of wood derived syngas. The technology list, with information on operating size ranges and conditions, materials of construction, and cleanup parameters, can be seen in Appendix D. After a review of technology options with NREL, flow schemes were developed for both the high and low pressure cases. The result of this analysis and justification for the technologies chosen is detailed in this section.

The compositions of the syngas from the gasifiers and the cleanup requirements are listed in Tables 1-1 and 1-2 below¹. Each case being evaluated assumed a wood feedrate of 2,000 metric tonnes per day (MTPD).

TABLE 1-1 SYNGAS COMPOSITIONS AND OPERATING PARAMETERS

| | Syngas from BCL Gasifier | Syngas from GTI Gasifier |
|---------------------------------------|--|--|
| Temperature, °F | 1,598°F (870°C) | 1,598°F (870°C) |
| Pressure | 33 psia (1.6 bar) | 460 psia (32 bar) |
| Steam/bone dry feed | 0.4 lb/lb | 0.76 kg/kg |
| | | |
| Compositions | Mol% (wet) | Mol% (wet) |
| H ₂ | 12.91 | 13.10 |
| CO ₂ | 6.93 | 19.40 |
| CO | 22.84 | 8.10 |
| H ₂ O | 45.87 | 50.70 |
| CH ₄ | 8.32 | 7.80 |
| C ₂ H ₂ | 0.22 | --- |
| C ₂ H ₄ | 2.35 | 0.10 |
| C ₂ H ₆ | 0.16 | 0.20 |
| C ₆ H ₆ | 0.07 | 0.30 |
| Tar (C ₁₀ H ₈) | 0.13 | 0.10 |
| NH ₃ | 0.18 | 0.10 |
| H ₂ S | 0.04 | 0.04 |
| Gas Yield | 0.04 lbmol of dry gas/lb bone dry feed | 0.05 lbmol of dry gas/lb bone dry feed |
| Char Yield | 0.22 lb/lb bone dry feed | 0.0514 lb/lb bone dry feed |
| H ₂ :CO molar ratio | 0.57 | 1.62 |

¹ Information provided by Pamela Spath, NREL.

The gas pressure assumed from the BCL gasifier, 33 psia, is higher than initially evaluated during this project. Preliminary investigations were performed using a syngas pressure of 23 psia. Raising the pressure by 10 psia allows for a simpler and more reliable design, by allowing a water wash upstream of the compression stage.

TABLE 1-2 GAS CLEANUP REQUIREMENTS

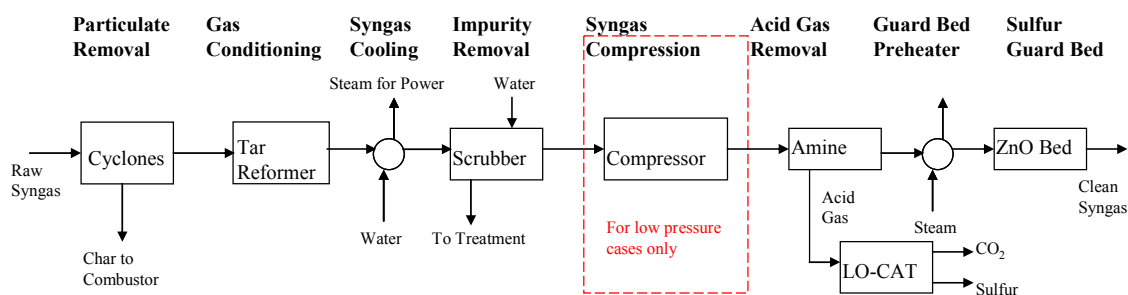
| Process | Contaminants | Level | Source/Comment |
|---------------------------|------------------|---|---|
| Fischer-Tropsch Synthesis | Sulfur | 0.2 ppm 1 ppmv 60 ppb | Dry, 1981 Boerrigter, et al, 2002 Turk, et al, 2001 |
| | Halides | 10 ppb | Boerrigter, et al, 2002 |
| | Nitrogen | 10 ppmv NH3 0.2 ppmv NOx 10 ppb HCN | Turk, et al, 2001 |
| Methanol Synthesis | Sulfur (not COS) | <0.5 ppmv (<0.1 ppmv preferred) | Kung, 1992 |
| | Halides | 0.001 ppmv | Twigg and Spencer 2001 |
| | Fe and Ni | 0.005 ppmv | Kung, 1992 |

The main impurities in the syngas exiting the gasifier that must be removed are char, tars, hydrocarbons, sulfur, and CO₂. In addition, trace contaminants such as ammonia, metals, halides, and alkali species were of sufficient concern that equipment was added to remove them as well. Finally, the syngas must also be adjusted to obtain the appropriate H₂/CO ratio.

1.2 PROCESS DESCRIPTION AND RATIONALE

A schematic for the process design developed for both cases can be seen in Figure 1-1. Both the low and high pressure cases used very similar processes for syngas clean-up: particulate removal with cyclones, tar reforming, cooling and water scrubbing, acid gas removal with amine, and sulfur polishing. The main difference between the cases is the inclusion of a compression step in the low-pressure case. A detailed description of each design is addressed in this section.

FIGURE 1-1 GENERAL SYNGAS CLEAN-UP PROCESS FLOW



1.2.1 Low-Pressure Syngas Process Description

Particulate Removal

The syngas exiting the gasifier contains impurities that must be removed in order to meet the specifications required for methanol or FT synthesis. Cyclones are used as the initial step in the gas cleanup process to remove the bulk of the char entrained in the syngas stream. This technology is standard in industry due to its low cost and high level of performance for removing particulates. Syngas from the low-pressure gasifier is sent through four parallel cyclones operating at 1598°F and 33 psia.

Tar Reforming

Syngas is fed to a tar reformer to remove tars, light hydrocarbons, and ammonia before any additional gas treating or cooling. Reforming must occur prior to cooling the syngas to prevent tar condensation and deposition on downstream equipment. The tar reformer was modeled using NREL's "goal design" reactor conversion for the Thermochemical Pilot Development Unit (TCPDU). Table 1-3 shows the assumed reactor conversion rate as provided by NREL. In the tar reformer, tars (mono and polyaromatic compounds) and light hydrocarbons such as methane, ethylene, and ethane are converted to H₂ and CO. Ammonia is converted to N₂ and H₂. Since the reactor effluent contains about 1.3 mol% CH₄, and 0.2 mol% of other hydrocarbons, additional downstream steam reforming was deemed not necessary. This conclusion was confirmed by NREL².

TABLE 1-3 TAR REFORMER PERFORMANCE

| Compound | % Conversion |
|---|--------------|
| Methane (CH ₄) | 80 |
| Ethane (C ₂ H ₆) | 99 |
| Ethylene (C ₂ H ₄) | 90 |
| Tars (C ₁₀ +)) | 99.9 |
| Benzene (C ₆ H ₆) | 99 |
| Ammonia (NH ₃) | 90 |

Syngas exiting the tar reformer enters another cyclone to separate both entrained reforming catalyst and any residual char. The solids are then sent to a catalyst regenerator. The catalyst is sent to a regenerator vessel, where char and residual carbon is combusted. The hot, regenerated catalyst is then recycled back to the reactor vessel, acting as the heat source for the reforming reactions.

Syngas Cooling

The remaining gas treatment steps require the syngas to be at a much lower temperature. Therefore, the gas is cooled in three stages from 1598°F to 225°F prior to scrubbing. The heat

² Nexant team discussion with Pamela Spath, April 2005.

recovered from the process is used for steam generation throughout the system. The process design has been optimized as much as possible to use this steam, reducing the plant utility load. Integration was limited to the needs of the clean-up section; broader heat integration with the overall thermochemical platform or biomass refinery may lead to additional efficiency gains.

Scrubbing and Quench

The syngas is sent to the Syngas Venturi Scrubber, C-200, to remove any remaining ammonia, particulates, metals, halides, or alkali remaining in the system. The water circulation rate to the scrubber is adjusted such that the exiting syngas is quenched to the appropriate temperature for feed to the first stage of the compressor.

Compression

Any residual condensate in the syngas exiting the scrubber is removed in the Syngas Compressor KO Drum, V-300. The cooled syngas stream is compressed to 445 psia using a 4-stage centrifugal compressor with interstage cooling. The compressor is modeled assuming a horizontally split centrifugal design, with a polytropic efficiency of 78% and 110°F intercoolers. After discussion with compressor vendors³ and internal analysis by Nexant, it was determined that this type of compressor is appropriate for this gas flowrate, pressure ratio, and reliability requirements. While an integrally geared compressor was considered due to its lower cost, this type of compressor was not recommended due to the high flowrate and reliability required. The discharge pressure is designed such that the compressed gas is at the operating pressure range for FT synthesis.

Sulfur Removal

Originally, the scheme developed was use of LO-CATTM and ZnO polishing for H₂S removal, followed by amine for CO₂ removal. After discussions with NREL, this was modified so that amine was used for both H₂S and CO₂ removal. The ZnO beds remained in the design as a guard/polishing step after the amine unit, while the LO-CATTM unit is now used to remove H₂S from the acid gas stream. The benefit of this design is reduced load on both the LO-CATTM and ZnO units; the flow going to the LO-CATTM unit in this case is now only the acid gas stream instead of the entire syngas stream, and the inlet H₂S concentration at the ZnO bed is expected to be lower. This should increase the lifespan of the ZnO catalyst.

The syngas exiting the gasifier contains ~400 ppmv of H₂S. An amine unit with a high circulation rate can reduce the syngas sulfur concentration to below 10 ppmv, with a target of 2-3 ppmv. Due to the high amount of CO₂ removal required, it is this component that drives the circulation rate and unit size, not H₂S. The ZnO beds are used as a polishing step to reduce the sulfur concentration to the < 0.1 ppmv level required for methanol and FT synthesis. The gas exiting the amine absorber is heated to the operating temperature of the ZnO beds, 750°F.

For the low-pressure case, DEA was selected, while MDEA is used for the high-pressure case. This selection is based on design simulation runs by matching the desired CO₂ and H₂S removal

³ Consultation made with both Elliott Compressor and GE.

requirements to the selectivity of the amine solvents. Attempts were also made to choose solvents that minimized net energy requirements.

Water-Gas Shift and CO₂ Removal

FT synthesis requires a H₂/CO ratio of 2:1, and methanol synthesis requires the following stoichiometric ratio of H₂, CO, and CO₂:

$$(H_2 - CO_2) / (CO + CO_2) = 2$$

The syngas stream exiting the ZnO beds has a H₂/CO ratio of 1.7 and a stoichiometric ratio of 0.89, which are inadequate for FT or methanol synthesis. A combination of water injection into the tar cracker, followed by CO₂ removal in the amine unit, has been selected to adjust these ratios. In methanol synthesis, H₂ will react preferentially with CO₂ over CO to form methanol. This results in a significantly lowered methanol yield, greatly impacting the process efficiency. In FT synthesis, CO₂ acts as a diluent; however, for a design in which the off-gas from the FT reactor is recycled back to the reactor to improve conversion, removal of CO₂ is necessary to prevent CO₂ buildup in the reactor.

The initial designs for the low pressure system incorporated a shift reactor instead of water injection to assist in obtaining the necessary composition ratios. Further analysis and review with NREL led to the determination that a shift reactor was unnecessary, and that steam injection into the tar cracker is sufficient to perform the required shift. Elimination of this unit operation helps to reduce the overall system cost.

CO₂ removal can be achieved through different processes such as chemical (amine) or physical (Selexol or Rectisol) absorption, as outlined in Appendix D. The syngas stream entering the CO₂ removal unit is at about 420 psia and 110°F. Since physical absorption process is best suited for high pressure (>700 psia) and low temperature systems, an amine system was selected to remove CO₂ from the syngas. In addition to the syngas already possessing the appropriate operating conditions for chemical absorption, an amine system is also likely to be less expensive than the Selexol or Rectisol system. A side-by-side cost analysis from vendors would be necessary to confirm the optimal design. Approximately 98% of the CO₂ in the syngas stream must be removed in order to meet the stoichiometric ratio requirement for methanol synthesis.

The treated syngas exits the amine absorber at approximately 110°F and 440 psia. The treated syngas is sent to either the methanol or FT reactor. For methanol synthesis, the treated gas is compressed and heated to the operating conditions of the methanol reactor, about 1160 psia and 460°F. For FT synthesis, the treated gas is heated to 350°F.

1.2.2 High-Pressure Syngas Process Description

The cleanup process scheme for the syngas from the high-pressure gasifier is similar to that of the syngas from the low-pressure gasifier with the exception of the syngas compression step, differences in the heat balances, and process unit size variations due to different syngas compositions and conditions. Information about these differences is presented below.

Similar to the low-pressure case, high-pressure syngas is sent through a series of cyclones to remove the bulk of the char entrained in the syngas stream. The syngas is then sent to the tar reformer for removal of tars, methane, other light hydrocarbons, and ammonia. Steam is added to the syngas entering the tar reformer so that the shift reaction that occurs in the reformer can yield the required H₂/CO ratio for methanol or FT synthesis. Due to a more appropriate synthesis ratio in the raw syngas stream, less steam is required relative to the low-pressure case. The reformer effluent is then sent to the water scrubbing unit for removal of residual char, alkali, metals, halides, and ammonia.

Following the water scrubbing unit, the syngas is sent to an amine unit where MDEA is used for the removal of both H₂S and CO₂. As in the low-pressure case, a LO-CAT™ unit is used for sulfur recovery, while ZnO beds are used for reducing the syngas sulfur content to below < 0.1 ppmv H₂S. Rationale for process selection of the sulfur and CO₂ removal units is similar to that of the low-pressure syngas case, although MDEA was used instead of DEA in the amine system. The treated syngas is sent to either the methanol or FT reactor. For methanol synthesis, the treated gas requires compression and pre-heating to 1160 psia and 460°F prior to entering the methanol reactor. For FT synthesis, the treated gas requires pre-heating to 350°F.

1.3 DISCUSSION

1.3.1 Technologies Not Chosen

As presented in Appendix D, a list of technologies was provided for performing the various gas cleanup tasks required. From this list, specific technologies have been selected for each of the designs presented here. Below is a list of the technologies that were not chosen, and the rationale behind those decisions.

Particulate Removal

Ceramic and Metal Candle Filters: Candle filters could be used in place of cyclones for char and catalyst separation from the syngas stream. Little commercial experience exists in operating these types of filters at the temperatures (1500°F+) that the cyclones operate under. At this temperature, only ceramic filters could be considered. A recent study performed by Nexant for the DOE's National Energy Technology Laboratory⁴ examined replacing a third stage cyclone with a ceramic candle filter. The cost of this high temperature filter, even assuming an "nth plant design", did not justify the change. Because of the limited commercial experience and high cost, these options were eliminated.

Baghouse Filters: As with candle filters, baghouse filters are not appropriate for high temperature applications. Therefore, they cannot replace the cyclones as an effective solids removal option.

Electrostatic Precipitators: Since dry ESPs can only operate up to ~750°F and wet ESPs up to ~200°F, this option cannot replace cyclones for solids removal. In addition, the high cost and waste streams produced make them unattractive relative to other filtration options.

⁴ "Gasification Alternatives for Industrial Applications: Subtask 3.3—Alternate Design for the Eastern Coal Case, DOE Contract DE-AC26-99FT40342, April 2005.

Tar and Hydrocarbon Removal

Wet Scrubbing: Due to the relatively low content of tar in the syngas stream and the non-power application being considered, wet scrubbing could be considered a viable option for tar removal. However, inclusion of a wet scrubber may make a steam reformer necessary to remove hydrocarbons from the system. In addition, wet scrubbing for tar removal creates considerable waste removal and treatment issues and lowers process efficiencies. A detailed analysis comparing the current configuration with a wet scrubber/steam reformer would be of interest to confirm these assumptions.

Hydrocarbon Reforming (SMR/POx/ATR): Due to the low content of hydrocarbons exiting the tar cracker, it was determined that this step was unnecessary. Both FT and methanol synthesis reactors should be able to handle the quantity of hydrocarbons without severely impacting performance.

Other Technologies: During the course of the design work for the current configuration, other alternatives, such as injection of cracking catalyst directly into the gasifier and changes in gasifier operation, were identified. Limited empirical data for these technology options make them impractical for design use at this time.

Sulfur Removal

LO-CAT™: The initial designs for sulfur removal from the syngas stream used the LO-CAT™ technology due to the low net syngas sulfur content. Redesigns of the combined sulfur and CO₂ removal system demonstrated that using LO-CAT™ for sulfur recovery and amine for sulfur and CO₂ removal was more economic.

Physical Solvents: As can be seen in Appendix D, physical solvents (Rectisol/Selexol processes, for example) typically operate at low temperatures and high pressures. Changes in the stream pressure leaving the scrubber/quench may be required prior to entering a physical solvent unit for optimum performance, whereas the current process conditions are more appropriate for feed to an amine system. In addition, previous Nexant studies have determined little to no cost benefit in implementing a physical solvent system over other treatment methods for systems of this nature. A more in-depth analysis would be required to confirm the cost difference between physical absorbents and an amine/ZnO treatment system.

COS Hydrolysis: Due to the limited COS expected to be produced from a biomass gasification system, this removal step was omitted.

2.1 INTRODUCTION AND METHODOLOGY

Design and cost estimates were obtained using three major sources:

- HYSYS and ICARUS were used to obtain design and cost estimates for generic equipment such as vessels, pumps, compressors, and heat exchangers. The design basis was agreed upon after the submission of the design information outlined in Section 1.
- Vendor quotes were obtained for unique and specialized equipment such as cyclones, ZnO catalyst/reactors, LO-CAT™ sulfur absorption, and compressors. Some items, such as compressors and blowers, were estimated both by HYSYS/ICARUS and through vendor quotes in order to validate the results.
- The amine unit performance and energy requirements were estimated using commercially available software that is specific for amine unit modeling. Once performance requirements were obtained, an industry developed cost curve was used for estimating installed cost.

An updated set of PFDs can be seen in Appendices A and B. The design and cost estimates for the high-pressure and low-pressure cases are presented in the Equipment List and Data Sheets, which can be seen in Appendix C. The Equipment List groups process equipment by the following categories: reactors, cyclones, vessels, heat exchangers, compressors, pumps, turbines, and packaged units (the amine and LO-CAT™ units). Shown in the Equipment List are the following items:

- Unit size and weight
- Design duty (exchangers)
- Design temperature and pressure
- Power usage
- Materials of construction
- Price (uninstalled) on both a Q2 2004 and Q2 2005 basis
- Source for cost estimate
- Comments and notes

An installation factor of 2.57 was applied to all base equipment costs, with the exception of the process gas compressor, to arrive at the total installed cost. The installation factor was derived based upon previous experience and vendor estimates. An installation factor of 2.47 was used for the compressor based on previous detailed compressor cost analysis. The total installed cost for the low-pressure case is \$109MM, while the installed cost for the high-pressure case is \$76MM. The difference is largely due to the process gas compressor used in the low-pressure case.

2.2 KEY DESIGN ASSUMPTIONS

A complete description of the process and rationale for choosing the technologies in this deliverable can be seen in Section 1. Each case assumed a feedrate of 2,000 MTPD. Issues encountered when performing the unit designs are outlined below.

2.2.1 Sulfur and CO₂ Removal

As mentioned in Section 1, DEA was selected for the low-pressure case, while MDEA is used for the high-pressure case. This selection is based on design simulation runs by matching the desired CO₂ and H₂S removal requirements to the selectivity of the amine solvents. The level of CO₂ removal is the major driving force in determining the amine system size and cost; without the need for CO₂ removal, the unit cost decreases significantly.

2.2.2 Tar Reforming

Design and cost estimation of the tar reformer/regenerator presented a challenge to the team. Because no commercial data exists on design or cost for the performance outlined by the “goal” TCPDU case, a number of assumptions have been made:

- Reaction temperatures equal to the inlet gas temperature (1598 and 1576°F). These temperatures are derived from conversations with NREL. Recent experimental studies at Iowa State University on catalytic tar destruction have demonstrated successful operation at ~1350 to 1550°F⁵. Sensitivity cases were run at 1472 and 1200°F; the results show that heat duty is strongly impacted by the reaction temperature. Since the catalyst is the heat carrier in the reaction, the reaction temperature will greatly impact natural gas use and catalyst circulation rates. Minimizing these factors will trade-off with catalyst activity as the reaction temperature is lowered. This may be an area for future optimization and testing at the TCPDU.
- Low pressure operation for the regenerator to cut down on combustion air blower costs. This design is assuming the use of a pressurized rotary lock to increase recycle catalyst pressure. There is the risk that a rotary lock may be inadequate for this service due to the high catalyst circulation rates leading to premature erosion. If this is the case, either a lockhopper system or pressurized regenerator vessel would need to be included, significantly adding to the cost.
- Catalyst recycle rate based entirely off of thermodynamic requirements. Because of the endothermic reforming reactions, the regenerated catalyst must carry the heat necessary to maintain reactor temperature.
- Catalyst heat capacity of 0.25 Btu/lb/°F
- Plug flow within the reactor, with a Gas Hour Space Velocity (GHSV) of 2000/hr, to establish the basis for the bed volume and catalyst inventory. The calculated cracker

⁵ Zhang, R., Brown, R., Suby, A., Cummer, K., “Catalytic Destruction of Tar in Biomass Derived Producer Gas”, Energy Conversion and Management, Vol. 45, pp. 995-1014, 2004.

bed length was multiplied by a factor of four to account for deviations from ideal plug flow.

- Bed diameter calculated by first estimating the minimum and maximum bed fluidization velocities, then an average of these estimates taken. Fluidization velocities calculated from catalyst and syngas properties.

Both ASPEN and HYSYS were used to model these systems, with all necessary thermodynamic and kinetic assumptions included. The results from both simulations came out very close to one another with a very high heat duty (~150 to 170 MMBTU/hr) and catalyst circulation rate (~24,000 to 29,000 MTPD) in each case. While the cost of the actual vessels are not very high (\$1.3MM to \$1.5MM), the catalyst load is substantial, and costs could be high based on what assumptions are made for catalyst losses and system maintenance requirements. Since the catalyst is regenerated in the process, minimizing losses is key to reducing operating costs.

2.2.3 Cyclones

A number of assumptions were made for the particle size distribution, efficiency, and outlet particle loading. Since no explicit direction was given by NREL, assumptions using experimental data from small-scale gasifiers was assumed and given to vendors for sizing (99%+ particulate removal and an average particle size of 50 μm).

2.2.4 Heat Integration

The process heating and cooling needs were evaluated and heat integration performed to maximize heat recovery. The process design includes a steam cycle that recovers the majority of the process heat by generating steam. For hot process streams that could not be integrated in the steam cycle, cooling water was used to provide cooling duty. A steam turbine is included in the design to generate power from the excess process steam.

2.2.5 Methanol Compressor

It was assumed that a clean syngas pressure of 1160 psia was required for methanol synthesis. Therefore, a compression system with interstage cooling has been included in the design.

2.3 OPERATING COSTS AND UTILITY REQUIREMENTS

Catalyst and chemical needs, along with utility requirements, can be seen in Tables 2-1 through 2-3. The units with the highest operating cost are the amine system and the tar cracker. Steam cost contributes the largest cost component for the amine unit. A portion of the steam required for the amine unit is extracted from the steam turbine, and the remainder is assumed to be imported. About 44,000 lb/hr of steam is imported for the low-pressure case, and 113,500 lb/hr for the high-pressure case. Imports may be unnecessary if excess steam from elsewhere in the gasification unit is available.

The other major source of operating cost is the catalyst requirement for the tar cracker. The tar cracker specifics were determined by estimating the minimum fluidization velocity, required space velocity, and the required heat duty demanded of the regenerated catalyst. The total

amount of catalyst is equal to the settled bed volume of the two fluidized beds, plus an additional 10% for transfer line inventory. Due to the very high heat load and quantity of gas to be handled, the initial catalyst loading is substantial: ~300 tonnes in the HP case, and ~830 tonnes in the LP case.

The remaining catalyst and chemicals cost are in-line with the assumptions made by NREL; in fact, some of the costs used by NREL in the biomass to hydrogen report are used here either for consistency, or because little other information exists. For example, it is unknown what the cost will be of tar cracker catalyst that can perform as expected in the NREL “goal” design.

Nexant has not made assumptions for the total yearly operating cost at this time; this cost could vary considerably based on the assumptions made for plant performance and the assumptions for catalyst, chemicals, and power costs. An estimate for operating cost should be performed for an entire integrated gasification unit or biorefinery, instead of the clean-up unit as a stand-alone facility. Suggestions for proper estimation and reducing operating costs include:

- An availability of 85 to 90% would be appropriate for this design
- Both low and high pressure designs would likely require steam imports. This could come from purchases or excess steam production elsewhere in the gasification plant
- A 0.01% per day catalyst loss in the tar cracker, as assumed by NREL in the “goal” hydrogen design, is appropriate for initial cyclone operation, but will likely degrade over time. Typical catalyst assumptions and make-up rates for similar technologies range from 0.01% to 0.1%.

If a loss rate of 0.01% is assumed, and costs for the ZnO beds are amortized over the year, the daily catalyst and chemical cost is \$1931/day for the low-pressure case, and \$1457/day for the high pressure case. This takes into account tar cracker losses, ZnO bed replacement, and LO-CAT™ requirements. This is shown in Table 2-1 below.

TABLE 2-1 CATALYST AND CHEMICAL REQUIREMENTS

| Variable | Amount Required | Cost | Notes |
|---------------------------|---|---|--|
| Tar Reformer Catalyst | Low- Pressure Case: 1,820,000 lbs High-Pressure Case: 662,000 lbs | Price: \$4.67/lb (NREL H ₂ Report) | No commercial catalyst is currently available for this operation. Assuming a GHSV of 2000/hr, and a catalyst volume equal to the settled bed volume of the two fluidized beds plus 10% for transfer lines. |
| ZnO Catalyst | Low-Pressure Case: 777 cubic feet High-Pressure Case: 707 cubic feet | Price: \$355/cubic foot (Johnson Matthey). | Initial fill then replaced every year. Catalyst inventory based on H ₂ S removal capacity from 2 ppmv to 0.1 ppmv. |
| Sulfur Recovery Chemicals | Low-Pressure Case: 1.7 Tonnes/Day of Sulfur Removal High-Pressure Case: 2.4 Tonnes/Day of Sulfur Removal | Price: \$191/tonne sulfur removed (GTP Quote) | Assumes price for all LO-CAT™ chemicals required. Does not include utility requirements. |

| Item No | Item Name | Load BHP | | Elect. Power KW | Steam M Pounds per Hour | | | | | Water, GPM | | Cooling MMBTU/HR | Nat. Gas MMSCFD | Combustion Air MMSCFD |
|---------|------------------------------------|---------------|------------|--------------------|----------------------------|------------|-----------|-----------|------------|--------------|-------------------|---------------------|--------------------|-----------------------------|
| | | Norm. | Max (3) | | 85 psig | 35 psig | 5 psig | — psig | Cond. | Proc. | C.W. circ. (2) | | | |
| H-200 | Quench Water Recirculation Cooler | | | | | | | | | | 2,213 | 22.2 | | |
| H-300A | 1st Stage intercooler | | | | | | | | | | 12,188 | 122.0 | | |
| H-300B | 2nd Stage intercooler | | | | | | | | | | 3,276 | 32.8 | | |
| H-300C | 3rd Stage intercooler | | | | | | | | | | 2,766 | 27.7 | | |
| H-300D | Post compressor cooler | | | | | | | | | | 1,819 | 18.2 | | |
| H-402 | Lean Solvent Cooler | | | | | | | | | | 11,388 | 114.0 | | |
| H-403 | Amine Stripper Reboiler | | | | 150.6 | | | | 151 | | | | | |
| H-405 | Acid Gas Condenser | | | | | | | | | | 2,900 | 29.0 | | |
| H-500A | K-500 Interstage Cooler | | | | | | | | | | 1,105 | 11.1 | | |
| H-501 | MeOH Reactor Preheater | | | | 18.8 | | | | 18.8 | | | | | |
| H-601 | Blowdown Cooler | | | | | | | | | | 61 | 0.6 | | |
| K-100 | Combustion Air Blower | 910 | | 679 | | | | | | | | | | |
| K-300 | Syngas Compressor - 4 Stages | 38,786 | | 28,934 | | | | | | | | | | |
| K-420 | Flue Gas Blower | 347 | | 259 | | | | | | | 3 | 0.03 | | |
| K-500 | MeOH Compressor - 2 Stages | 8,717 | | 6,503 | | | | | | | 87 | 0.9 | | |
| P-201 | Quench Water Recirculation Pump | 20 | | 15 | | | | | | | | | | |
| P-400 | Lean Solvent Pump | 802 | | 599 | | | | | | | | | | |
| P-600 | Condensate Make-up Water Pump | 1 | | 1 | | | | | | | | | | |
| P-601 | Deaerator Feed Pump | 7 | | 5 | | | | | | | | | | |
| P-602 | Boiler Feed Water Pump | 570 | | 425 | | | | | | | | | | |
| R-xxx | Gasifier | | | | | 73.47 | | | | | | | | |
| R-100 | Tar Reformer | | | | | 53 | | | | | | | | |
| R-101 | Catalyst Regenerator | | | | | | | | | | | | 7.0 | 74.8 |
| | LO-CAT unit | 639.9 | | 477 | | | 0.56 | | | 1,800 | | | | |
| M-601 | Extraction Steam Turbine/Generator | (26,019) | | (19,410) | (18.8) | (232.9) | | | | | | | | |
| | TOTAL | 24,781 | | 18,486 | 0 | 44 | 1 | | 169 | 1,800 | 37,806 | 378 | 7 | 75 |

NOTES: 1. All Figures shown above represent normal utility usage requirements except:
 () indicates normal utility make
 * indicates intermittent usage or make, not included in totals
 2. CWS temperature is 80 F and CWR temperature is 100 F. Makeup water to cooling tower is not shown
 3. Utility consumption for max. load conditions is not shown.

2.4 DIFFERENCES WITH NREL BIOMASS TO HYDROGEN DESIGN

In general, the cost of the clean-up section of the biomass to chemicals designs is more expensive than for the NREL Biomass to Hydrogen design⁶. There are three main reasons for this: more equipment necessary in the chemicals designs, the increase in steel prices from 2002 to 2005, and different engineering assumptions made in the chemicals case. Information on each reason will be elaborated upon below.

2.4.1 Added Equipment to Chemicals Design

The two major unit operations that are new to this design versus the hydrogen cases are the amine unit and the syngas compressor for methanol synthesis. In the hydrogen cases, a LO-CATTM unit and ZnO bed was used for H₂S removal, while the PSA removed carbon dioxide. The chemicals cases also use the LO-CATTM and ZnO units, but instead of a PSA, an amine unit is used for the bulk H₂S and CO₂ removal. The cost for the amine units is driven largely by the need for CO₂ removal; due to the low H₂S content in the syngas, the cost of the amine unit would be roughly half as much if CO₂ removal was not required. The LO-CATTM unit is used in this case for clean-up of the acid gas stream from the amine unit instead of bulk H₂S removal. Because of the CO₂ content and different operating requirements versus the hydrogen case, the quote provided by GTP is roughly double the price used in the hydrogen case.

⁶ Spath, P.; Aden, A.; Eggeman, T.; Ringer, M.; Wallace, B.; Jechura, J. (2005). Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. 161 pp.; NREL Report No. TP-510-37408.

In order to compress the clean syngas up to methanol synthesis pressure, a ~8,000 HP compressor is required. This unit was not necessary in the hydrogen case, adding to the overall cost. Taking into account a \$12MM credit by not using the PSA, the LP cost increases by ~\$8.5MM, while the HP cost increases by ~\$18.5MM due specifically to the extra equipment needed.

2.4.2 Increase in Steel Price

NREL used 2002 as the cost basis for the biomass to hydrogen designs, while Nexant is using Q2 2005. The increase in steel price between 2002 and 2005 has been significant, impacting the prices quoted in the Nexant design. The Q2 2005 basis for hot-rolled steel is ~\$400 to \$450/ton, up from ~\$250 to \$300/ton in 2002⁷. Steel prices have been very volatile in the last 3 years due to strong worldwide demand, a sharp rise in energy prices, consolidation in the US steel market, and a weak US dollar.

Because of this basis difference, the 2002 NREL basis would need to be escalated not only for inflation but also for steel price in order to put it on the same basis as this study. It is difficult to place a blanket escalation factor on the design due to the impacts that steel price has on different pieces of equipment; for example, this may make up much of the difference in price in equipment like vessels and exchangers, but have less of an impact on compressor prices. Each unit should be evaluated independently to determine the impact that steel price has on overall unit cost.

2.4.3 Engineering Assumptions

A side-by-side comparison of all the major process units was performed for the HP and LP cases versus the NREL hydrogen design. A few differences were noticed that are outlined below. A direct comparison cannot be performed on units that were lumped into the “Gas Cleanup” section of the NREL design and not explicitly sized. While the major differences are outlined here, only a brief attempt at determining the cost difference has been made.

Reactors and Columns

ZnO Beds: While the size of the ZnO beds in this design is smaller than the hydrogen case, the installed cost is roughly double. This is likely due to the difference in steel price.

Tar Reformer/Regenerator: In the hydrogen design, this is included in the “Cleanup” costs, so no explicit design information is available. The NREL assumption for “Cleanup” took the average of a number of different studies; however, only one of these studies, Weyerhaeuser (2000), had a tar cracker. The “Cleanup” section for the Weyerhaeuser study was ~\$9MM greater than the other designs, implying that the majority of the cost may be due to the tar cracker cost. The NREL “Cleanup” assumption may be low since the hydrogen design has a tar cracker, yet only one of the studies used to obtain the “Cleanup” cost also has a tar cracker.

⁷ For more information, see the Bureau of Labor Statistics “Producer Price Series”, along with Lazaroff, Leon, “Steel Regains Some Luster”, Detroit Free Press, 25 July 2005

Cyclones

Since these were part of the “Cleanup” average, no explicit design numbers were provided as part of the hydrogen study. Design quotes from vendors are used for this part of the plant in the chemicals design.

Vessels

The Nexant estimate is higher than the hydrogen design due to 1) the venturi and quench being included as part of the “Cleanup” estimate, 2) larger vessel sizes for the steam system than what was assumed in the hydrogen design, and 3) steel prices. Depending on the price assumed for the venturi /quench in the hydrogen design, the Nexant estimate appears to be ~\$3MM greater than the hydrogen case.

Heat Exchangers

A number of differences exist between the hydrogen and chemicals designs, making the installed cost for exchangers in the chemical production case ~\$4MM to \$6MM higher than in the hydrogen case:

- There is a large cost discrepancy between the exchangers downstream of the tar reformer. The Nexant designs are larger and considerably more expensive; Nexant assumed refractory lining, while it is unclear if this assumption is made in the hydrogen design.
- The Nexant design has a number of exchangers not included in the hydrogen design: amine precoolers (HP case), methanol compressor coolers (both cases), and ZnO coolers (both cases).
- A few of the exchangers in the hydrogen design are included in the “Cleanup” section, so it is difficult to make a direction comparison.

Compressors and Blowers

As mentioned earlier, the syngas compressor for methanol synthesis adds ~\$7MM to the installed cost relative to the hydrogen case. This compressor was not necessary in the NREL hydrogen design.

There is a major difference between the NREL and Nexant assumptions for the syngas compressor in the LP case. While NREL shows an installed cost of ~\$12MM for a 30,000 HP compressor, Nexant estimates that a ~38,000 HP compressor is required at an installed cost of ~\$37MM (\$15MM for the equipment alone). The equipment cost comes directly from Elliott Compressor; checks on the validity of the estimate using cost curves, ICARUS, and other vendors show that this is within the +/- 30% estimate desired by the study. The NREL study assumed that an integrally geared compressor type would be appropriate, while this report uses a horizontally split centrifugal compressor recommended by vendors. Analysis using cost estimating software shows that this assumption is the main reason for the cost difference.

Pumps

Both Nexant and NREL designs are in agreement in regards to the pumps.

Steam Turbine

The Nexant estimate is slightly higher than the NREL estimate, ~\$12MM installed versus \$10MM. This difference is likely due to steel prices.

The other difference that should be pointed out between the hydrogen and chemicals cases is the assumption made for the installation factor. NREL used a 2.47 installation factor, which is derived from literature sources. Nexant used 2.57 in both the HP and LP cases, except on the process gas compressor, where 2.47 is used. These numbers are derived independently from previous experience and vendor engineering estimates. While the factors are very similar to one another, this difference can make a 4% difference (\$2MM) on an equipment cost of \$20MM.

2.5 CHANGING FLOWS, CONDITIONS, AND COMPOSITIONS

Per the scope of work outlined by NREL as part of this project, Nexant has been asked to provide input on how the design estimates will be adjusted if the syngas flowrates or compositions vary. Information for both the high and low-pressure cases, along with the scaling factors appropriate for each major piece of process equipment, are outlined below.

2.5.1 Flowrate Impacts

In general the limits on process equipment sizes are usually the result of manufacturing restraints, transportation limits, and maintenance restrictions. For this evaluation, it was assumed that the throughput would be increased by 50% and the equipment size or capacity would increase accordingly. The affects of this change are discussed below with respect to both the low- and high-pressure cases.

Low-Pressure Syngas Design Cases

For the Low-Pressure Syngas Design Cases some of the equipment has already reached size limitations that required multiple trains or parallel equipment. Thus, increasing the capacity by 50% will require more parallel equipment and a more complex and expensive piping manifold. Examples include:

- Gasifier Cyclones (4 required for the base capacity)
- Tar Reformer SG Cooler/Steam Generator (2 required)
- Tar Reformer SG Cooler/BFW Preheater (2 required)
- Compressor Interstage Cooling - 1st stage (2 required)
- Syngas Venturi Scrubber/Quench Tower (2 required)

Thus, for a 50% increase in capacity, the design would require 6 gasifier cyclones, 3 of each major heat exchanger, and 3 venturi scrubbers.

Other items, such as the 1st Stage KO Drum, may require either a parallel unit or field construction due to equipment size and weight limitations during transportation. While the limits for ground transportation vary from state to state, typically, codes limit standard transport sizes to ~14 feet in width and height, 53 feet long and 80,000 pounds. Locating this facility in Iowa will mean that most equipment will be transported to the site either by rail or truck. Access to the Mississippi or Missouri Rivers may allow larger vessels to be used. For the 1st Stage KO Drum, the inside diameter would increase to about 16 feet (from a 13 foot diameter) at a capacity 50% greater than the base case. However, when considering transportation by road, auxiliary equipment such as nozzles and flanges must be taken into consideration. This item would be well beyond most road transportation limits in the U.S. To manage this limitation, options are either transportation by rail or barge, parallel pieces of equipment, or field fabrication.

Other equipment may exceed the maximum recommended size for a single train, and would require a second, parallel unit. This includes items such as the Syngas Compressor and the shell and tube heat exchanger for the Flue Gas Cooler/Steam Superheater service. In the latter case, the size of the heat exchanger is actually a maintenance issue. The diameter of the tube bundle of these units is larger than a normal bundle puller could handle (maximum limit is about 6-7 feet diameter). It then becomes an economic question of bringing in special maintenance equipment during turnarounds or using smaller, parallel process equipment.

High-Pressure Syngas Design Cases

For the High-Pressure Syngas Design Cases, most of the equipment is smaller than the corresponding equipment for the Low-Pressure Syngas Design Cases as a result of the high pressure operation. Only a few items, when scaled by +50%, would require a parallel unit. Two major exchangers, the Tar Reformer SG Cooler/Steam Generator and Flue Gas Cooler/Steam Superheater, were discussed above. Another area is equipment within the LO-CAT™ unit. These include the Inlet Gas KO Drum and the LO-CAT™ Oxidizer Vessel. The former would require a vessel with an inside diameter of over 17 feet and the latter would require an inside diameter of about 16 feet. As noted previously, the outside diameter (including nozzles and flanges) would be well beyond most road transportation limits in the U.S. Vendors for process items of this nature can provide input for the appropriate process configuration for this service.

Appropriate vessel sizing for the amine system is also of concern in this design. The amine system contains two relatively large columns – the scrubber and the regenerator. Considering a 50% increase in capacity, the column diameters will increase by about 20 to 25%. In particular, the regeneration column may exceed the transportation size limitations and thus, require parallel trains or field fabrication.

General Information

A plant that is 50% larger will require more plot area not only due to the larger equipment and storage, but due to offsite considerations. For example, the flare will have to be designed for a load that is 50% larger. This will require either a taller flare or moving the flare further away from the main process units. A higher flare may meet with height restrictions. Thus, the area that is restricted around the flare may increase.

Estimating the Capital Investment Cost

In most cases the capital cost for a capacity increase or decrease of 50% can be estimated using exponential methods. That is, the new capital cost can be estimated by using capacity ratio exponents based on published correlations and the following formula:

$$C_2 = C_1 (q_2/q_1)^n$$

where C stands for cost, q for flowrate, and where the value of the exponent n depends on the type of equipment. In reviewing the literature for the various exponents, some discrepancies in published factors are apparent due to variation in definition, scope and size. Technology has also advanced over time, making it less expensive to produce larger machinery now than in years past. In addition, new regulations dictate expenditures for environmental control and safety not included in earlier equipment. In the table that follows, the most recent literature information is listed. Traditionally, when a specific value is not known, an exponent value of 0.6 is often used for equipment and a value of 0.7 for chemical process plants (usually expressed in terms of annual production capacity). Table 2-4 gives typical values of n for most of the equipment included in these designs.^{8,9,10,11,12}

TABLE 2-4 EXAMPLES OF TYPICAL EXPONENTS FOR EQUIPMENT COST VERSUS CAPACITY

| Equipment | Size Range | Units | Exponent** |
|------------------------------|------------------|---|--------------|
| Reactor – fixed beds | N/A | | 0.65-0.70 |
| Column (including internals) | 300-30,000 | Feed rate, million lb/yr | 0.62 |
| Cyclone | 20-8,000 | Cubic feet/m | 0.64 |
| Vessel – vertical | 100-20,000 | US gallons | 0.30 |
| Vessel – horizontal | 100-80,000 | US gallons | 0.62 |
| Heat exchanger (S&T) | 20-20,000 | Square feet | 0.59 |
| Venturi scrubber | N/A | | 0.60 |
| Compressor – centrifugal* | 200-30,000 | hp | 0.62 |
| Blower* | 0.5 - 150 | Thousand standard cubic feet per minute | 0.60 |
| Pump* | 0.5-40 40-400 | hp | 0.30 0.67 |
| Turbine | | hp | 0.81 |
| Pressure discharge | 20-5,000 | | |
| Vacuum discharge | 200-8,000 | | |
| Motor | 10-25 | hp | 0.56 |

⁸ Perry, Robert H., and Green Don W., Perry's Chemical Engineers' Handbook, 7th edition, page 9-69.

⁹ Walas, Stanley M., "Chemical Process Equipment – Selection and Design," Butterworths, page 665

¹⁰ Blank, L. T. and A. J. Tarquin, "Engineering Economy," McGraw-Hill

¹¹ Peters, Max S. and Timmerhaus, Klaus D., "Plant Design and Economics for Chemical Engineers," McGraw-Hill, page 170

¹² Remer, Donald S. and Chai, Lawrence H., "Design Cost Factors for Scaling-up Engineering Equipment," *Chemical Engineering Progress*, August 1990, pp 77-82

| Equipment | Size Range | Units | Exponent** |
|--------------|------------|-------|------------|
| | 25-200 | | 0.77 |
| Package unit | N/A | | 0.75 |
| Other | N/A | | 0.6 – 0.7 |

* excluding driver

** this estimating method gives only the purchase price of the equipment; additional installation cost for labor, foundations and construction expenses will make the final cost higher.

2.5.2 Composition Impacts

The major units that will be impacted by a large change in syngas composition are the tar reformer and the venturi scrubber. Due to the relatively low concentration of sulfur in the syngas stream, +/-50% fluctuations in the H₂S content should not impact how the sulfur removal system is designed. Significant changes in the inlet H₂/CO ratio may also require modifications of the design in order to establish the appropriate downstream composition.

The obvious change that will influence the design of the tar reformer is the amount of hydrocarbons in the syngas from the gasifier. Currently, the design is assuming that a separate reformer is not necessary, with the tar reformer converting most hydrocarbons exiting the gasifier. If either the hydrocarbon yield increases or the tar reformer conversion is lower than planned, a separate reformer for light hydrocarbons should be considered. The amount and type of hydrocarbons will affect the operating conditions which will in turn affect the water gas shift reaction. A change in the H₂/CO ratio may require divorcing the shift reaction from the tar reformer (i.e., a separate shift reactor instead of just adding steam to the tar reformer).

A 50% increase in particulates may require different/larger cyclones or a redesign of the venturi scrubber in order to handle the larger load. This is largely controlled by the gasifier operation; reliable performance data should be established prior to deciding upon a particulate removal scheme. Higher particulate loading than planned can significantly hurt overall plant performance.

A 50% increase in H₂S will not affect the sulfur recovery processes. LO-CAT™ can handle between 150 lbs to 20 tonnes of sulfur per day, and concentrations between 100 ppm and about 10% H₂S. Even at 50 percent more H₂S, the concentration still remains within the operating limits for LO-CAT™. In addition, the solvent circulation rate in the amine unit can be increased to remove additional H₂S if the sulfur concentration is higher than expected.

2.6 FOLLOW-UP AND AREAS FOR FURTHER STUDY

The analysis performed sets the base case for the clean-up section of two different biomass-to-chemicals designs. After in-depth analysis of these cases, the team has identified a number of areas for further study:

- **Alternatives for Tar Removal:** A number of assumptions have been made for sizing and costing of this unit. Greater study and analysis, both in the laboratory and through simulations, should be performed to determine if the methods used are valid. In addition, alternative tar removal technology should be considered, including:

- Introduction of tar cracking catalyst into the gasifier. Typically, this has not been done due to concerns with deactivation and erosion.
- Gasifier operation to reduce hydrocarbon yields.
- Using a water wash for tars, followed by a standard reformer for hydrocarbons. While this increases the cost of quenching and wastewater handling, the cost tradeoff may be economic.
- **Process Integration, Gasification Systems and Biorefinery:** Integration of the clean-up section with the other parts of the gasification plant will provide a better picture of the overall plant costs. In addition, use of this thermochemical platform has been considered for future application into an integrated “biorefinery”. This base case could be used for a determination of the process requirements and offerings that a thermochemical platform could provide.
- **Alternate CO₂/Sulfur Removal Steps:** Based on the design information provided and past studies that have been examined, the steps incorporated for CO₂ and sulfur removal has been determined to be appropriate at this stage. A cost comparison of amine versus physical solvents and new technologies for acid gas removal would provide additional data to confirm the appropriate use of amine in this design.

New technology is currently being explored to remove sulfur without having to cool to 110°F or below. Since none of this technology is currently commercial, it has not been evaluated for use in this design. If available however, warm sulfur clean-up may increase efficiency in this design, by reducing the amount of reheat necessary prior to entering the shift reactor.

- **Other Impurities in the Syngas:** For the low pressure case, a scrubber has been included to remove residual ammonia, and any metals, halides, or alkali remaining in the system. If it is deemed that the level of these impurities entering the scrubber will not adversely impact the FT or methanol catalysts, this step could be removed.

3.1 SUMMARY

The labor projections for the 2000 MTPD biomass gasification plant are based on a combination of 1) models developed from Emery Energy's 70MWe Gasification Plant design completed under prior DOE contracts, 2) additional "adders" for the scale and complexity (chemical plant nature / hydrogen production) of the 2000 MTPD plant being considered, and 3) previous experience of Nexant and other team members. The high pressure, oxygen-blown, 2000 MTPD plant requires labor skills with slightly greater operating experience than power-only facilities, and thus commands a premium for these skills.

The labor rates derived from Emery's 70 MWe Biomass IGCC (1200 MTPD plant) case were ~\$1,650,000 per year (not including subcontracted services) versus the \$2,274,720 projected for the labor costs for the 2000 MTPD biomass to chemicals design. This difference of roughly \$625,000 represents the higher level of experience needed for the larger plant, greater materials handling rates, and increased labor for plant maintenance. A discussion of the reasons for this difference, along with differences between the recent NREL Biomass to Hydrogen report, is contained below. Some of the main differences with the NREL Hydrogen report include different job descriptions, the use of a back-up shift crew, utilization of contract labor, and lower assumptions for overhead costs.

3.2 LABOR REQUIREMENTS

The following labor categories and positions will be required for the 2000 MTPD biomass plant.

- **General Plant Manager:** Responsible for all personnel and plant decisions, including new employee hiring, operator training, fuel contracts, maintenance contracts, general equipment purchases, external communications, and operating schedules. Engineering degree required, with 10+ years of chemical plant operating experience. Salary of \$100,000/yr.
- **Administrative Assistant/Company Controller:** Support the general plant manager, manages personnel records, completes company payroll, manages time accounting records, manages company benefits, employee investment accounts, and insurance enrollments. Accountant degree required with 5+ years of experience. Salary of \$45,000/yr.
- **Secretary/Receptionist:** Supports the General Plant Manager and Company Controller. Receives visitors, answers phone, and attends to office administrative duties. Salary/Wages of \$25,000/yr.
- **Laboratory Manager:** Oversees all laboratory equipment and laboratory technicians. Responsible for product quality; testing performed both on finished product and intermediate streams (via on-line equipment and sample draws). Works straight days, with some overtime possible. Salary/Wages of \$50,000/yr.
- **Laboratory Technician:** Responsible for sample gathering, analytical equipment maintenance, and laboratory testing. Works straight days, with some overtime

possible. Shift operating crew can assist with some sample gathering as necessary; contract equipment technicians can assist with analytical equipment repair as necessary. Salary/Wages of \$35,000/yr.

- **Shift Operating Crew:** The plant will be operated by a four-member crew shift each week, with responsibilities defined below:
- **Shift Superintendent.** The shift superintendent is the chief operator who mans the control station and simultaneously directs the activities of the shift crew. The shift superintendent is a degreed engineer who understands the plant, understands the technical and physical operations, and makes key operating decisions. The shift superintendent ensures compliance with plant quality, safety, industrial hygiene, and environmental requirements. 5-10 years of chemical plant operating experience is preferred for this position. Salary of \$75,000/yr.
- **Support Operator.** The support operator aids the shift superintendent with plant operation. The support operator is also tasked with bulk material handling such as feedstock receipts/inspection/weigh-in and ash weigh-out/disposal shipments. The support operator attends to feed and ash sampling/characterization, waste water disposal sampling, and provides general plant support in relief of the shift superintendent. The support operator is also tasked with monitoring plant emissions rates, including daily/weekly calibration of effluent gas monitors. The support operator verifies that plant operating records and daily logs are correct. This position coordinates fuel characterizations and waste water analyses. A novice degreed engineer or experienced technician is sufficient for this position. Salary of \$45,000/yr.
- **Millwright.** The shift millwright conducts hourly and daily equipment inspections, safety rounds, completes scheduled equipment process maintenance, supports equipment maintenance and equipment replacements, contracts and supervises crafts such as pipe fitters, electricians, welders, and special instrument technicians when such functions exceed the millwright's capabilities. The millwright preferably has an associate degree in mechanical, industrial, or design engineering technology with 5-10 years experience. Salary of \$60,000.
- **Millwright Assistant/Yard Labor.** Supports millwright and accompanies millwright and contracted crafts, particularly during dangerous work activities, such as confined space entries and working from heights. The millwright assistant supports tool setup, job errands, and plant cleanup. Salary of \$35,000.

Shifts run for 12 hours with two crews per day. Crews report to work 30 minutes prior to the shift turnover to perform receive shift operating instructions and to pass information on critical operations and maintenance. Each crew member is allotted 30 minutes for a meal break. Thus, each shift extends 12.5 hours, with 0.5 hours meal break, or 12 hours of labor. Crews operate on a 4 days on / 4 days off rotation. This requires 84 hours on average per crew member for any two-week pay period.

Five complete shift teams are engaged. The fifth crew provides coverage for individual vacations, sick leave, and holidays. The fifth crew also fills in for continuing training and for

new hire training. The fifth crew also supports ongoing maintenance and periodic outage/turnaround planning. In addition, the fifth crew supports updates to control system programming, data collection, and instruments. The millwright assistant on the fifth crew supports plant cleanup and janitorial activities. The fifth crew works 40-hour straight days when not substituting for members of the four-crew rotation.

Table 3-1 summarizes the plant operating labor by category, salary, and total cost.

TABLE 3-1 LABOR COSTS

| Position | Number | Base Salary or Hourly Rate | Annual Overtime and Holiday Hours | Overtime Rate | Total Annual Cost |
|--|---------|----------------------------|-----------------------------------|---------------|--------------------|
| General Plant Manager | 1 | \$100,000 | N/A | N/A | \$100,000 |
| Company Controller | 1 | \$45,000 | N/A | N/A | \$45,000 |
| Secretary/ Receptionist | 1 | \$25,000 | None | N/A | \$25,000 |
| Laboratory Manager | 1 | \$50,000 | 240 | \$30 | \$57,200 |
| Laboratory Technician | 2 | \$35,000 | 240 | \$22.50 | \$80,800 |
| Shift Superintendent | 5 | \$75,000 | 680 | \$45 | \$405,600 |
| Support Operator | 5 | \$45,000 | 680 | \$25 | \$242,000 |
| Millwright | 5 | \$60,000 | 680 | \$32.50 | \$322,100 |
| Millwright Assistant | 5 | \$15.00/hr | 560 | \$22.50 | \$144,000 |
| Total Base Salaries and Wages | | | | | \$1,421,700 |
| General Overhead and Benefits (60% of total salaries) | | | | | \$853,020 |
| Total Base Wages and Benefits | | | | | \$2,274,720 |
| Subcontracted Crafts | | | | | |
| Welder | \$80/hr | 1200 | | | \$96,000 |
| Electrician | \$75/hr | 640 | | | \$48,000 |
| Pipe Fitter | \$65/hr | 600 | | | \$39,000 |
| Insulator/Painter | \$60/hr | 400 | | | \$24,000 |
| Carpenter | \$55/hr | 400 | | | \$22,000 |
| Instrument Technician | \$90/hr | 400 | | | \$36,000 |
| Total Subcontracted Labor | | | | | \$265,000 |
| Total Labor and Benefits (Operating Labor Cost) | | | | | \$2,539,720 |

3.3 DIFFERENCES WITH EMERY ENERGY 70 MWE CASE

Both the complexity and size of this facility increases the labor costs over what Emery Energy has assumed for their 70 MWe biomass gasification facility. The size of the unit (1200 MTPD vs. 2000 MTPD) slightly increases the number of shift workers and contract hours required, but does not increase the plant management or engineering requirements. This represents an economy-of-scale advantage enjoyed by larger gasification facilities; while the total labor requirement is greater than the 1200 MTPD facility, the marginal amount of labor required decreases as plant size increases.

This design contains additional equipment than what is assumed in Emery Energy's 70 MWe facility design. While this design does not contain a gas turbine, steam turbine, or HRSG, additional equipment includes enhanced sulfur removal (an amine system and ZnO beds), chemicals synthesis equipment, and tar cracking. It is this increase in complexity, rather than the increase in size, that adds the majority of the increase in labor costs.

3.4 DIFFERENCES WITH NREL BIOMASS TO HYDROGEN CASE

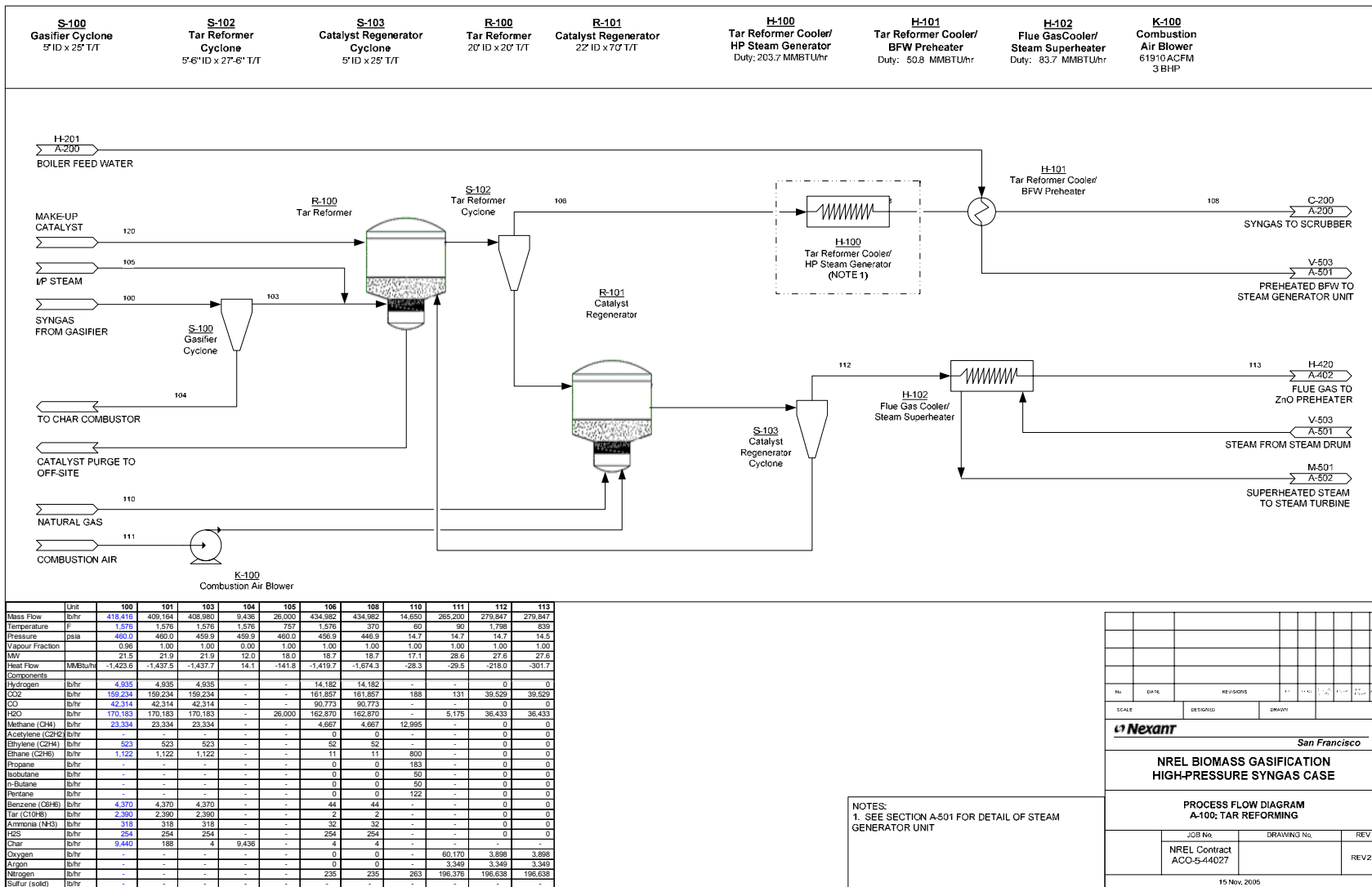
In the 2005 study, NREL made assumptions for the labor requirements necessary for a 2000 TPD wood gasification to hydrogen plant. The size being considered in this design is exactly the same, and the complexity is roughly the same as the NREL case. The only main difference is the inclusion of chemicals synthesis equipment, which takes the place of the PSA and related equipment required for hydrogen production.

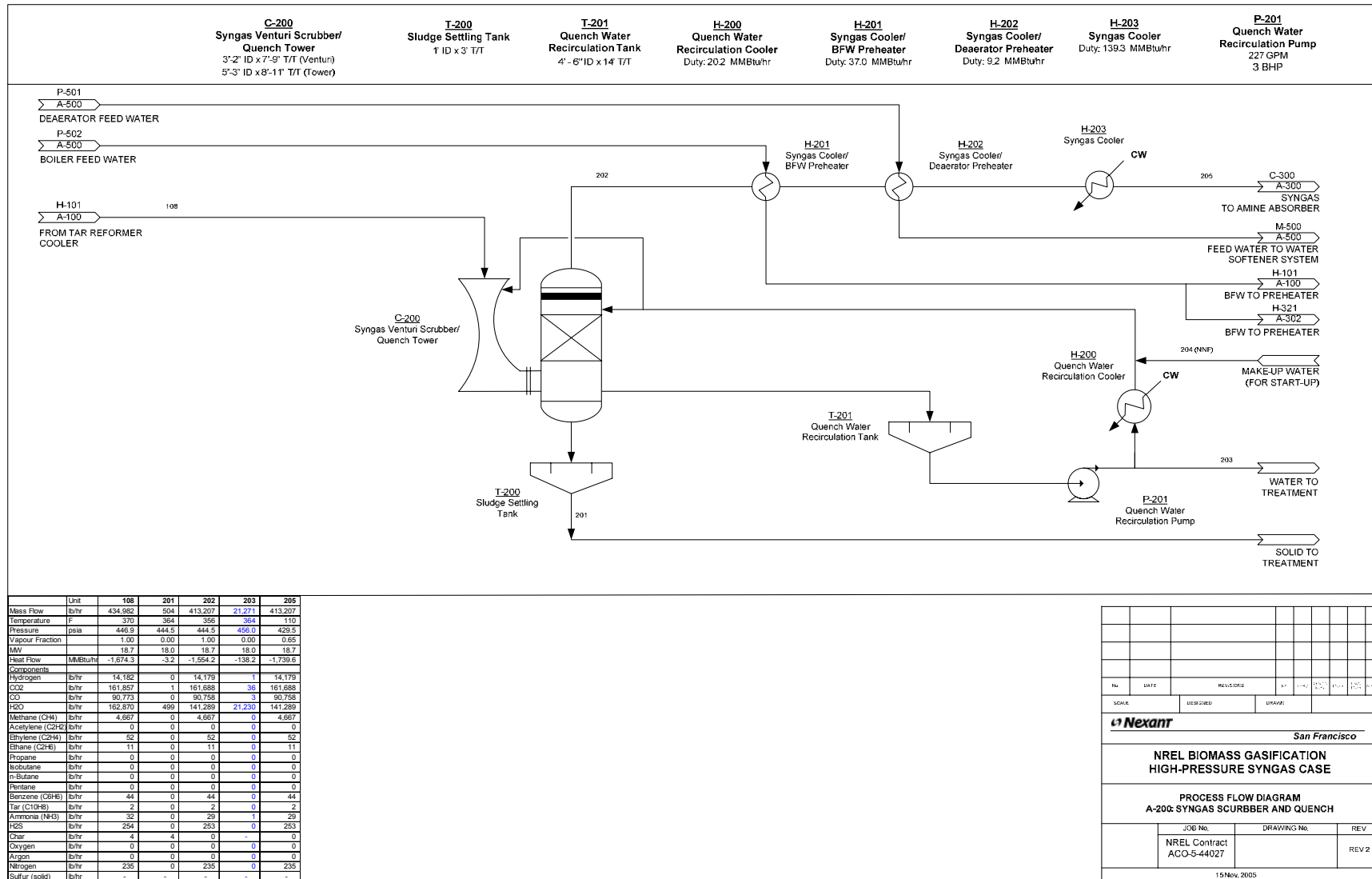
The labor requirements developed for the chemicals synthesis cases are lower by almost \$1.5MM due to the assumptions made by the Nexant team. The main differences are highlighted below:

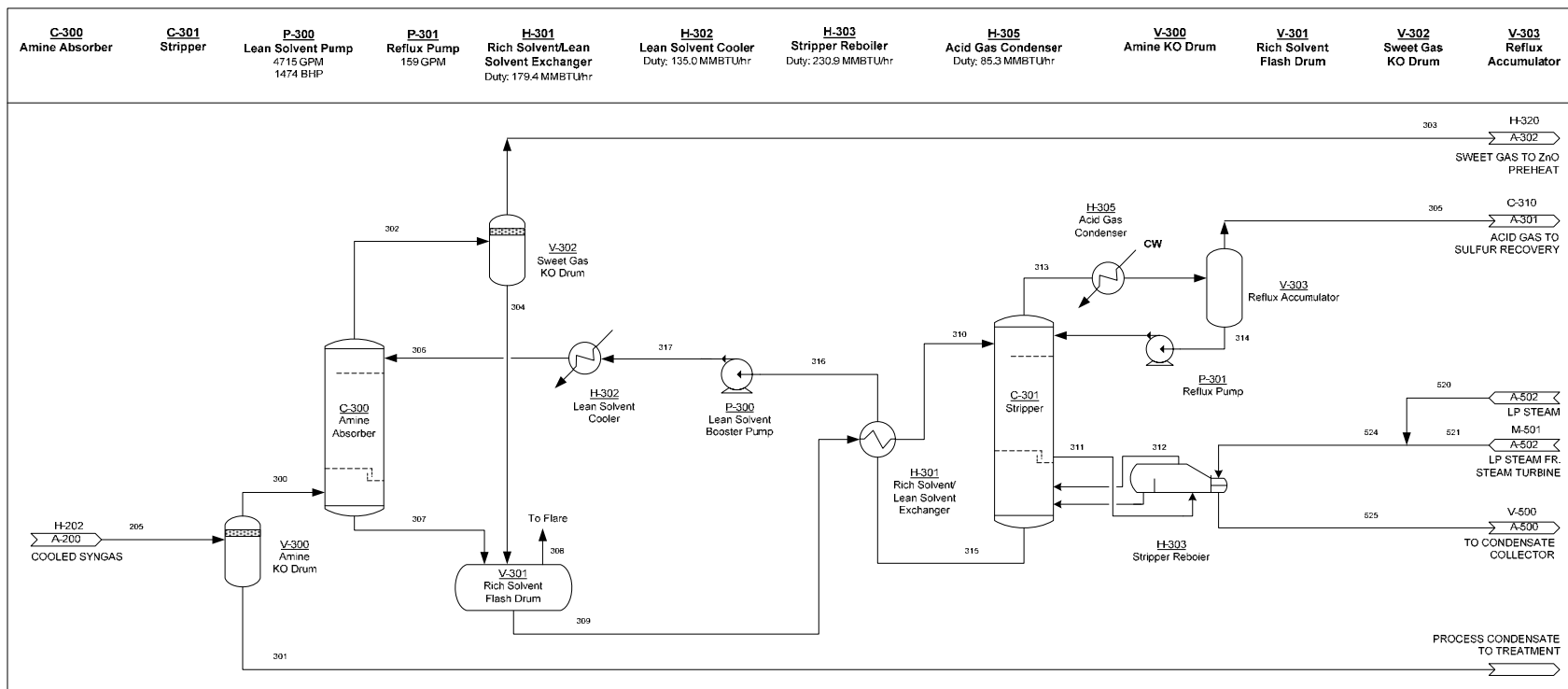
- **Salary Assumptions:** In general, slightly higher salaries are assumed in the chemicals synthesis design for employees such as the plant manager, engineers, and operators. Higher salaries may be necessary to attract workers to facilities employing complicated and novel technologies.
- **Administrative Assistants:** Instead of the three assistants assumed by NREL, this design assumes only two: the company controller/administrative assistant and the main receptionist. The main difference is that the truck handling work performed by the assistant in the NREL design will now be split amongst the millwrights and assistants.
- **Work Assignments for Shift Workers:** As mentioned in the job descriptions, it is assumed that support operators will assist with yard issues, feedstock delivery, and field work, while the superintendent will largely be responsible for control issues. This reduces the need for yard employees and operators whose sole job is to man control boards. The five crews effectively allow for additional personnel capable of supporting offloading and weighing of the biomass feedstock.
- **Subcontract Labor:** In order to reduce the need for full-time staff for part-time work, a number of specific skills, such as welders, electricians, and carpenters, will be

contracted out. This reduces the overall labor costs and overhead. No subcontract labor was assumed in the NREL hydrogen case.

- **Overhead:** The labor estimate made in this case has roughly half as much full-time staff by utilizing more contract labor and changing the job description of day and shift employees. This is one reason that the estimate for overhead expenses (60%) is less than the biomass to hydrogen case (95%). In addition, the assumption has been made that a small firm will own and operate this facility. In general, overhead has been found to be less in smaller firms than in large multinationals; this assumption could be revised based on the ownership basis. This assumption for the overhead rate has been confirmed by Emery Energy, and is consistent with other small gasification companies that have limited facilities and indirect labor costs.
- **Overtime Assumptions:** The NREL hydrogen case assumed straight salaries for all employees, with no overtime. The chemicals case assumes ~2500 hours of overtime per year, roughly split over the 4 main shift worker categories. Allowing overtime reduces the number of full-time employees required, and decreases overall labor costs versus the NREL hydrogen case.
- **Back-Up Shift Crew:** Unlike the NREL hydrogen design, the back-up fifth shift team would be available to cover a number of different duties during the day shift, decreasing the need for specialty workers in each area.

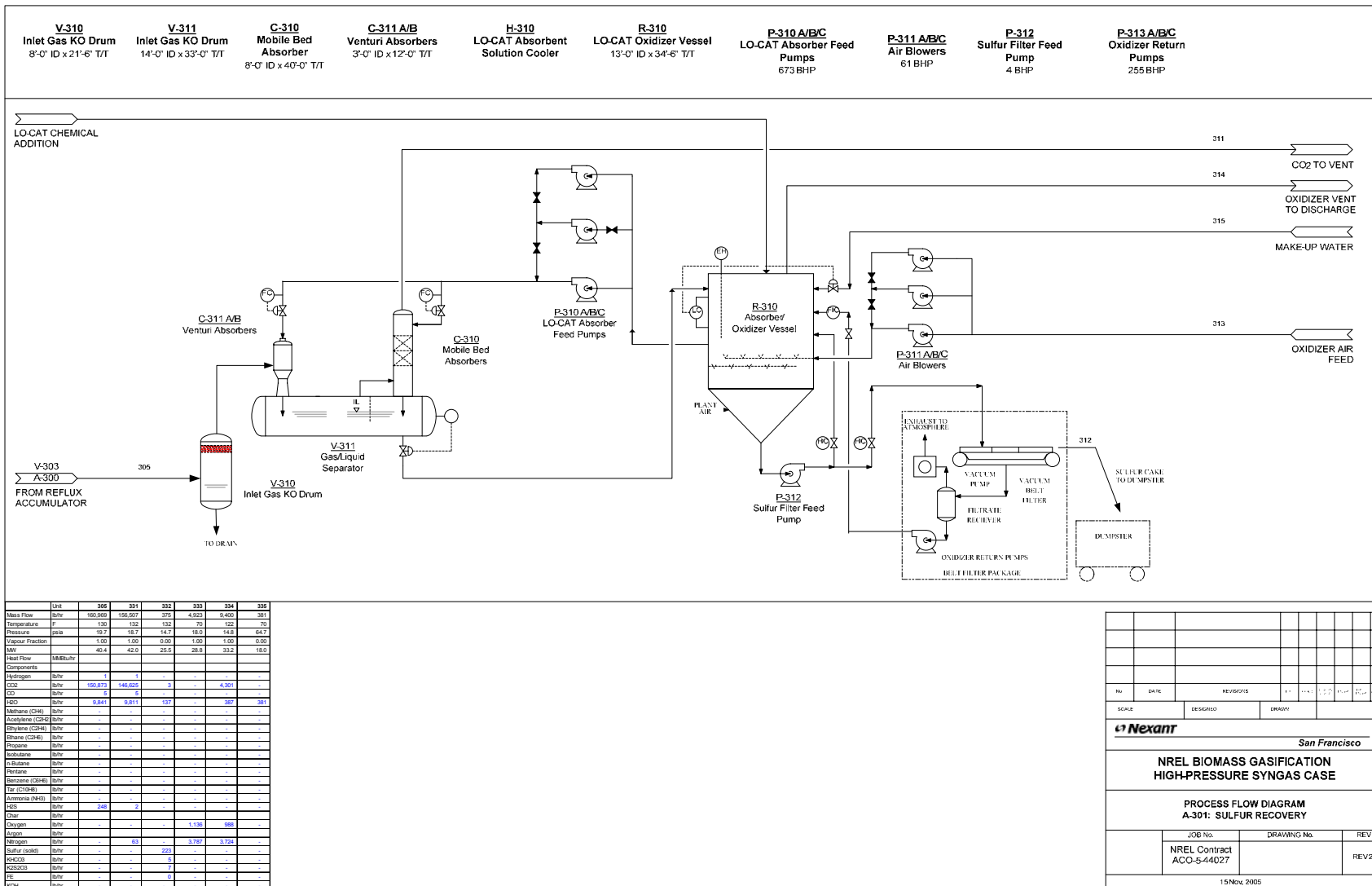


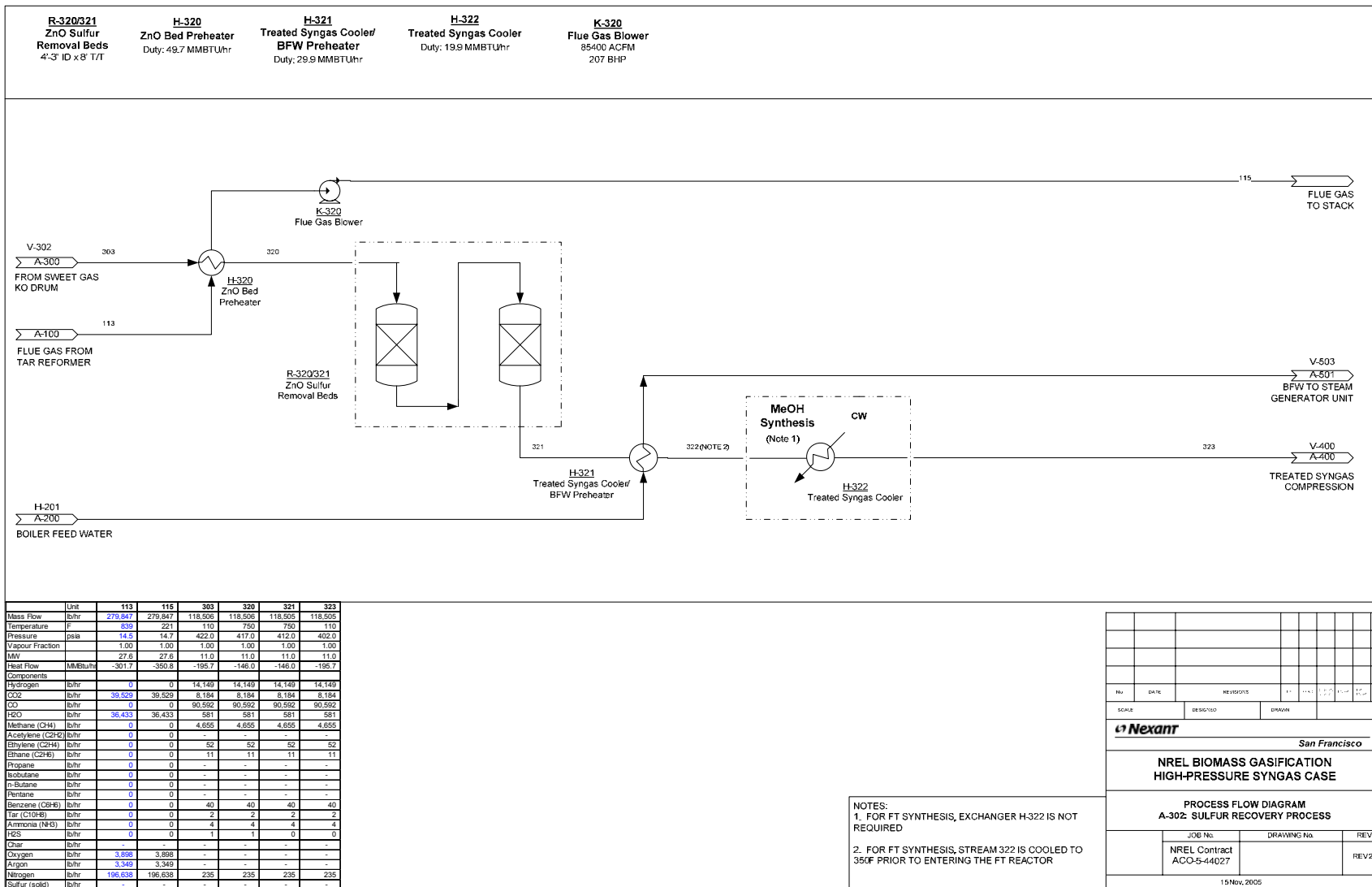


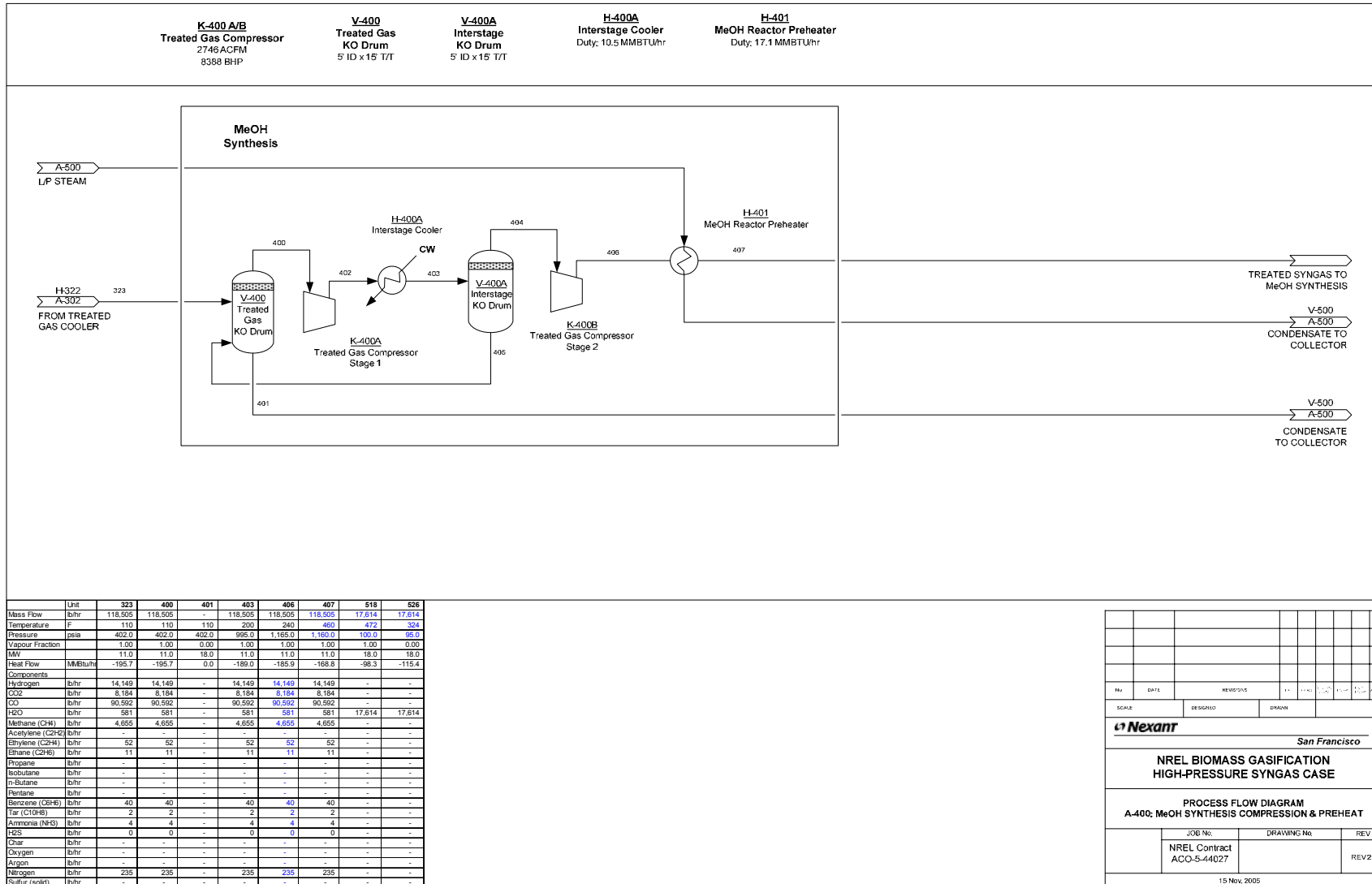


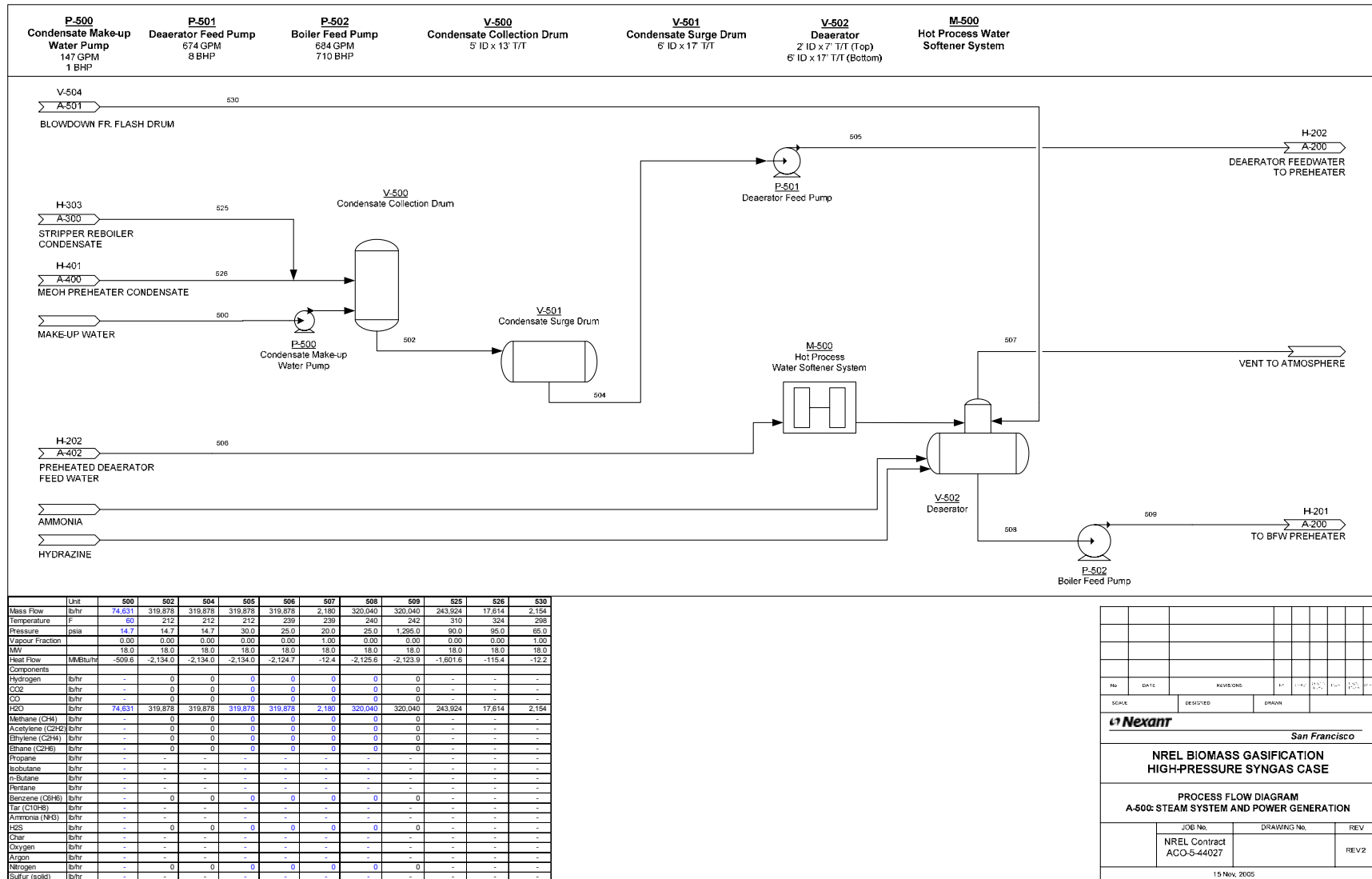
| | Unit | 205 | 300 | 301 | 302 | 303 | 305 | 306 | 307 | 308 | 309 | 310 | 311 | 312 | 313 | 314 | 315 | 316 | 317 | 520 | 521 | 524 | 525 | |
|------------------|----------|----------|---------|---------|---------|---------|---------|-----------|-----------|-------|-----------|-----------|-----------|---------|---------|--------|-----------|-----------|-----------|---------|---------|----------|----------|--|
| Mass Flow | lb/hr | 413,207 | 272,078 | 141,125 | 118,906 | 118,906 | 167,485 | 2,384,401 | 2,537,894 | 1,689 | 2,536,269 | 2,587,826 | 2,587,826 | 213,042 | 240,048 | 78,954 | 2,374,785 | 2,374,785 | 113,499 | 130,438 | 243,938 | 243,938 | | |
| Temperature | F | 110 | 110 | 100 | 100 | 100 | 100 | 110 | 192 | 192 | 200 | 245 | 296 | 303 | 330 | 358 | 376 | 376 | 376 | 338 | 472 | 470 | 310 | |
| Pressure | psia | 429.5 | 429.5 | 429.5 | 422.0 | 422.0 | 19.6 | 432.0 | 445.0 | 30.0 | 30.0 | 25.0 | 25.0 | 21.4 | 16.4 | 30.0 | 432.0 | 432.0 | 100.0 | 100.0 | 100.0 | 100.0 | 90.0 | |
| Vapour Fraction | | 0.65 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | |
| MW | | 18.7 | 19.0 | 18.1 | 11.0 | 11.0 | 40.4 | 31.3 | 31.9 | 28.9 | 31.9 | 31.9 | 29.7 | 18.3 | 28.7 | 18.0 | 31.4 | 31.4 | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 | |
| Heat Flow | MMBtu/hr | -1,739.6 | | 953.9 | | | | | | | | | | | | | | | | -640.6 | -727.6 | -1,368.1 | -1,607.6 | |
| Components | | | | | | | | | | | | | | | | | | | | | | | | |
| Hydrogen | lb/hr | 14,179 | 14,178 | 0 | 14,149 | 14,149 | 1 | | 30 | 29 | 1 | 1 | | | 1 | 0 | | | | | | | | |
| CO2 | lb/hr | 181,888 | 160,811 | 378 | 8,188 | 8,188 | 191,360 | 1,796 | 154,523 | 1,387 | 153,166 | 153,156 | 6,432 | 4,637 | 191,419 | 99 | 1,796 | 1,796 | | | | | | |
| CO | lb/hr | 90,756 | 90,755 | 3 | 90,592 | 90,592 | 9 | | 191 | 191 | 51 | 51 | | | 5 | 0 | | | | | | | | |
| H2O | lb/hr | 141,289 | 970 | 140,319 | 581 | 581 | 9,868 | 1,189,367 | 1,189,733 | 114 | 1,189,619 | 1,189,619 | 1,387,605 | 207,854 | 88,372 | 78,504 | 1,179,751 | 1,179,751 | 113,499 | 130,438 | 243,938 | 243,938 | | |
| Methane (CH4) | lb/hr | 4,667 | 4,666 | 0 | 4,655 | 4,655 | 0 | | 11 | 11 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Acetylene (C2H2) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Ethylene (C2H4) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Ethane (C2H6) | lb/hr | 11 | 11 | 0 | 11 | 11 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Propane | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Isobutane | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| n-Butane | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Pentane | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Benzene (C6H6) | lb/hr | 44 | 44 | 0 | 40 | 40 | 2 | | 3 | 1 | 2 | 2 | | | 2 | 0 | | | | | | | | |
| Tar (C10H8) | lb/hr | 2 | 2 | 0 | 2 | 2 | 0 | | 2 | 1 | 1 | 1 | | | 2 | 0 | | | | | | | | |
| Ammonia (NH3) | lb/hr | 29 | 4 | 25 | 4 | 4 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| H2S | lb/hr | 253 | 249 | 4 | 1 | 1 | 248 | 3 | 252 | 1 | 251 | 251 | 3 | 1 | 248 | 0 | 3 | 3 | 3 | | | | | |
| Chlor | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Oxygen | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Argon | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Nitrogen | lb/hr | 235 | 235 | 0 | 235 | 235 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| Sulfur (total) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | | | 0 | 0 | | | | | | | | |
| MICA | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 | 1,193,235 | 1,193,235 | 0 | 1,193,235 | 1,193,235 | 1,193,786 | 551 | 0 | 0 | 1,193,235 | 1,193,235 | 1,193,235 | | | | | |

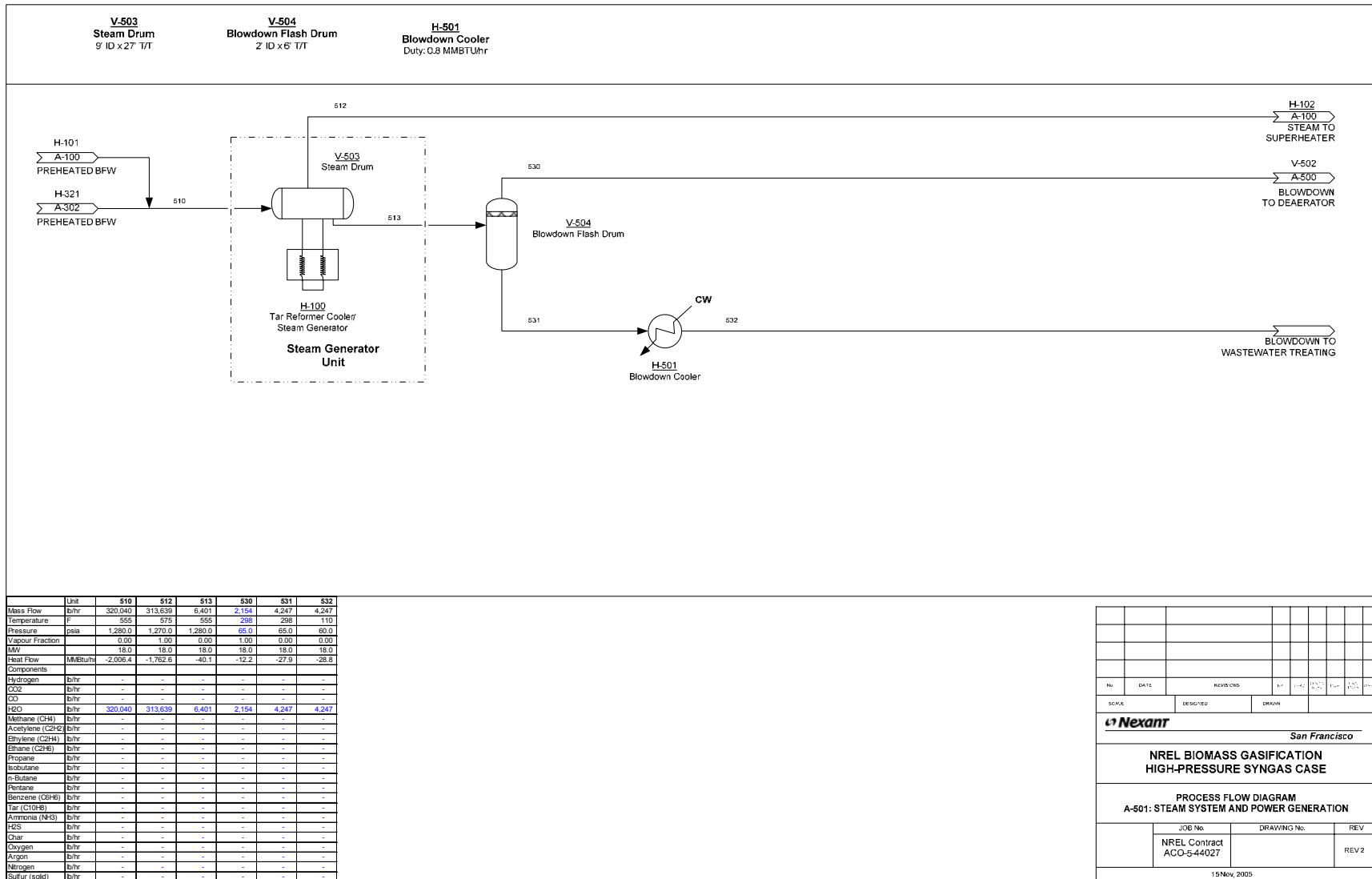
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| No. | DATE | REVISIONS | | | | | | | | | | | | | | | | | | | | | |
| SCALE | | DESIGNED | | DRAWN | | | | | | | | | | | | | | | | | | | |
| San Francisco | | | | | | | | | | | | | | | | | | | | | | | |
| NREL BIOMASS GASIFICATION HIGH-PRESSURE SYNGAS CASE | | | | | | | | | | | | | | | | | | | | | | | |
| PROCESS FLOW DIAGRAM A-300: AMINE SYSTEM | | | | | | | | | | | | | | | | | | | | | | | |
| JOB No. | | | | | | DRAWING No. | | | | | | REV | | | | | | | | | | | |
| NREL Contract | | | | | | ACO-5-44027 | | | | | | | | | | | | REV 2 | | | | | |
| 15 Nov, 2005 | | | | | | | | | | | | | | | | | | | | | | | |

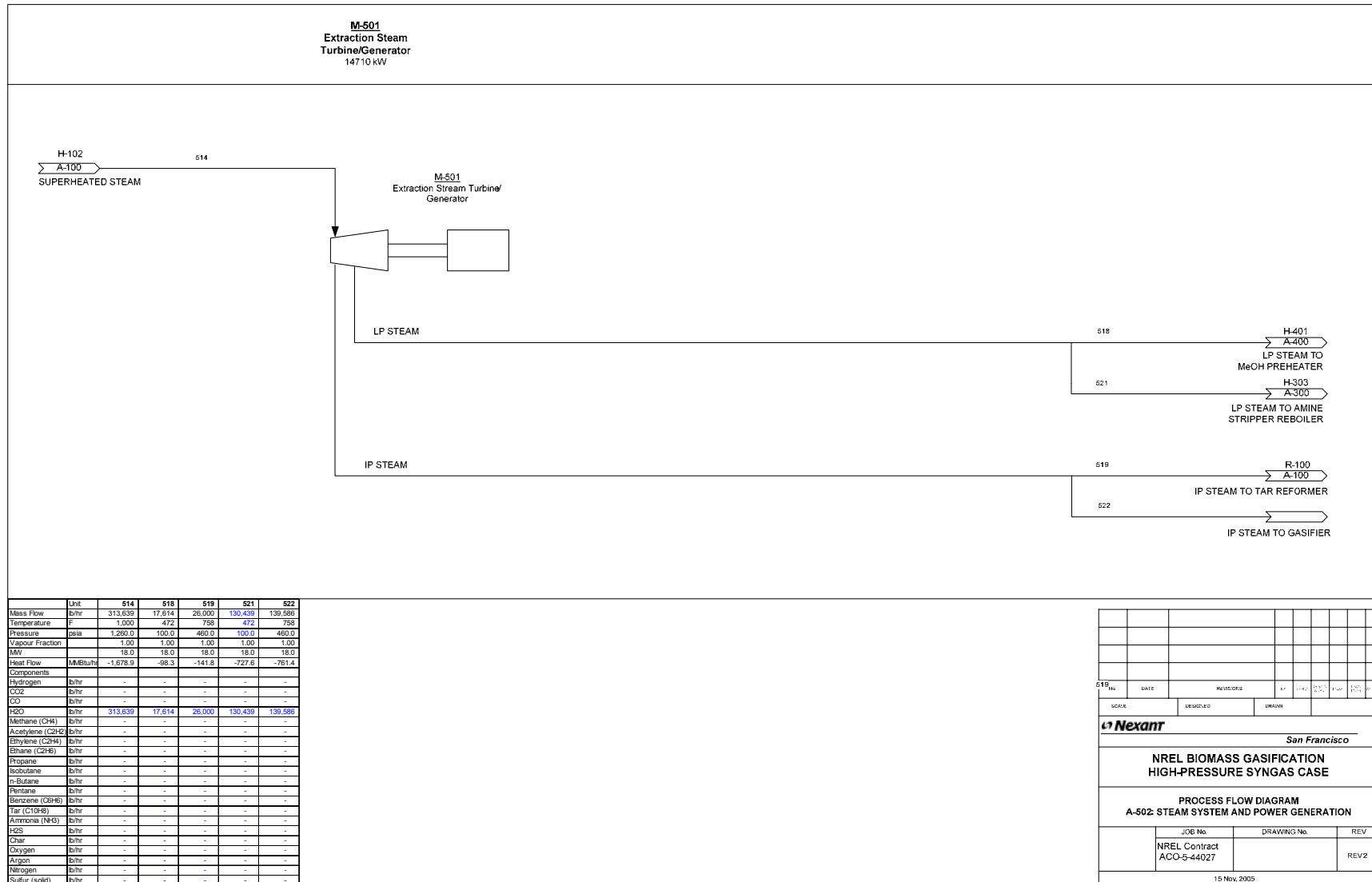


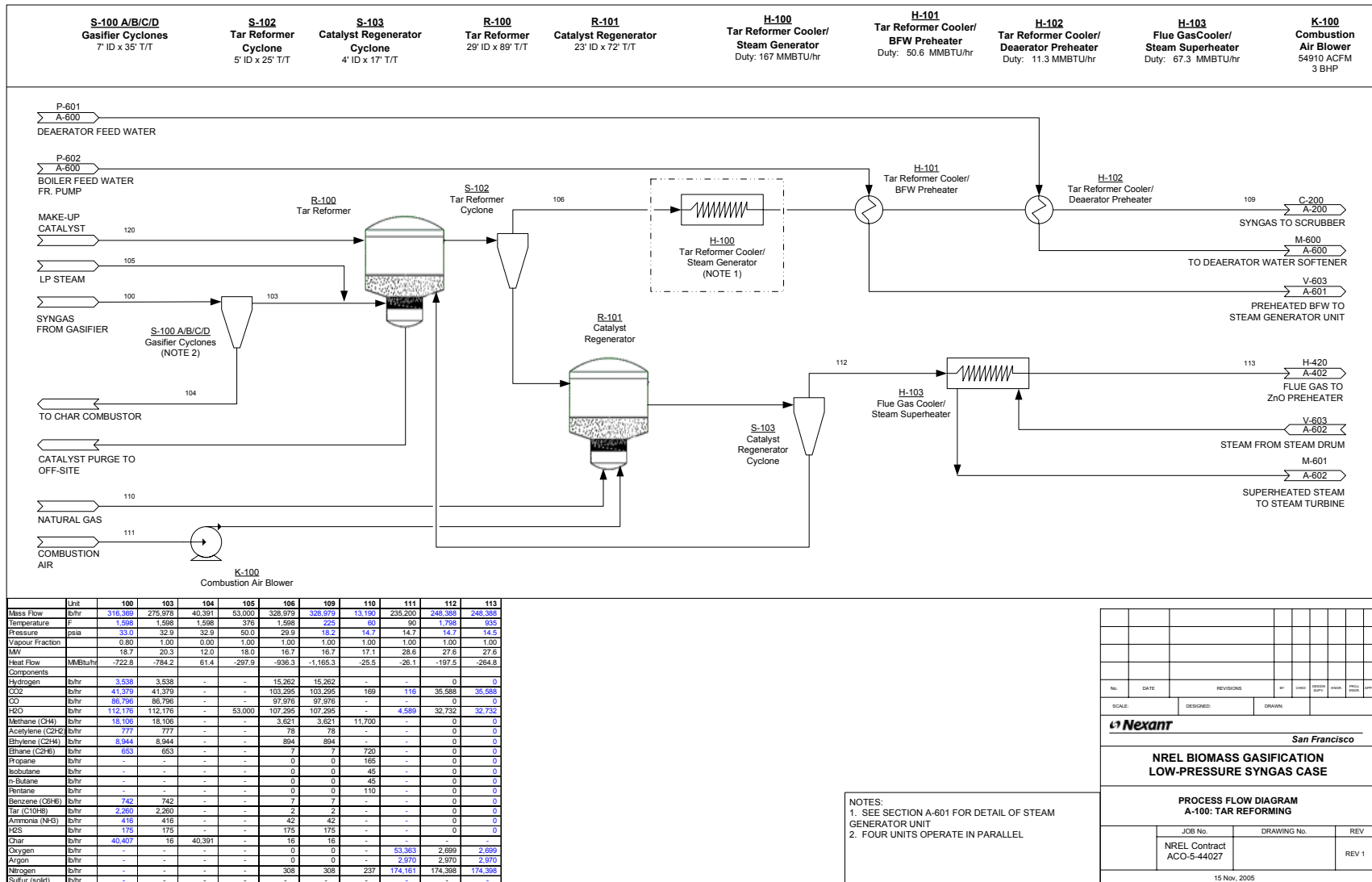


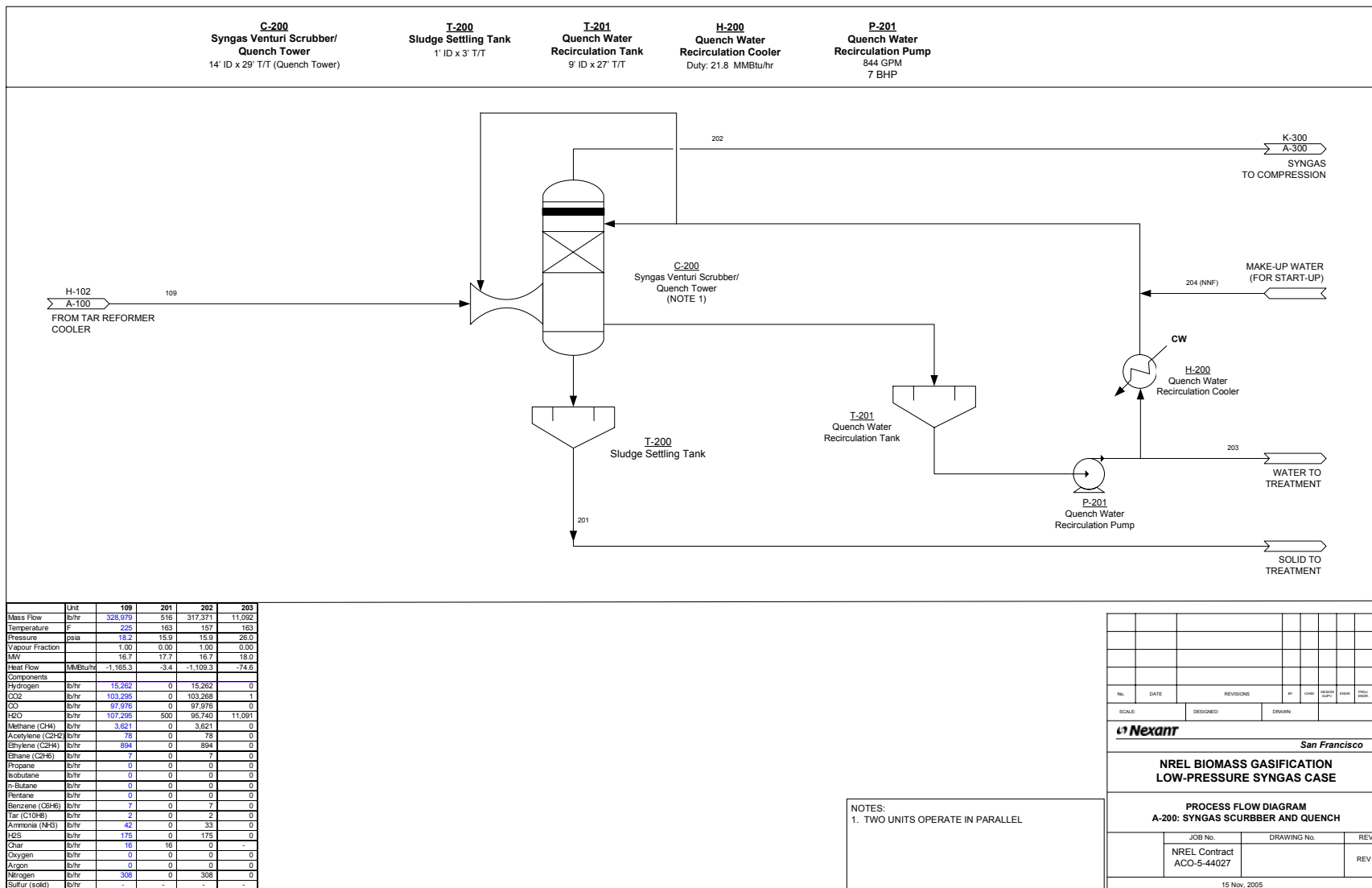


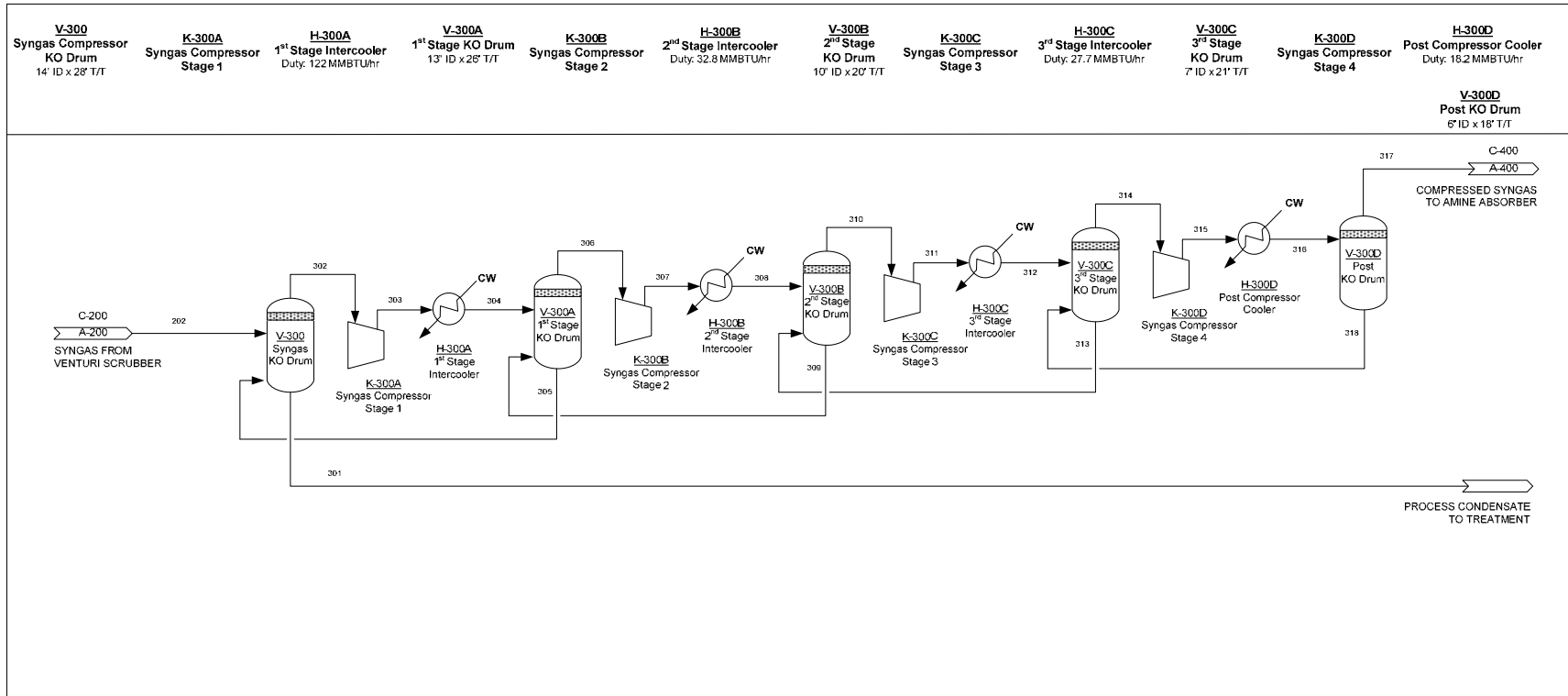






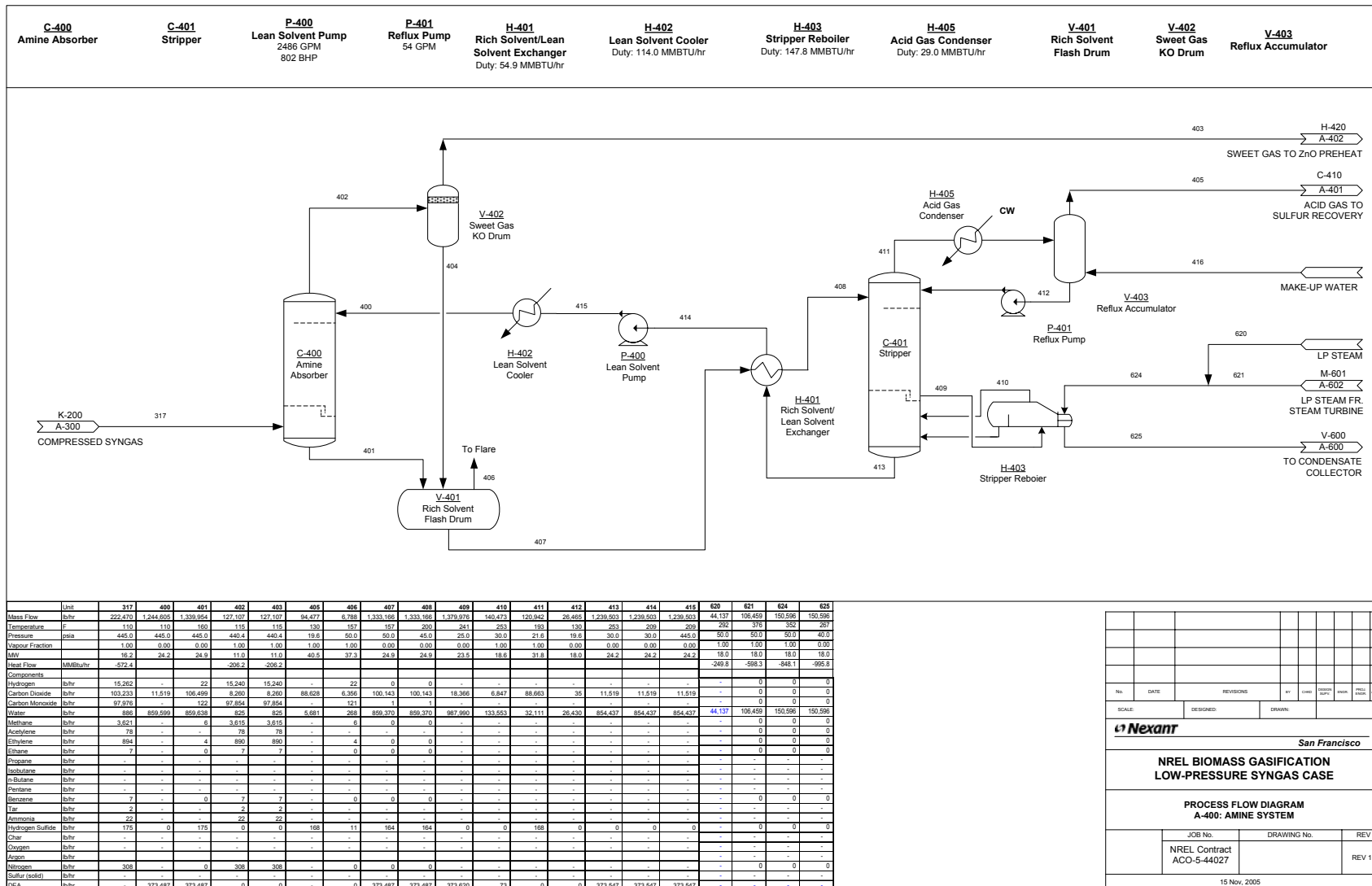


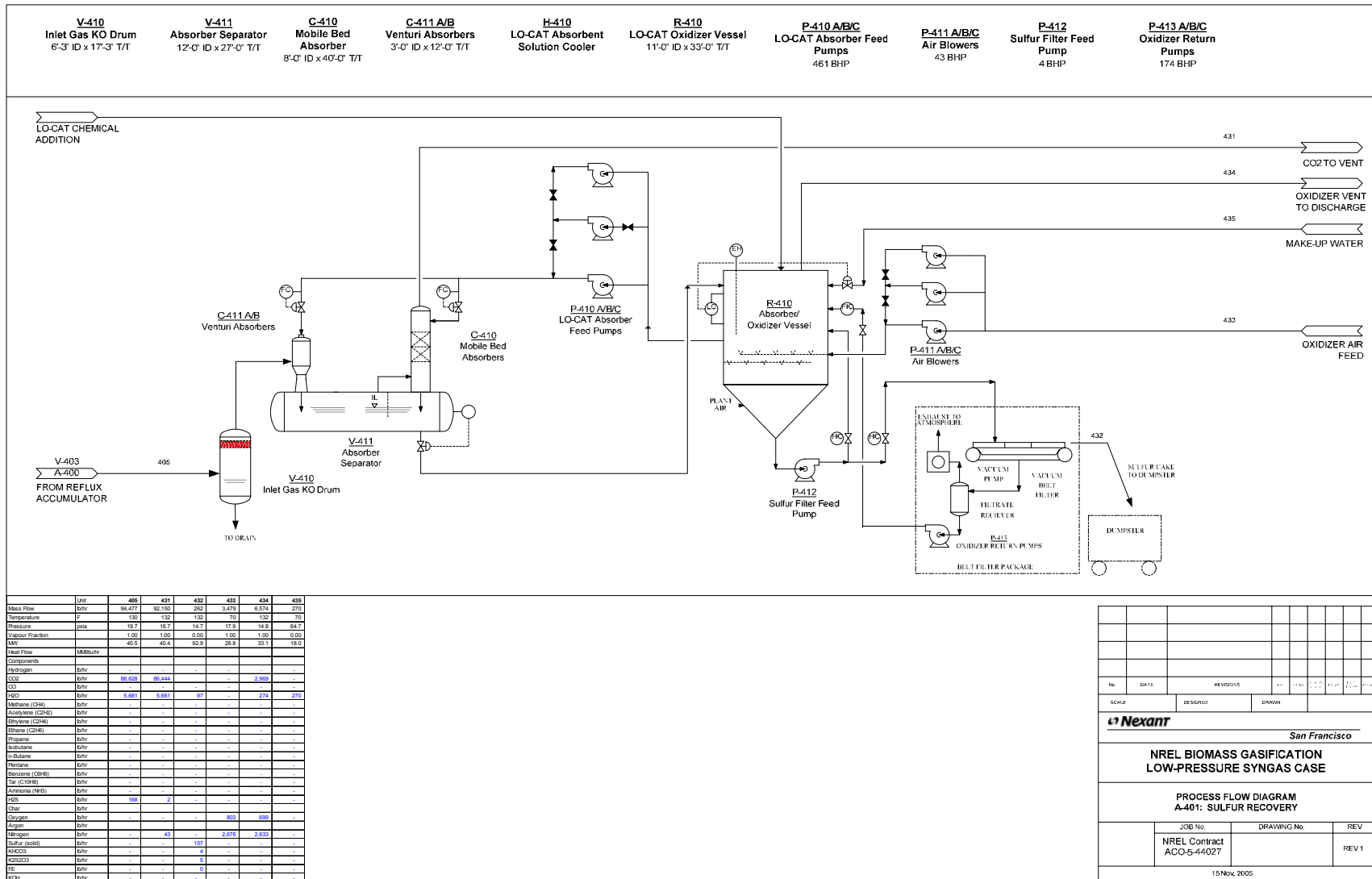


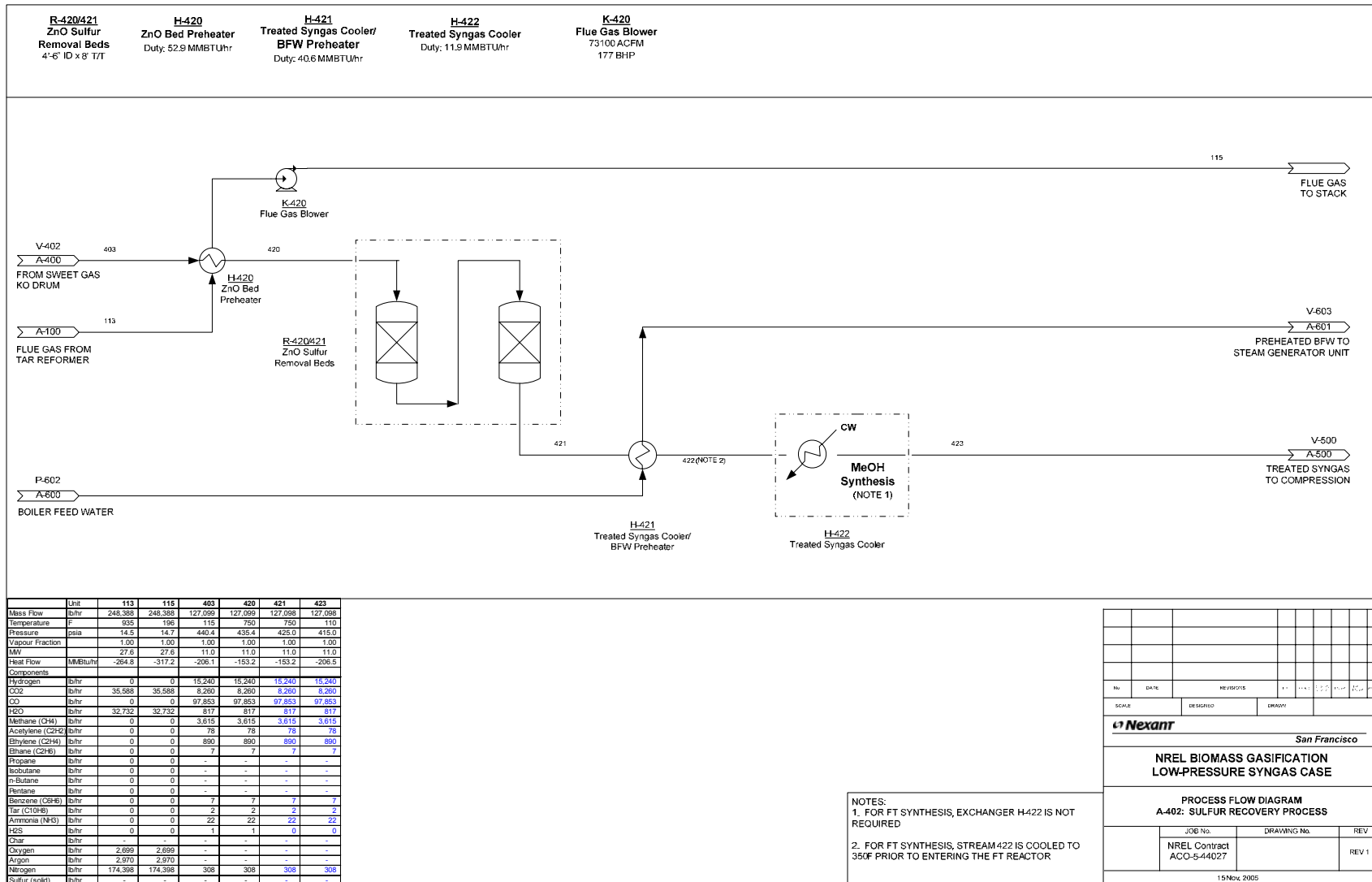


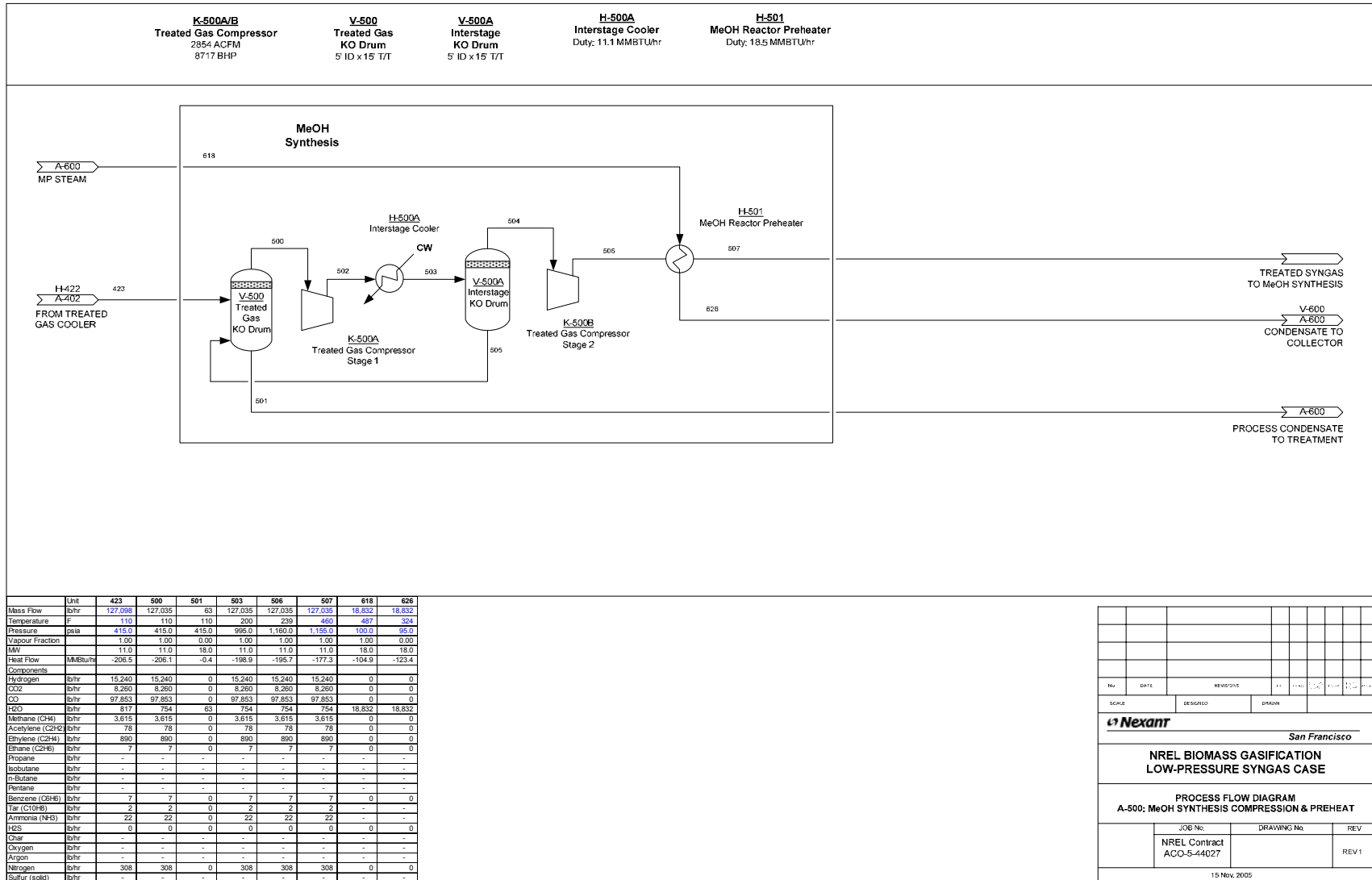
| Unit | 301 | 302 | 304 | 306 | 308 | 310 | 312 | 314 | 316 | 317 |
|------------------|--------|----------|----------|---------|---------|---------|---------|---------|---------|---------|
| Mass Flow | 94,902 | 317,371 | 317,371 | 232,617 | 232,617 | 225,773 | 225,773 | 223,220 | 223,220 | 222,469 |
| Temperature | 110 | 157 | 110 | 110 | 110 | 110 | 110 | 110 | 110 | 110 |
| Pressure | 15.9 | 15.9 | 30.0 | 30.0 | 79.0 | 79.0 | 215.0 | 215.0 | 445.0 | 445.0 |
| Vapour Fraction | 0.00 | 1.00 | 0.75 | 1.00 | 0.97 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 |
| MW | 18.0 | 16.7 | 16.7 | 16.3 | 16.3 | 16.2 | 16.2 | 16.2 | 16.2 | 16.2 |
| Heat Flow | -643.0 | -1,109.3 | -1,204.1 | -629.8 | -637.0 | -590.7 | -593.6 | -576.3 | -577.5 | -572.4 |
| Components | | | | | | | | | | |
| Hydrogen | 0 | 15,262 | 15,262 | 15,262 | 15,262 | 15,262 | 15,262 | 15,262 | 15,262 | 15,262 |
| CO2 | 36 | 103,268 | 103,268 | 103,245 | 103,245 | 103,240 | 103,240 | 103,235 | 103,235 | 103,232 |
| CO | 0 | 97,976 | 97,976 | 97,976 | 97,976 | 97,976 | 97,976 | 97,976 | 97,976 | 97,976 |
| H2O | 94,884 | 95,740 | 95,740 | 11,017 | 11,017 | 4,160 | 4,160 | 1,633 | 1,633 | 869 |
| Methane (CH4) | 0 | 3,621 | 3,621 | 3,621 | 3,621 | 3,621 | 3,621 | 3,621 | 3,621 | 3,621 |
| Acetylene (C2H2) | 0 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 |
| Ethylene (C2H4) | 0 | 894 | 894 | 894 | 894 | 894 | 894 | 894 | 894 | 894 |
| Ethane (C2H6) | 0 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Propane | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Isobutane | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| n-Butane | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pentane | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Benzene (C6H6) | 0 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Tar (C10H8) | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Ammonia (NH3) | 12 | 33 | 33 | 26 | 26 | 24 | 24 | 23 | 23 | 22 |
| H2S | 0 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 |
| Char | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oxygen | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Argon | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Nitrogen | 0 | 308 | 308 | 308 | 308 | 308 | 308 | 308 | 308 | 308 |
| Sulfur (solid) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

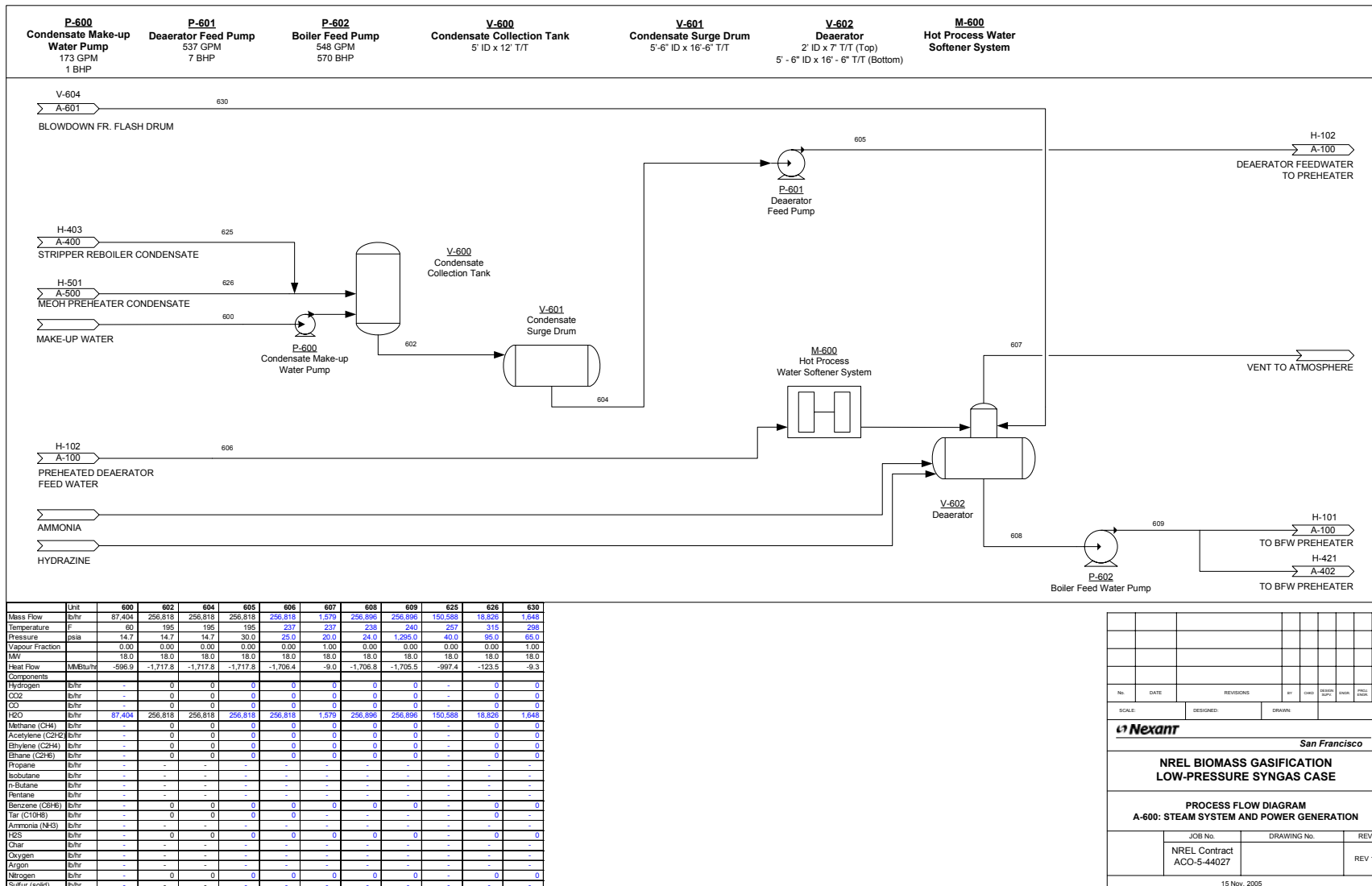
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|---|----------|-----------|-------------|---|---|-----|---|---|-------|---|---|----|
| NO | DATE | REVISIONS | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| SCALE | UNSCALED | DRAWING | | | | | | | | | | |
| San Francisco | | | | | | | | | | | | |
| NREL BIOMASS GASIFICATION LOW-PRESSURE SYNGAS CASE | | | | | | | | | | | | |
| PROCESS FLOW DIAGRAM A-300: SYNGAS COMPRESSION | | | | | | | | | | | | |
| JOB No. | | | DRAWING No. | | | REV | | | | | | |
| NREL Contract ACO-544027 | | | | | | | | | REV 1 | | | |
| 13 Dec, 2005 | | | | | | | | | | | | |

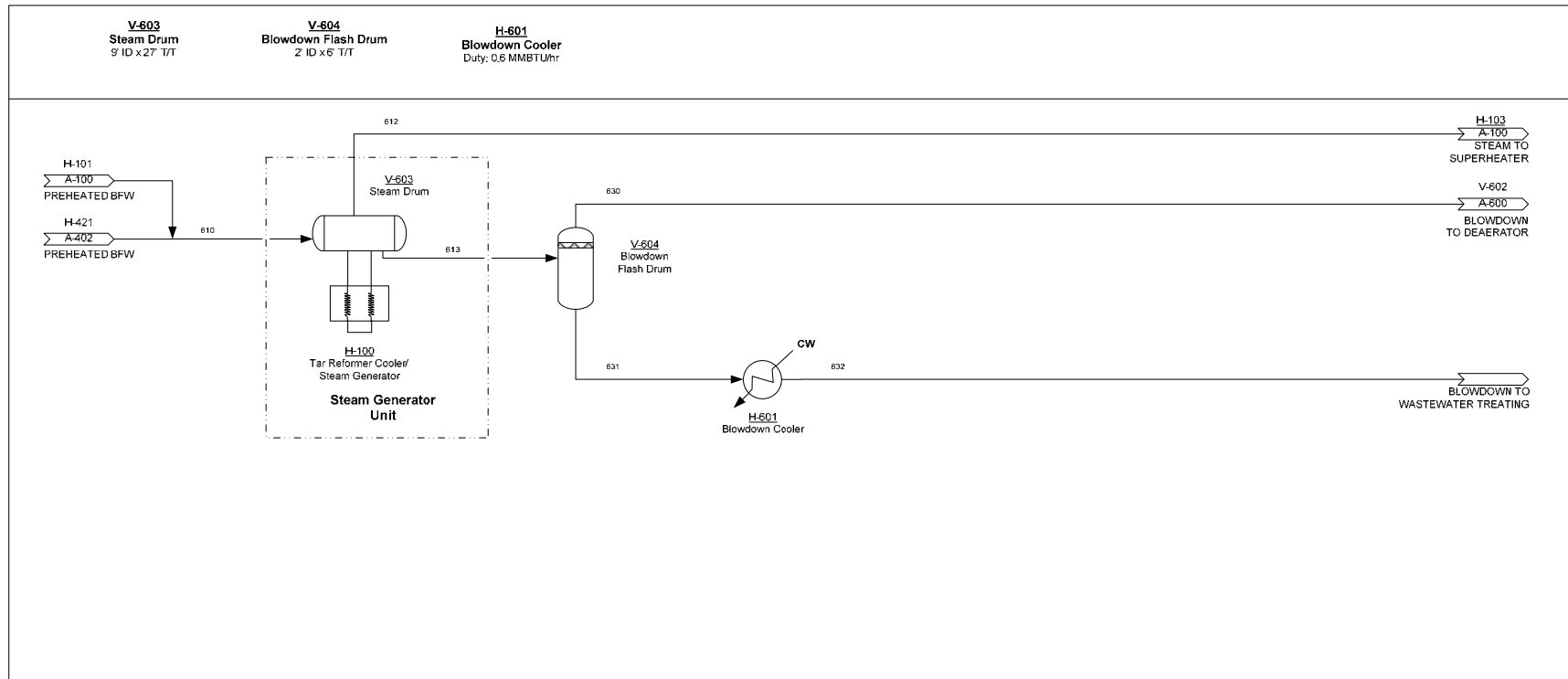






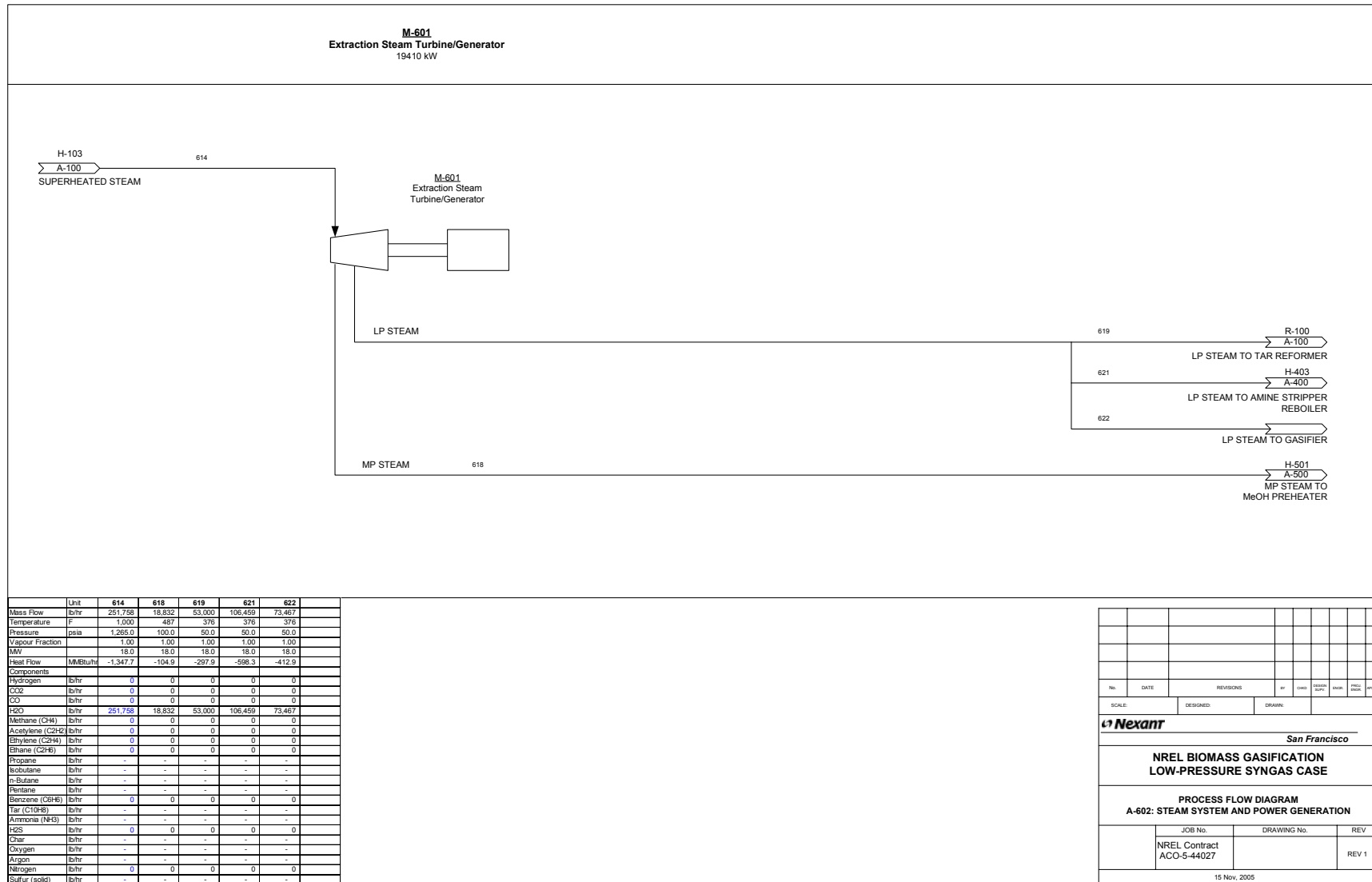






| | Unit | 610 | 612 | 613 | 630 | 631 | 632 |
|--|----------|----------|----------|---------|-------|-------|-------|
| Mass Flow | lb/hr | 256,896 | 251,758 | 5,138 | 1,648 | 3,490 | 3,490 |
| Temperature | F | 547 | 575 | 547 | 298 | 298 | 115 |
| Pressure | psia | 1,285.0 | 1,275.0 | 1,285.0 | 65.0 | 65.0 | 60.0 |
| Vapour Fraction | | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| MW | | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 | 18.0 |
| Heat Flow | MMBtu/hr | -1,614.3 | -1,415.0 | -32.3 | -9.3 | -23.0 | -23.6 |
| Components | | | | | | | |
| Hydrogen | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| CO ₂ | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| CO | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| H ₂ O | lb/hr | 256,896 | 251,758 | 5,138 | 1,648 | 3,490 | 3,490 |
| Methane (CH ₄) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Acetylene (C ₂ H ₂) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Ethylene (C ₂ H ₄) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Ethane (C ₂ H ₆) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Propane | lb/hr | - | - | - | - | - | - |
| Isobutane | lb/hr | - | - | - | - | - | - |
| n-Butane | lb/hr | - | - | - | - | - | - |
| Pentane | lb/hr | - | - | - | - | - | - |
| Benzene (C ₆ H ₆) | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Tar (C10H8) | lb/hr | - | - | - | - | - | - |
| Ammonia (NH ₃) | lb/hr | - | - | - | - | - | - |
| H ₂ S | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Char | lb/hr | - | - | - | - | - | - |
| Oxygen | lb/hr | - | - | - | - | - | - |
| Argon | lb/hr | - | - | - | - | - | - |
| Nitrogen | lb/hr | 0 | 0 | 0 | 0 | 0 | 0 |
| Sulfur (solid) | lb/hr | - | - | - | - | - | - |

| | | | | | | | |
|--|----------|-------------|----|-------|------|----|------|
| No. | DATE | REVISIONS | BY | CHECK | DATE | BY | DATE |
| SCALE | DESIGNED | DRAWN | | | | | |
| Nexant | | | | | | | |
| San Francisco | | | | | | | |
| NREL BIOMASS GASIFICATION LOW-PRESSURE SYNGAS CASE | | | | | | | |
| PROCESS FLOW DIAGRAM A-601: STEAM SYSTEM AND POWER GENERATION | | | | | | | |
| JOB No. | | DRAWING No. | | REV | | | |
| NREL Contract ACO-5-44027 | | | | REV 1 | | | |
| 15 Nov, 2005 | | | | | | | |



The following two appendices show the equipment lists for the high-pressure and low-pressure syngas design cases, along with detailed data sheets for some of the major pieces of equipment. No specific detail was developed for the tar cracking equipment due to the preliminary nature of its design. In addition, no additional information beyond what is presented in the equipment list was produced for vessels and pumps. Detailed equipment sheets are only shown for exchangers, cyclones, and compressors, where additional design data was developed.

DATA SHEETS, HIGH PRESSURE DESIGN

| Heat Exchanger Specification sheet | | | | | |
|---|---|------------------------------------|------------------|---------------------------|---------------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Tar Reformer SG Cooler/HP Steam Generator | | Item No | H-100 | |
| Size 67x 144 | Type | BEM - HORZ Connected in | | 2 Parallel | 1 Series |
| Surf/Unit (Eff) | 10411 ft ² | Shells/Unit | 2 | Surface/Shell (Effective) | 5206 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr Tar Reformer | | Preheated BFW | |
| Total Fluid Entering | lb/hr | 435,000 | | 313,900 | |
| Vapor | | 435,000 | | 0 | |
| Liquid | | 0 | | 313,900 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 313,900 | |
| Liquid Density (In/Out) | lb/ft ³ | 0.000/0.000 | | 46.162/45.419 | |
| Liquid Viscosity | | cP 0.000 | | 0.091 | |
| Liquid Specific Heat | | Btu/lb-F 0.000 | | 1.644 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.320 | |
| Vapor Mol. Weight (In/Out) | | 18.66/18.66 | | 0.0/18.02 | |
| Vapor Viscosity | | cP 0.0285 | | 0.0200 | |
| Vapor Specific Heat | | Btu/lb-F 0.492 | | 0.774 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.067 | | 0.025 | |
| Temperature (In/Out) | | °F 1,576.0/624.0 | | 556.0/575.0 | |
| Operating Pressure | | psi(Abs) 457.000 | | 1,285.000 | |
| Velocity | | ft/sec 43.504 | | 8.337 | |
| Pressure Drop (Allow/Calc) | | psi 5.000/3.245 | | 5.000/1.133 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.001000 | | 0.005000 | |
| Heat Exchanged | | 203,700,000 Btu/hr | mtd (corr) | 307.674 | °F |
| Transfer Rate, Service | | 63.6 | Clean | 128.2 | Btu/hr-ft ² -F |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 500/ | 1,360/ | | |
| Design Temp. °F | | 1675 | 600 | | |
| No. Passes per Shell | | 1 | 6 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-19.0 | 6.0 | | |
| Size & | Out | 1-17.0 | 12.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 1912 | OD 1.000 in | Thk 0.065 | Length 12.00 ft | Pitch 1.25000 / 30.0° |
| Tube Type | | PLAIN | Material | | |
| Shell | | I.D 67.00 OD in | Shell Cover | | INT |
| Channel or Bonnet | | Channel Cover | | | |
| Tubesheet-Stationary | | Tubesheet-Floating | | | |
| Floating Head Cover | | Impingement Protection | | YES | |
| Baffles Cross | | Type VERT- SEG | %Cut 19.1 (Area) | Spacing-cc 29.1 | |
| Baffles-Long | | Seal Type | | | |
| Supports-Tube | | U-Bend | Type | | |
| Bypass Seal Arrangement | | Tube-Tubesheet Joint | | | |
| Expansion Joint | | Type | | | |
| Rho-V2 Inlet Nozzle | | 2,412 | Bundle Entrance | 1,266 | Bundle Exit 2,915 |
| Gasket-Shellside | | Tubeside | | Floating Head | |
| Code Requirement | | ASME Section 8, Division 1 | | TEMA Class R | |
| Weight/Shell | | Filled with Water | | Bundle | |

| Heat Exchanger Specification sheet | | | | | |
|--|----------------------------|---------------------------|-----------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit Tar Reformer SG Cooler/BFW Preheater | | | Item No | H-101 | |
| Size 90x 240 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 23969 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 23969 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr Tar Reformer | | BFW | |
| Total Fluid Entering | lb/hr | 435,000 | | 208,600 | |
| Vapor | | 435,000 | | 0 | |
| Liquid | | 0 | | 208,600 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 55.214/46.316 | |
| Liquid Viscosity | | cP | 0.000 | 0.116 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.368 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.358 | |
| Vapor Mol. Weight (In/Out) | | | 18.66/18.66 | 0.0/0.0 | |
| Vapor Viscosity | | cP | 0.0199 | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | 0.461 | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.044 | 0.000 | |
| Temperature (In/Out) | | °F | 624.0/370.0 | 349.0/551.0 | |
| Operating Pressure | | psi(Abs) | 452.000 | 1,285.000 | |
| Velocity | | ft/sec | 33.096 | - | |
| Pressure Drop (Allow/Calc) | | psi | 10.000/8.600 | 5.000/0.359 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.005000 | |
| Heat Exchanged | | 50,840,000 Btu/hr | mtd (corr) | 41.736 °F | |
| Transfer Rate, Service | | 50.8 | Clean | 86.9 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 500/ | 1,350/ | | |
| Design Temp. °F | | 675 | 600 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections In | | 1-19.0 | 6.0 | | |
| Size & Out | | 1-19.0 | 6.0 | | |
| Rating Intermediate | | 0 | 0 | | |
| Tube No | 6830 | OD 0.750 in | Thk 0.065 | Length 20.00 ft | Pitch 1.00000 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 90.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 13.8 (Area) | Spacing-cc | 24.1 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 5,194 | Bundle Entrance | 1,440 | Bundle Exit | 4,997 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------------------|-------------------------|------------------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Flue Gas Cooler/Steam Superheater | | Item No | H-102 | |
| Size 100x 168 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 8915 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 8915 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Flue Gas fr. Tar Regen | | Superheated Steam | |
| Total Fluid Entering | lb/hr | 280,200 | | 313,900 | |
| Vapor | | 280,200 | | 313,900 | |
| Liquid | | 0 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 0.000/0.000 | | 0.000/0.000 | |
| Liquid Viscosity | cP | 0.000 | | 0.000 | |
| Liquid Specific Heat | Btu/lb-F | 0.000 | | 0.000 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 27.56/27.56 | | 18.02/18.02 | |
| Vapor Viscosity | cP | 0.0399 | | 0.0254 | |
| Vapor Specific Heat | Btu/lb-F | 0.314 | | 0.676 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.039 | | 0.036 | |
| Temperature (In/Out) | °F | 1,798.0/839.0 | | 575.0/1,000.0 | |
| Operating Pressure | psi(Abs) | 14.700 | | 1,270.000 | |
| Velocity | ft/sec | 211.463 | | 4.576 | |
| Pressure Drop (Allow/Calc) | psi | 2.000/1.798 | | 5.000/0.484 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.005000 | |
| Heat Exchanged | 83,650,000 Btu/hr | mtd (corr) | | 482.751 °F | |
| Transfer Rate, Service | 19.4 | Clean | | 22.7 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 30/ | 1,350/ | | |
| Design Temp. °F | | 1900 | 1100 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-61.0 | 15.0 | | |
| Size & | Out | 1-55.0 | 15.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 3900 | OD 0.750 in | Thk 0.065 | Length 14.00 ft | Pitch 1.25000 / 45.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 100.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | Type VERT- SEG | %Cut 40.7 (Area) | | Spacing-cc 69.9 | |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 880 | Bundle Entrance | 3,144 | Bundle Exit | 1,037 |
| Gasket-Shellside | | | Tubeside | | Floating Head |
| Code Requirement | ASME Section 8, Division 1 | | TEMA Class | | R |
| Weight/Shell | | | Filled with Water | | Bundle |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|------------------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Csa | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Quench Water Recirculation | | Item No | H-200 | |
| Size 42x 120 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 2867 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 2867 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Cooling Water | | Quench Water | |
| Total Fluid Entering | lb/hr | 1,117,000 | | 105,700 | |
| Vapor | | 0 | | 0 | |
| Liquid | | 1,117,000 | | 105,700 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ 61.436/61.060 | | 57.041/61.765 | |
| Liquid Viscosity | | cP 0.510 | | 0.301 | |
| Liquid Specific Heat | | Btu/lb-F 1.005 | | 1.017 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 1.122 | | 0.381 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 0.0/0.0 | |
| Vapor Viscosity | | cP 0.0000 | | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F 0.000 | | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.000 | |
| Temperature (In/Out) | | °F 80.0/100.0 | | 311.0/110.0 | |
| Operating Pressure | | psi(Abs) 20.000 | | 456.000 | |
| Velocity | | ft/sec 3.475 | | - | |
| Pressure Drop (Allow/Calc) | | psi 5.000/3.632 | | 5.000/0.424 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.002000 | | 0.001000 | |
| Heat Exchanged | | 22,340,000 Btu/hr | mtd (corr) | 92.789 °F | |
| Transfer Rate, Service | | 84.0 | Clean | 115.0 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 35/ | 500/ | | |
| Design Temp. °F | | 150 | 415 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-12.0 | 4.0 | | |
| Size & | Out | 1-12.0 | 4.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 1558 | OD 0.750 in | Thk 0.065 | Length 10.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 42.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 22.8 (Area) | | Spacing-cc 24.0 | |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 2,540 | Bundle Entrance | 1,308 | Bundle Exit | 3,750 |
| Gasket-Shellside | | | Tubeside | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | TEMA Class R | | |
| Weight/Shell | | | Filled with Water | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------------|-------------------------|-----------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. | |
| Service of Unit | Amine Precooler/BFW Preheat | | Item No | H-201 | |
| Size 56x 168 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 7511 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 7511 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | BFW | | Syngas to Amine Absorber | |
| Total Fluid Entering | lb/hr | 320,300 | | 414,200 | |
| Vapor | | 0 | | 414,200 | |
| Liquid | | 320,300 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 40,260 | |
| Liquid Density (In/Out) | lb/ft ³ | 58.527/55.201 | | 0.000/56.407 | |
| Liquid Viscosity | cP | 0.188 | | 0.150 | |
| Liquid Specific Heat | Btu/lb-F | 1.086 | | 1.037 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.393 | | 0.404 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 18.69/18.69 | |
| Vapor Viscosity | cP | 0.0000 | | 0.0176 | |
| Vapor Specific Heat | Btu/lb-F | 0.000 | | 0.467 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.040 | |
| Temperature (In/Out) | °F | 242.0/349.0 | | 356.0/338.0 | |
| Operating Pressure | psi(Abs) | 1,295.000 | | 442.000 | |
| Velocity | ft/sec | 0.893 | | 18.179 | |
| Pressure Drop (Allow/Calc) | psi | 5.000/0.697 | | 5.000/0.635 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.002000 | | 0.001000 | |
| Heat Exchanged | 36,985,000 Btu/hr | mtd (corr) | | 34.052 °F | |
| Transfer Rate, Service | 144.6 | Clean | | 300.2 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. | psi | 1,425/ | 1,360/ | | |
| Design Temp. | °F | 410 | 400 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. | in | 0.0625 | 0.0625 | | |
| Connections | In | 1-8.0 | 23.0 | | |
| Size & | Out | 1-8.0 | 23.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 3030 | OD 0.750 in | Thk 0.065 | Length 14.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 56.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 10.0 (Area) | Spacing-cc | | 11.1 |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 1,110 | Bundle Entrance | 167 | Bundle Exit | 1,585 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |

| Heat Exchanger Specification sheet | | | | | |
|---|--------------------------------------|------------------------------------|---------------------------------|---------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Amine Precooler/Deaerator FW Preheat | | Item No | H-202 | |
| Size 40x 72 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 585 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 585 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas to Amine Absorber | | Deaerator Feed Water | |
| Total Fluid Entering | lb/hr | 414,200 | | 320,000 | |
| Vapor | | 373,940 | | 0 | |
| Liquid | | 40,260 | | 320,000 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 9,444 | | 0 | |
| Liquid Density (In/Out) | | 55.290/55.492 | | 59.180/58.595 | |
| Liquid Viscosity | | cP 0.092 | | 0.262 | |
| Liquid Specific Heat | | Btu/lb-F 1.111 | | 1.020 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.395 | | 0.385 | |
| Vapor Mol. Weight (In/Out) | | 18.96/18.9436 | | 0.0/0.0 | |
| Vapor Viscosity | | cP 0.0179 | | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F 0.445 | | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.041 | | 0.000 | |
| Temperature (In/Out) | | °F 338.0/332.0 | | 212.0/239.4 | |
| Operating Pressure | | psi(Abs) 437.000 | | 30.000 | |
| Velocity | | ft/sec 25.051 | | - | |
| Pressure Drop (Allow/Calc) | | psi 5.000/1.075 | | 5.000/0.287 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.001000 | | 0.002000 | |
| Heat Exchanged | 9,238,000 Btu/hr | mtd (corr) 108.950 °F | | | |
| Transfer Rate, Service | 145.0 | Clean | 322.3 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 480/ | 45/ | | |
| Design Temp. °F | | 400 | 300 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-23.0 | 8.0 | | |
| | Out | 1-19.0 | 8.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 550 | OD 0.750 in | Thk 0.065 | Length 6.00 ft | Pitch 1.25000 / 45.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 40.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 49.0 (Area) | Spacing-cc 38.9 | | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 1,486 | Bundle Entrance | 2,490 | Bundle Exit | 2,529 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|--------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Amine Precooler | | Item No | H-203 | |
| Size 96x 96 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 11541 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 11541 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas to Amine Absorber | | Cooling Water | |
| Total Fluid Entering | lb/hr | 414,200 | | 6,965,000 | |
| Vapor | | 364,537 | | 0 | |
| Liquid | | 49,663 | | 6,965,000 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 97,296 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 55.608/62.120 | | 62.000/61.573 | |
| Liquid Viscosity | cP | 0.211 | | 0.627 | |
| Liquid Specific Heat | Btu/lb-F | 1.063 | | 1.001 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.384 | | 0.365 | |
| Vapor Mol. Weight (In/Out) | | 18.8591/18.96 | | 0.0/0.0 | |
| Vapor Viscosity | cP | 0.0168 | | 0.0000 | |
| Vapor Specific Heat | Btu/lb-F | 0.424 | | 0.000 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.041 | | 0.000 | |
| Temperature (In/Out) | °F | 332.0/110.0 | | 80.0/100.0 | |
| Operating Pressure | psi(Abs) | 432.000 | | 65.000 | |
| Velocity | ft/sec | 13.546 | | - | |
| Pressure Drop (Allow/Calc) | psi | 5.000/1.874 | | 5.000/0.592 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.002000 | |
| Heat Exchanged | 139,300,000 Btu/hr | mtd (corr) | | 98.751 °F | |
| Transfer Rate, Service | 122.2 | Clean | | 210.0 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. | psi | 475/ | 80/ | | |
| Design Temp. | °F | 350 | 150 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. | in | 0.0625 | 0.0625 | | |
| Connections | In | 1-23.0 | 31.0 | | |
| Size & | Out | 1-17.0 | 31.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 8842 | OD 0.750 in | Thk 0.065 | Length 8.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 96.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | | | Impingement Protection | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 18.6 (Area) | | Spacing-cc | 39.8 |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 1,463 | Bundle Entrance | 1,418 | Bundle Exit | 3,610 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | | |
|---|----------------------------|---------------------------|------------------------|---------------------------|-----------------------|------|
| | | | Job No. | | | |
| Customer | NREL | | Ref No. | HP Syngas Case | | |
| Address | | | Proposal No. | | | |
| Plant Location | | | Date | Rev. 0 | | |
| Service of Unit | ZnO Preheater | | Item No | H-320 | | |
| Size 96x 96 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series | |
| Surf/Unit (Eff) | 19400 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 19400 ft ² | |
| PERFORMANCE OF ONE UNIT | | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | | |
| Fluid Name | | Flue Gas fr. Tar Regen | | Sweet Syngas | | |
| Total Fluid Entering | | lb/hr | 280,200 | 118,500 | | |
| Vapor | | | 280,200 | 118,500 | | |
| Liquid | | | 0 | 0 | | |
| Steam | | | | | | |
| Noncondensable | | | | | | |
| Fluid Vaporized or Condensed | | | 0 | 0 | | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 0.000/0.000 | | |
| Liquid Viscosity | | cP | 0.000 | 0.000 | | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 0.000 | | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.000 | | |
| Vapor Mol. Weight (In/Out) | | | 27.56/27.56 | 10.99/10.99 | | |
| Vapor Viscosity | | cP | 0.0157 | 0.0182 | | |
| Vapor Specific Heat | | Btu/lb-F | 0.312 | 0.659 | | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.012 | 0.076 | | |
| Temperature (In/Out) | | °F | 839.0/214.0 | 100.0/750.0 | | |
| Operating Pressure | | psi(Abs) | 14.500 | 422.000 | | |
| Velocity | | ft/sec | 64.628 | 2.701 | | |
| Pressure Drop (Allow/Calc) | | psi | 2.000/1.675 | 5.000/0.488 | | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.002000 | 0.002000 | | |
| Heat Exchanged | | 49,960,000 Btu/hr | mtd (corr) | 96.31 °F | | |
| Transfer Rate, Service | | 26.55 | Clean | Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | | |
| | | Shellside | Tubeside | Sketch | | |
| Design/Test Pres. psi | | 30/ | 465/ | | | |
| Design Temp. °F | | 910 | 800 | | | |
| No. Passes per Shell | | 1 | 1 | | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | | |
| Connections | | In | 1-53.0 | | | 12.0 |
| Size & | | Out | 1-47.0 | | | 15.0 |
| Rating | | Intermediate | 0 | | | 0 |
| Tube No | 14190 | OD 0.750 in | Thk 0.065 | Length 8.00 ft | Pitch 1.25000 / 45.0° | |
| Tube Type | PLAIN | | Material | | | |
| Shell | I.D 163.00 OD in | | Shell Cover | | INT | |
| Channel or Bonnet | Channel Cover | | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | | |
| Floating Head Cover | | | Impingement Protection | YES | | |
| Baffles Cross | Type VERT- SEG | %Cut 36.0 (Area) | | Spacing-cc | 65.0 | |
| Baffles-Long | Seal Type | | | | | |
| Supports-Tube | U-Bend | | Type | | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | | |
| Expansion Joint | Type | | | | | |
| Rho-V2 Inlet Nozzle | 900 | Bundle Entrance | 673 | Bundle Exit | 651 | |
| Gasket-Shellside | Tubeside | | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | | Bundle | | |
| Remarks: | | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------------|-------------------------|--------------|--------------------------------|----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | ZnO SG Cooler/BFW Preheater | | Item No | H-321 | |
| Size 60x 192 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 5440 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 5440 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr ZnO Beds | | BFW | |
| Total Fluid Entering | lb/hr | 118,500 | | 111,600 | |
| Vapor | | 118,500 | | 0 | |
| Liquid | | 0 | | 111,600 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 0.000/0.000 | | 54.688/45.460 | |
| Liquid Viscosity | cP | 0.000 | | 0.115 | |
| Liquid Specific Heat | Btu/lb-F | 0.000 | | 1.429 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.352 | |
| Vapor Mol. Weight (In/Out) | | 10.99/10.99 | | 0.0/0.0 | |
| Vapor Viscosity | cP | 0.0203 | | 0.0000 | |
| Vapor Specific Heat | Btu/lb-F | 0.663 | | 0.000 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.086 | | 0.000 | |
| Temperature (In/Out) | °F | 750.0/370.0 | | 349.0/565.0 | |
| Operating Pressure | psi(Abs) | 412.000 | | 1,285.000 | |
| Velocity | ft/sec | 30.448 | | - | |
| Pressure Drop (Allow/Calc) | psi | 5.000/3.935 | | 5.000/0.407 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.002000 | |
| Heat Exchanged | 29,850,000 Btu/hr | mtd (corr) | | 75.373 °F | |
| Transfer Rate, Service | 72.8 | Clean | | 99.1 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 455/ | 1,350/ | | |
| Design Temp. °F | | 800 | 615 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-15.0 | 4.0 | | |
| Size & | Out | 1-13.0 | 6.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 1902 | OD 0.750 in | Thk 0.065 | | |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 60.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 14.0 (Area) | | Spacing-cc 14.5 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 2,063 | Bundle Entrance | 272 | Bundle Exit | 2,203 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|------------------------|------------------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Post ZnO Syngas Cooler | | Item No | H-322 | |
| Size 36x 96 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 1620 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 1620 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr. ZnO Beds | | Cooling Water | |
| Total Fluid Entering | lb/hr | 118,500 | | 995,500 | |
| Vapor | | 118,500 | | 0 | |
| Liquid | | 0 | | 995,500 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ 0.000/0.000 | | 62.000/62.000 | |
| Liquid Viscosity | | cP 0.000 | | 0.762 | |
| Liquid Specific Heat | | Btu/lb-F 0.000 | | 1.000 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.363 | |
| Vapor Mol. Weight (In/Out) | | 10.99/10.99 | | 0.0/0.0 | |
| Vapor Viscosity | | cP 0.0148 | | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F 0.647 | | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.065 | | 0.000 | |
| Temperature (In/Out) | | °F 370.0/110.0 | | 80.0/100.0 | |
| Operating Pressure | | psi(Abs) 407.000 | | 65.000 | |
| Velocity | | ft/sec 47.403 | | - | |
| Pressure Drop (Allow/Calc) | | psi 5.000/3.747 | | 5.000/0.585 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.001000 | | 0.002000 | |
| Heat Exchanged | 19,910,000 Btu/hr | mtd (corr) 109.229 °F | | | |
| Transfer Rate, Service | 112.6 | Clean | | 183.2 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 450/ | 80/ | | |
| Design Temp. °F | | 420 | 150 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-13.0 | 12.0 | | |
| Size & | Out | 1-12.0 | 12.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 1102 | OD 0.750 in | Thk 0.065 | Length 8.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 36.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | Type VERT- SEG | %Cut 24.3 (Area) | | Spacing-cc 24.0 | |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 2,539 | Bundle Entrance | 1,981 | Bundle Exit | 3,675 |
| Gasket-Shellside | | Tubeside | | Floating Head | |
| Code Requirement | | ASME Section 8, Division 1 | | TEMA Class R | |
| Weight/Shell | | Filled with Water | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------------------|------------------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | HP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | MeOH Compressor Interstage Cooler | | Item No | H-400A | |
| Size 23x 72 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 476 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 476 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Cooling water | | Syngas | |
| Total Fluid Entering | lb/hr | 537,000 | | 118,500 | |
| Vapor | | 0 | | 118,500 | |
| Liquid | | 537,000 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ 62.000/62.000 | | 0.000/0.000 | |
| Liquid Viscosity | | cP 0.762 | | 0.000 | |
| Liquid Specific Heat | | Btu/lb-F 1.000 | | 0.000 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.363 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 10.99/10.99 | |
| Vapor Viscosity | | cP 0.0000 | | 0.0155 | |
| Vapor Specific Heat | | Btu/lb-F 0.000 | | 0.655 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.068 | |
| Temperature (In/Out) | | °F 80.0/100.0 | | 338.0/200.0 | |
| Operating Pressure | | psi(Abs) 65.000 | | 1,000.000 | |
| Velocity | | ft/sec 4.236 | | 25.340 | |
| Pressure Drop (Allow/Calc) | | psi 5.000/2.578 | | 5.000/0.675 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.002000 | | 0.001000 | |
| Heat Exchanged | 10,470,000 Btu/hr | mtd (corr) 172.318 °F | | | |
| Transfer Rate, Service | 127.7 | Clean | | 216.4 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 80/ | 1,050/ | | |
| Design Temp. °F | | 150 | 390 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-10.0 | 12.0 | | |
| Size & | Out | 1-10.0 | 10.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 442 | OD 0.750 in | Thk 0.065 | Length 6.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 23.25 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | Type VERT- SEG | %Cut 23.5 (Area) | | Spacing-cc | 16.3 |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 1,206 | Bundle Entrance | 1,316 | Bundle Exit | 1,940 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | | |
|---|----------------------------|---------------------------|------------------------|--------------------------------------|-----------------------|--------|
| | | | Job No. | | | |
| Customer | NREL | | Ref No. | HP Syngas Case | | |
| Address | | | Proposal No. | | | |
| Plant Location | | | Date | Rev. 0 | | |
| Service of Unit | MeOH Syngas Preheat | | Item No | H-401 | | |
| Size 72x 216 | Type | BEM - HORZ | Connected in | 1 Parallel | 1 Series | |
| Surf/Unit (Eff) | 16212 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 16212 ft ² | |
| PERFORMANCE OF ONE UNIT | | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | | |
| Fluid Name | | Steam | | Syngas to MeOH Rxn | | |
| Total Fluid Entering | | lb/hr | | 17,610 | | |
| Vapor | | 17,610 | | 118,500 | | |
| Liquid | | 0 | | 0 | | |
| Steam | | | | | | |
| Noncondensable | | | | | | |
| Fluid Vaporized or Condensed | | 17,610 | | 0 | | |
| Liquid Density (In/Out) | | lb/ft ³ | | 0.000/54.780 | | |
| Liquid Viscosity | | cP | | 0.128 | | |
| Liquid Specific Heat | | Btu/lb-F | | 1.157 | | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | | 0.393 | | |
| Vapor Mol. Weight (In/Out) | | 18.02/18.02 | | 10.99/10.99 | | |
| Vapor Viscosity | | cP | | 0.0161 | | |
| Vapor Specific Heat | | Btu/lb-F | | 0.483 | | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | | 0.020 | | |
| Temperature (In/Out) | | °F | | 471.7/324.0 | | |
| Operating Pressure | | psi(Abs) | | 100.000 | | |
| Velocity | | ft/sec | | 4.482 | | |
| Pressure Drop (Allow/Calc) | | psi | | 5.000/0.586 | | |
| Fouling resistance | | hr-ft ² -F/Btu | | 0.005000 | | |
| Heat Exchanged | | 17,140,000 Btu/hr | | mtd (corr) 45.146 °F | | |
| Transfer Rate, Service | | 23.4 | | Clean 27.4 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | | |
| | | Shellside | | Tubeside | | Sketch |
| Design/Test Pres. psi | | 130/ | | 1,225/ | | |
| Design Temp. °F | | 545 | | 515 | | |
| No. Passes per Shell | | 1 | | 1 | | |
| Corrosion Allow. in | | 0.0625 | | 0.0625 | | |
| Connections | | In | | 1-8.0 | | |
| Size & Rating | | Out | | 1-2.0 | | |
| | | Intermediate | | 0 | | |
| Tube No | 5044 | OD 0.750 in | Thk 0.065 | Length 18.00 ft | Pitch 0.93750 / 30.0° | |
| Tube Type | PLAIN | | Material | | | |
| Shell | I.D 72.00 OD in | | Shell Cover | | INT | |
| Channel or Bonnet | Channel Cover | | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | | |
| Floating Head Cover | | | Impingement Protection | NO | | |
| Baffles Cross | Type VERT- SEG | %Cut 10.2 (Area) | Spacing-cc | | 14.3 | |
| Baffles-Long | Seal Type | | | | | |
| Supports-Tube | U-Bend | | Type | | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | | |
| Expansion Joint | Type | | | | | |
| Rho-V2 Inlet Nozzle | 1,057 | Bundle Entrance | 1,398 | Bundle Exit | 1,158 | |
| Gasket-Shellside | Tubeside | | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | | Bundle | | |
| Remarks: | | | | | | |

| Heat Exchanger Specification sheet | | | | | | |
|---|----------------------------|---------------------------|------------------------|--------------------------------|-----------------------|-----|
| | | | Job No. | | | |
| Customer | NREL | | Ref No. | HP Syngas Case | | |
| Address | | | Proposal No. | | | |
| Plant Location | | | Date | Rev. 0 | | |
| Service of Unit | Blowdown Cooler | | Item No | H-501 | | |
| Size 15x 48 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series | |
| Surf/Unit (Eff) | 130 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 130 ft ² | |
| PERFORMANCE OF ONE UNIT | | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | | |
| Fluid Name | | Blowdown | | Cooling water | | |
| Total Fluid Entering | | lb/hr | 3,987 | 41,985 | | |
| Vapor | | | 0 | 0 | | |
| Liquid | | | 3,987 | 41,985 | | |
| Steam | | | | | | |
| Noncondensable | | | | | | |
| Fluid Vaporized or Condensed | | | 0 | 0 | | |
| Liquid Density (In/Out) | | lb/ft ³ | 56.607/62.000 | 62.000/62.000 | | |
| Liquid Viscosity | | cP | 0.311 | 0.762 | | |
| Liquid Specific Heat | | Btu/lb-F | 1.059 | 1.000 | | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.382 | 0.363 | | |
| Vapor Mol. Weight (In/Out) | | | 0.0/0.0 | 0.0/0.0 | | |
| Vapor Viscosity | | cP | 0.0000 | 0.0000 | | |
| Vapor Specific Heat | | Btu/lb-F | 0.000 | 0.000 | | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.000 | | |
| Temperature (In/Out) | | °F | 298.0/110.0 | 80.0/100.0 | | |
| Operating Pressure | | psi(Abs) | 65.000 | 65.000 | | |
| Velocity | | ft/sec | 0.143 | 0.528 | | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/0.154 | 5.000/0.206 | | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.002000 | | |
| Heat Exchanged | | 839,700 Btu/hr | mtd (corr) | 89.027 °F | | |
| Transfer Rate, Service | | 72.7 | Clean | 97.5 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | | |
| | | Shellside | Tubeside | Sketch | | |
| Design/Test Pres. psi | | 80/ | 80/ | | | |
| Design Temp. °F | | 350 | 150 | | | |
| No. Passes per Shell | | 1 | 1 | | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | | |
| Connections | | In | 1-1.0 | | | 3.0 |
| Size & | | Out | 1-1.0 | | | 3.0 |
| Rating | | Intermediate | 0 | | | 0 |
| Tube No | 170 | OD 0.750 in | Thk 0.065 | Length 4.00 ft | Pitch 0.93750 / 30.0° | |
| Tube Type | PLAIN | | Material | | | |
| Shell | I.D 15.25 OD in | | Shell Cover | | INT | |
| Channel or Bonnet | Channel Cover | | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | | |
| Floating Head Cover | | | Impingement Protection | YES | | |
| Baffles Cross | Type VERT- SEG | %Cut 8.6 (Area) | | Spacing-cc | 3.0 | |
| Baffles-Long | Seal Type | | | | | |
| Supports-Tube | U-Bend | | Type | | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | | |
| Expansion Joint | Type | | | | | |
| Rho-V2 Inlet Nozzle | 728 | Bundle Entrance | 9 | Bundle Exit | 423 | |
| Gasket-Shellside | Tubeside | | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | | Bundle | | |
| Remarks: | | | | | | |

| | | | | | |
|--|------------------|---|-------------|-------------------|---------------------------|
| COMPRESSOR NUMBER | | K-100 | | | |
| SERVICE | | Combustion Air | | | |
| GAS HANDLED | | Air | | | |
| NORMAL FLOW | SCFM | 58,597 | | | |
| NORMAL FLOW | LB/HR | 265,200 | | | |
| DESIGN FLOW | SCFM | | | | |
| MOL WT. | | 28.63 | | | |
| C_p/C_v | Value | 1.4 | | | |
| | @ F / PSIA | 90 / 14.7 | | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | PSIA | 14.7 | | | |
| COMPR. FACTOR @ SUCTION | | 0.999 | | | |
| FLOW AT SUCTION | ACFM | 61,910 | | | |
| ORIGIN | PSIA | | | | |
| TEMPERATURE | F | 90 | | | |
| LINE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (1, 2) | | | | |
| CONTINGENCY | PSI | | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | PSIA | 20 | | | |
| DISCH. TEMPERATURE | F (2) | 157 | | | |
| COMPR. FACTOR @ DISCH. | | 0.999 | | | |
| DELIVERY | PSIA | | | | |
| LINE LOSS | PSI (2) | | | | |
| EXCHANGER LOSS | PSI (2) | | | | |
| HEATER LOSS | PSI (2) | | | | |
| CONTROL VALVE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (2) | | | | |
| CONTINGENCY | PSI (2) | | | | |
| TOTAL LOSSES | PSI (2) | | | | |
| COMPRESSION RATIO | | 1.36 | | | |
| EFFICIENCY | (2) | 0.75 | | | |
| BHP | (2) | 1800 | | | |
| COMPRESSOR TYPE | | | | | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | H ₂ O | 3.1 | | | |
| | O ₂ | 20.3 | | | |
| | Ar | 0.9 | | | |
| | N ₂ | 75.7 | | | |
| <p>(1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER</p> <p>(2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN</p> | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: High Pressure Syngas Case (GTI Gasifier) | | | |
| | | | | JOB NO | NREL Contract ACO-5-44027 |
| | | | | DRAWING NO | REV |

| | | | | | | |
|--|-------------|---|-------------|--------------|---------------|---|
| COMPRESSOR NUMBER | | K-320 | | | | |
| SERVICE | | Flue Gas Blower | | | | |
| GAS HANDLED | | Flue Gas | | | | |
| NORMAL FLOW | SCFM | 64,194 | | | | |
| NORMAL FLOW | LB/HR | 279,800 | | | | |
| DESIGN FLOW | SCFM | | | | | |
| MOL. WT. | | 27.58 | | | | |
| C_p/C_v | Value | 1.365 | | | | |
| | @ F / PSIA | 202.5 / 14.3 | | | | |
| SUCTION CONDITIONS | | | | | | |
| SUCTION PRESSURE | PSIA | 14.3 | | | | |
| COMPR. FACTOR @ SUCTION | | 0.9985 | | | | |
| FLOW AT SUCTION | ACFM | 85,400 | | | | |
| ORIGIN | PSIA | | | | | |
| TEMPERATURE | F | 214 | | | | |
| LINE LOSS | PSI | (2) | | | | |
| OTHER LOSSES | PSI | (1, 2) | | | | |
| CONTINGENCY | PSI | | | | | |
| DISCHARGE CONDITIONS | | | | | | |
| DISCH. PRESSURE | PSIA | 14.7 | | | | |
| DISCH. TEMPERATURE | F | (2) 221 | | | | |
| COMPR. FACTOR @ DISCH. | | 0.9985 | | | | |
| DELIVERY | PSIA | | | | | |
| LINE LOSS | PSI | (2) | | | | |
| EXCHANGER LOSS | PSI | (2) | | | | |
| HEATER LOSS | PSI | (2) | | | | |
| CONTROL VALVE LOSS | PSI | (2) | | | | |
| OTHER LOSSES | PSI | (2) | | | | |
| CONTINGENCY | PSI | (2) | | | | |
| TOTAL LOSSES | PSI | (2) | | | | |
| COMPRESSION RATIO | | 1.03 | | | | |
| EFFICIENCY | | (2) 0.75 | | | | |
| BHP | | (2) 207 | | | | |
| COMPRESSOR TYPE | | | | | | |
| DRIVER TYPE | | | | | | |
| GAS COMPOSITION: Vol. % | | | | | | |
| | | CO ₂ | 14.33 | | | |
| | | H ₂ O | 10.93 | | | |
| | | O ₂ | 1.03 | | | |
| | | Ar | 0.73 | | | |
| | | N ₂ | 72.98 | | | |
| <p>(1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER</p> <p>(2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN</p> | | | | | | |
| | | | | | | |
| | | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT | |
| | | NREL BIOMASS GASIFICATION: High Pressure Syngas Case (GTI Gasifier) | | | | JOB NO NREL Contract ACO-5-44027 DRAWING NO REV |

| COMPRESSOR NUMBER | | K-400A | K-400B | | |
|--|------------|---|----------------|------------|---------------------------|
| SERVICE | | MeOH Comp-1 | MeOH Comp-2 | | |
| GAS HANDLED | | Treated Syngas | Treated Syngas | | |
| NORMAL FLOW | SCFM | 68,247 | 68,247 | | |
| NORMAL FLOW | LB/HR | 118,500 | 118,500 | | |
| DESIGN FLOW | | SCFM | | | |
| MOL WT. | | 10.99 | 10.99 | | |
| C _p /C _v | Value | 1.418 | 1.423 | | |
| | @ F / PSIA | 110 / 402 | 200 / 995 | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | | PSIA | 402 | 995 | |
| COMPR. FACTOR @ SUCTION | | | 1.006 | 1.021 | |
| FLOW AT SUCTION | | ACFM | 1,567 | 1,306 | |
| ORIGIN | | PSIA | | | |
| TEMPERATURE | | F | 110 | 200 | |
| LINE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (1, 2) | | | |
| CONTINGENCY | | PSI | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | | PSIA | 1,000 | 1,165 | |
| DISCH. TEMPERATURE | | F (2) | 334.8 | 240.4 | |
| COMPR. FACTOR @ DISCH. | | | 1.022 | 1.026 | |
| DELIVERY | | PSIA | | | |
| LINE LOSS | | PSI (2) | | | |
| EXCHANGER LOSS | | PSI (2) | | | |
| HEATER LOSS | | PSI (2) | | | |
| CONTROL VALVE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (2) | | | |
| CONTINGENCY | | PSI (2) | | | |
| TOTAL LOSSES | | PSI (2) | | | |
| COMPRESSION RATIO | | | 2.49 | 1.17 | |
| EFFICIENCY | | (2) | 0.75 | 0.75 | |
| BHP | | (2) | 7,102 | 1,286 | |
| COMPRESSOR TYPE | | | | | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | | H ₂ | 65.10 | 65.1 | |
| | | CO ₂ | 1.50 | 1.5 | |
| | | CO | 30.08 | 30.08 | |
| | | H ₂ O | 0.27 | 0.27 | |
| | | CH ₄ | 2.70 | 2.7 | |
| | | C ₂ H ₂ | | | |
| | | C ₂ H ₄ | 0.02 | 0.02 | |
| | | C ₂ H ₆ | 0.00003 | 0.00003 | |
| | | Benzene (C ₆ H ₆) | 0.00005 | 0.00005 | |
| | | Tar (C ₁₀ H ₈) | 0.000001 | 0.000001 | |
| | | NH ₃ | 0.00002 | 0.00002 | |
| | | N ₂ | 0.08 | 0.08 | |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER | | | | | |
| (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: High Pressure Syngas Case (GTI Gasifier) | | | |
| | | | | JOB NO | NREL Contract ACO-5-44027 |
| | | | | DRAWING NO | REV |

| COMPRESSOR NUMBER | | M-501A | M-501B | | |
|--|------------|---|---------------------------------------|--------|--------|
| SERVICE | | Steam Turbine - Extraction Stage 1 | Steam Turbine - Extraction Stage 2 | | |
| GAS HANDLED | | Steam | Steam | | |
| NORMAL FLOW | SCFM | 110,138 | 51,979 | | |
| NORMAL FLOW | LB/HR | 313,600 | 148,100 | | |
| DESIGN FLOW | | SCFM | | | |
| MOL WT. | | 18.02 | 18.02 | | |
| C _p /C _v | Value | 1.384 | 1.353 | | |
| | @ F / PSIA | 1000 / 1260 | 758 / 460 | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | | PSIA | 1260 | 460 | |
| COMPR. FACTOR @ SUCTION | | | 0.9334 | 0.9521 | |
| FLOW AT SUCTION | | ACFM | 3,369 | 3,709 | |
| ORIGIN | | PSIA | | | |
| TEMPERATURE | | F | 1000 | 758 | |
| LINE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (1, 2) | | | |
| CONTINGENCY | | PSI | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | | PSIA | 460 | 100 | |
| DISCH. TEMPERATURE | | F (2) | 758 | 472 | |
| COMPR. FACTOR @ DISCH. | | | 0.9521 | 0.974 | |
| DELIVERY | | PSIA | | | |
| LINE LOSS | | PSI (2) | | | |
| EXCHANGER LOSS | | PSI (2) | | | |
| HEATER LOSS | | PSI (2) | | | |
| CONTROL VALVE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (2) | | | |
| CONTINGENCY | | PSI (2) | | | |
| TOTAL LOSSES | | PSI (2) | | | |
| COMPRESSION RATIO | | | - | - | |
| EFFICIENCY | | (2) | 0.75 | 0.75 | |
| kW Generated | | (2) | 9,341 | 5,371 | |
| Turbine TYPE | | | Steam | Steam | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | | H ₂ | | | |
| | | CO ₂ | | | |
| | | CO | | | |
| | | H ₂ O | 100% | 100% | |
| | | CH ₄ | | | |
| | | C ₂ H ₂ | | | |
| | | C ₂ H ₄ | | | |
| | | C ₂ H ₆ | | | |
| | | Benzene (C ₆ H ₆) | | | |
| | | Tar (C ₁₀ H ₈) | | | |
| | | NH ₃ | | | |
| | | N ₂ | | | |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER | | | | | |
| (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: High Pressure Syngas Case (GTI Gasifier) | | | |
| | | | JOB NO NREL Contract ACO-5-44027 | | |
| | | | DRAWING NO | | REV |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|-------------------------|-------------------------------|-------------------------------------|---------------------------|--|----------------------------------|-----------------------|-------------|---------------------|-------------|
| Site Location | | | | | | | | Date | Rev. | |
| SERVICE OF HIGH PRESSURE UNIT S-100 | | | | | | | | | | |
| Inlet Conditions | | Flow | Viscosity | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | lb/ft-sec | lb/ft3 | lb/mole | | acfm | °F | | |
| Gas | | 418,416.00 | 2.54E-05 | 0.47800 | 21.5 | | 14,589.00 | 1,576 | | |
| Particulate | | 9,440.00 | | 62.40 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 460.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 455.57 | | | | | | | | |
| Pressure Drop, Max Allow. (" .WC.) | | 120.00 | | | | | | | | |
| Design/Test Pressure Psig | | 460.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-100 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | Overall Height (ft) | |
| Connections Size & Rating | In | 32 | 42 | Upper Shell | 58 | 60 | 1 | ASME VIII | 25 | |
| | Out | 24 | 34 | Inner Tube | 24 | 26 | 1 | | | |
| | Bottom | | | Cone | | | 1 | ASME VIII | | |
| | | | | Refractory | 50 | | 4 | | | |
| Component Data | | | | | Cyclone Body Materials of Construction | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 1598 | | | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 1598 | | | | Cercast™ | MS | Cercast™ | MS | Cercast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, KY | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| Recommendation: Replace S-100 and S-101 with one (1) cyclone only: | | | | | | | | | | |
| One (1) cyclone (XQ120-30M) with the following features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius Cercast 3300 castable refractory | | | | | |
| 1-1/4" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| Inlet transition to 24"Ø gas inlet flange | | | | | Design pressure (psig) | | 460 | | | |
| 30"Ø verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 5 ftØ x 25 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | 14,589 | | Specific Gravity | | 1.000 | | | | |
| Density (lbm/ft3) | | 0.478 | | Dust Loading (Grains/acf) | | 31.3 | | | | |
| Viscosity (lbm/ft-sec) | | 2.54E-05 | | | | | | | | |
| Inlet Velocity (ft/sec) | | | | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | | | |
| No load pres. drop (in.W.C.) | | 106.35 | | Dia.(microns) | | Weight % | | | | |
| Full load pres. Drop (in. W.C.) | | 85.46 | | 2.5 | | 6.11 | | | | |
| | | | | 3 | | 15.75 | | | | |
| | | | | 3.5 | | 21.47 | | | | |
| | | | | 4 | | 27.4 | | | | |
| | | | | 4.5 | | 33.3 | | | | |
| | | | | 5 | | 39.04 | | | | |
| | | | | 6 | | 44.49 | | | | |
| | | | | 6.5 | | 49.6 | | | | |
| | | | | 7.5 | | 58.71 | | | | |
| | | | | 8.5 | | 66.32 | | | | |
| | | | | 9.5 | | 72.57 | | | | |
| | | | | 12 | | 83.53 | | | | |
| | | | | 16 | | 89.99 | | | | |
| | | | | 23 | | 95.08 | | | | |
| | | | | 33 | | 97.84 | | | | |
| Price (2005 U.S.\$) | | \$ 355,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|-------------------------|-------------------------------------|-------------------------------------|---------------------------|--|----------------------------------|-----------------------|-------------|-------------|-------------|
| Site Location | | SERVICE OF HIGH PRESSURE UNIT S-102 | | | | | | Date | Rev. | |
| Inlet Conditions | | Flow | Viscosity | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | lb/ft-sec | lb/ft3 | lb/mole | | acfm | °F | | |
| Gas | | 434,982.00 | | 0.38390 | 27.6 | | 18,883.00 | 1,576 | | |
| Particulate | | 9,440.00 | | 62.40 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 460.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 455.57 | | | | | | | | |
| Pressure Drop, Max Allow. (" .WC.) | | 120.00 | | | | | | | | |
| Design/Test Pressure Psig | | 460.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-102 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | Height (In) | Height (ft) |
| Connections Size & Rating | In | 32.0769 | 42.10 | Upper Shell | | | 1 | ASME VIII | 160 | 13.4 |
| | Out | | | Inner Tube | 32.10 | | 4 | | | |
| | Bottom | | | Cone | | | 1 | ASME VIII | | |
| | | | | Refractory | | | 4 | | | |
| Component Data | | | | | Cyclone Body Materials of Construction | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 1598 | 20.4 | 15 | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 1598 | | | | Cercast™ | MS | Cercast™ | MS | Cercast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, KY | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| Recommendation: | | | | | | | | | | |
| One (1) cyclone (XQ120-30M) with the following features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius Cercast 3300 castable refractory | | | | | |
| 1-1/4" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| Inlet transition to 24" Ø gas inlet flange | | | | | Design pressure (psig) | | 460 | | | |
| 30" Ø verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 5-1/2 ft Ø x 27 1/2 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | 18.883 | | Specific Gravity | | 1.000 | | | | |
| Density (lbm/ft3) | | 0.3839 | | Dust Loading (Grains/acf) | | 6.97 | | | | |
| Viscosity (lbm/ft-sec) | | 2.78E-05 | | | | | | | | |
| Inlet Velocity (ft/sec) | | | | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | | | |
| No load pres. drop (in.W.C.) | | 83.63 | | Dia.(microns) | | Weight % | | | | |
| Full load pres. Drop (in. W.C.) | | 72.52 | | 3 | | 7.64 | | | | |
| | | | | 4 | | 16.37 | | | | |
| | | | | 4.5 | | 21.33 | | | | |
| | | | | 5 | | 26.43 | | | | |
| | | | | 5.5 | | 31.53 | | | | |
| | | | | 6 | | 36.52 | | | | |
| | | | | 7 | | 45.88 | | | | |
| | | | | 8 | | 54.2 | | | | |
| | | | | 9 | | 61.4 | | | | |
| | | | | 10 | | 67.53 | | | | |
| | | | | 11 | | 72.7 | | | | |
| | | | | 14 | | 83.68 | | | | |
| | | | | 18 | | 89.34 | | | | |
| | | | | 25 | | 94.31 | | | | |
| | | | | 35 | | 97.29 | | | | |
| | | | | 80 | | 99.72 | | | | |
| Price (2005 U.S.\$) | | \$ 410,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|-------------------------|-------------------------------|-------------------------------------|-------------|--|----------------------------------|--|-------------|-----------------|-------------|
| Site Location | | Date | | | | | Rev. | | | |
| SERVICE OF HIGH PRESSURE UNIT S-103 | | | | | | | | | | |
| Inlet Conditions | | Flow | Specific Heat | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | BTU/lb*F | lb/ft3 | lb/mole | | acfm | °F | | |
| Gas | | 434,982.00 | | 0.41421 | 20.14507 | | 16,835.82 | 1576.0 | | |
| Particulate | | 9,440.00 | | 33.00 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 460.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 455.57 | | | | | | | | |
| Pressure Drop, Max Allow. ("WC.) | | 120.00 | | | | | | | | |
| Design/Test Pressure Psig | | 460.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-103 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | Height (in) | Height (ft) |
| Connections Size & Rating | In | 32.0769 | 42.10 | Upper Shell | | | | 1 ASME VIII | 160 | 13.4 |
| | Out | | | Inner Tube | 32.10 | | | 4 | | |
| | Bottom | | | Cone | | | | 1 ASME VIII | | |
| | | | | | Refractory | | | | 4 | |
| Component Data | | | | | Cyclone Body Materials of Construction | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 1598 | 20.4 | 15 | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 1598 | | | | Cercast™ | MS | Cercast™ | MS | Cercast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, KY | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| Recommendation: | | | | | | | | | | |
| One (1) cyclone (XQ120-30M) with the following features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius Cercast 3300 castable refractory | | | | | |
| 1-1/4" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| Inlet transition to 24" gas inlet flange | | | | | Design pressure (psig) | | 460 | | | |
| 30" verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 4 ft Ø x 18 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | | | | 8.223 | | Specific Gravity | | 1.000 | |
| Density (lbm/ft3) | | | | | 0.5679 | | Dust Loading (Grains/acf) | | 16 | |
| Viscosity (lbm/ft-sec) | | | | | 2.87E-05 | | | | | |
| Inlet Velocity (ft/sec) | | | | | 68.53 | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | |
| No load pres. drop (in.W.C.) | | | | | 103.76 | | Dia.(microns) | | Weight % | |
| Full load pres. Drop (in. W.C.) | | | | | 85.86 | | 2.5 | | 6.71 | |
| | | | | | | | 3.5 | | 15.89 | |
| | | | | | | | 4 | | 21.16 | |
| | | | | | | | 4.5 | | 26.55 | |
| | | | | | | | 5 | | 31.91 | |
| | | | | | | | 5.5 | | 37.11 | |
| | | | | | | | 6 | | 42.08 | |
| | | | | | | | 7 | | 51.14 | |
| | | | | | | | 8 | | 58.96 | |
| | | | | | | | 9 | | 65.59 | |
| | | | | | | | 10 | | 71.14 | |
| | | | | | | | 13 | | 82.8 | |
| | | | | | | | 17 | | 89.12 | |
| | | | | | | | 24 | | 94.37 | |
| | | | | | | | 34 | | 97.41 | |
| | | | | | | | 89 | | 99.83 | |
| Price (2005 U.S.\$) | | \$ 265,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

DATA SHEETS, LOW PRESSURE DESIGN

| Heat Exchanger Specification sheet | | | | | |
|---|---|---------------------------|-----------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Tar Reformer SG Cooling/Steam Generator | | Item No | H-100 Tar Ref Cooler | |
| Size 72x 168 | Type | BEM - HORZ Connected in | | 2 Parallel | 1 Series |
| Surf/Unit (Eff) | 10708 ft ² | Shells/Unit | 2 | Surface/Shell (Effective) | 5354 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr Tar Reformer | | Preheated BFW | |
| Total Fluid Entering | | lb/hr | 329,000 | 251,800 | |
| Vapor | | | 329,000 | 0 | |
| Liquid | | | 0 | 251,800 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | | 0 | 251,800 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 46.533/45.419 | |
| Liquid Viscosity | | cP | 0.000 | 0.092 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.636 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.321 | |
| Vapor Mol. Weight (In/Out) | | | 16.74/16.74 | 0.0/18.02 | |
| Vapor Viscosity | | cP | 0.0280 | 0.0200 | |
| Vapor Specific Heat | | Btu/lb-F | 0.520 | 0.774 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.078 | 0.025 | |
| Temperature (In/Out) | | °F | 1,598.0/624.0 | 546.5/575.0 | |
| Operating Pressure | | psi(Abs) | 29.900 | 1,285.000 | |
| Velocity | | ft/sec | 280.241 | 7.682 | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/3.920 | 5.000/0.977 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.005000 | |
| Heat Exchanged | | 167,000,000 Btu/hr | mtd (corr) | 318.656 °F | |
| Transfer Rate, Service | | 48.9 | Clean | 80.8 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 45/ | 1,350/ | | |
| Design Temp. °F | | 1700 | 625 | | |
| No. Passes per Shell | | 1 | 6 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | | In | 1-33.0 | 6.0 | |
| Size & | | Out | 1-29.0 | 10.0 | |
| Rating | | Intermediate | 0 | 0 | |
| Tube No | 1664 | OD 1.000 in | Thk 0.065 | Length 14.00 ft | Pitch 1.25000 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D. 72.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 34.7 (Area) | Spacing-cc | 73.7 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 2,611 | Bundle Entrance | 3,399 | Bundle Exit | 4,375 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class | R |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------|----------------------------|-------------------------------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | | | Tar Reformer SG Cooling/BFW Preheat | | Item No |
| | | | | | H-101 Tar Ref Cooler |
| Size | 57x 168 | Type | BEM - HORZ Connected in | | 2 Parallel |
| | | | | | 1 Series |
| Surf/Unit (Eff) | 13334 ft ² | Shells/Unit | 2 | Surface/Shell (Effective) | 6667 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr Tar Reformer | | BFW | |
| Total Fluid Entering | | lb/hr | 329,000 | 142,594 | |
| Vapor | | 329,000 | | 0 | |
| Liquid | | 0 | | 142,594 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 58.509/46.533 | |
| Liquid Viscosity | | cP | 0.000 | 0.139 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.340 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.359 | |
| Vapor Mol. Weight (In/Out) | | 16.74/16.74 | | 0.0/0.0 | |
| Vapor Viscosity | | cP | 0.0189 | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | 0.475 | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.049 | 0.000 | |
| Temperature (In/Out) | | °F | 624.0/300.0 | 240.0/546.5 | |
| Operating Pressure | | psi(Abs) | 26.900 | 1,295.000 | |
| Velocity | | ft/sec | 234.572 | - | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/4.568 | 5.000/0.513 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.002000 | |
| Heat Exchanged | | 50,610,000 Btu/hr | mtd (corr) | 68.377 °F | |
| Transfer Rate, Service | | 55.5 | Clean | 68.5 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 35/ | 1,360/ | | |
| Design Temp. °F | | 675 | 600 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | | In 1-29.0 | 3.0 | | |
| Size & Rating | | Out 1-29.0 | 4.0 | | |
| | | Intermediate 0 | 0 | | |
| Tube No | 2688 | OD 0.750 in | Thk 0.065 | Length 14.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | | PLAIN | Material | | |
| Shell | | I.D 57.00 OD in | Shell Cover | | INT |
| Channel or Bonnet | | Channel Cover | | | |
| Tubesheet-Stationary | | Tubesheet-Floating | | | |
| Floating Head Cover | | Impingement Protection | | YES | |
| Baffles Cross | | Type VERT- SEG | %Cut 37.1 (Area) | Spacing-cc 75.5 | |
| Baffles-Long | | Seal Type | | | |
| Supports-Tube | | U-Bend | Type | | |
| Bypass Seal Arrangement | | Tube-Tubesheet Joint | | | |
| Expansion Joint | | Type | | | |
| Rho-V2 Inlet Nozzle | | 2,563 | Bundle Entrance | 2,914 | Bundle Exit 3,741 |
| Gasket-Shellside | | Tubeside | | Floating Head | |
| Code Requirement | | ASME Section 8, Division 1 | | TEMA Class R | |
| Weight/Shell | | Filled with Water | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|---|---------------------------|--------------------------------|---------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Tar Reformer SG Cooler/Deaerator FW Preheat | | Item No | H-102 Tar Ref Cooler | |
| Size 75x 168 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 5621 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 5621 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr H-101 | | Deaerator Feed Water | |
| Total Fluid Entering | lb/hr | 329,000 | | 257,000 | |
| Vapor | | 329,000 | | 0 | |
| Liquid | | 0 | | 257,000 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 59.592/58.402 | |
| Liquid Viscosity | | cP | 0.000 | 0.273 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.054 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.392 | |
| Vapor Mol. Weight (In/Out) | | | 16.74/16.74 | 0.0/0.0 | |
| Vapor Viscosity | | cP | 0.0156 | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | 0.461 | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.040 | 0.000 | |
| Temperature (In/Out) | | °F | 300.0/225.0 | 195.0/237.0 | |
| Operating Pressure | | psi(Abs) | 23.880 | 30.000 | |
| Velocity | | ft/sec | 168.427 | - | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/2.790 | 5.000/0.489 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.002000 | |
| Heat Exchanged | 11,340,000 Btu/hr | mtd (corr) | | 44.478 °F | |
| Transfer Rate, Service | 45.4 | Clean | 58.8 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 35/ | 45/ | | |
| Design Temp. °F | | 350 | 280 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-41.0 | 6.0 | | |
| | Out | 1-42.0 | 6.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 2096 | OD 0.750 in | Thk 0.065 | Length 14.00 ft | Pitch 1.25000 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 75.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 41.0 (Area) | | Spacing-cc | 81.9 |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 2,021 | Bundle Entrance | 1,271 | Bundle Exit | 2,155 |
| Gasket-Shellside | Tubeside | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | Bundle | | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-----------------------------------|-------------------------|--------------------------------|---------------------------|----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Flue Gas Cooler/Steam Superheater | | Item No | H-103 | |
| Size 90x 168 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 5770 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 5770 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Flue Gas fr. Tar Regen | | Superheated Steam | |
| Total Fluid Entering | lb/hr | 248,400 | | 251,800 | |
| Vapor | | 248,400 | | 251,800 | |
| Liquid | | 0 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 0.000/0.000 | | 0.000/0.000 | |
| Liquid Viscosity | cP | 0.000 | | 0.000 | |
| Liquid Specific Heat | Btu/lb-F | 0.000 | | 0.000 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 27.57/27.57 | | 18.02/18.02 | |
| Vapor Viscosity | cP | 0.0405 | | 0.0254 | |
| Vapor Specific Heat | Btu/lb-F | 0.313 | | 0.678 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.040 | | 0.036 | |
| Temperature (In/Out) | °F | 1,798.0/935.0 | | 575.0/1,000.0 | |
| Operating Pressure | psi(Abs) | 14.700 | | 1,275.000 | |
| Velocity | ft/sec | 215.255 | | 5.762 | |
| Pressure Drop (Allow/Calc) | psi | 2.000/1.727 | | 5.000/0.629 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.005000 | |
| Heat Exchanged | 67,260,000 Btu/hr | mtd (corr) | 550.248 °F | | |
| Transfer Rate, Service | 21.2 | Clean | 25.0 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. | psi | 30/ | 1,350/ | | |
| Design Temp. | °F | 1900 | 1100 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. | in | 0.0625 | 0.0625 | | |
| Connections | In | 1-57.0 | 12.0 | | |
| Size & | Out | 1-53.0 | 15.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 2475 | OD 0.750 in | Thk 0.065 | | |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 90.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 38.4 (Area) | | Spacing-cc | 71.2 |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 906 | Bundle Entrance | 2,230 | Bundle Exit | 1,030 |
| Gasket-Shellside | Tubeside | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | Bundle | | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|---------------------------|-----------------|---------------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | NREL Biomass | | Item No | H-200 Quech Water Cooler | |
| Size 71x 120 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 9232 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 9232 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Quench Water | | Cooling Water | |
| Total Fluid Entering | | lb/hr | | 1,189,000 | |
| Vapor | | 0 | | 0 | |
| Liquid | | 1,189,000 | | 1,107,500 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | | 61.342/61.765 | |
| Liquid Viscosity | | cP | | 0.578 | |
| Liquid Specific Heat | | Btu/lb-F | | 1.003 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | | 0.366 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 0.0/0.0 | |
| Vapor Viscosity | | cP | | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | | 0.000 | |
| Temperature (In/Out) | | °F | | 128.0/110.0 | |
| Operating Pressure | | psi(Abs) | | 26.000 | |
| Velocity | | ft/sec | | 1.924 | |
| Pressure Drop (Allow/Calc) | | psi | | 5.000/1.722 | |
| Fouling resistance | | hr-ft ² -F/Btu | | 0.001000 | |
| Heat Exchanged | | 22,150,000 Btu/hr | | mtd (corr) 28.989 °F | |
| Transfer Rate, Service | | 82.8 | | Clean 115.4 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | | Tubeside | |
| Design/Test Pres. psi | | 45/ | | 45/ | |
| Design Temp. °F | | 215 | | 150 | |
| No. Passes per Shell | | 1 | | 1 | |
| Corrosion Allow. in | | 0.0625 | | 0.0625 | |
| Connections | | In | | 1-13.0 | |
| Size & | | Out | | 1-13.0 | |
| Rating | | Intermediate | | 0 | |
| | | | | Sketch | |
| Tube No | 4860 | OD 0.750 in | Thk 0.065 | Length 10.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 71.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 9.2 (Area) | Spacing-cc 14.1 | | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 2,093 | Bundle Entrance | 913 | Bundle Exit | 2,867 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-------------------------------|------------------------------------|------------------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Compressor Interstage Cooling | | Item No | H-300A | |
| Size 82x 144 | Type | BEM - HORZ Connected in | | 2 Parallel | 1 Series |
| Surf/Unit (Eff) | 28471 ft ² | Shells/Unit | 2 | Surface/Shell (Effective) | 14235 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Cooling water | | 1st Stage Syngas | |
| Total Fluid Entering | lb/hr | 6,100,000 | | 317,400 | |
| Vapor | | 0 | | 317,400 | |
| Liquid | | 6,100,000 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 85,698 | |
| Liquid Density (In/Out) | | lb/ft ³ 62.000/62.000 | | 0.000/62.020 | |
| Liquid Viscosity | | cP 0.762 | | 0.432 | |
| Liquid Specific Heat | | Btu/lb-F 1.000 | | 1.035 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.363 | | 0.380 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 16.7/16.7 | |
| Vapor Viscosity | | cP 0.0000 | | 0.0157 | |
| Vapor Specific Heat | | Btu/lb-F 0.000 | | 0.460 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.043 | |
| Temperature (In/Out) | | °F 80.0/100.0 | | 344.0/110.0 | |
| Operating Pressure | | psi(Abs) 65.000 | | 35.000 | |
| Velocity | | ft/sec 3.977 | | 39.521 | |
| Pressure Drop (Allow/Calc) | | psi 5.000/4.889 | | 5.000/0.642 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.002000 | | 0.001000 | |
| Heat Exchanged | 122,000,000 Btu/hr | mtd (corr) | | 80.189 °F | |
| Transfer Rate, Service | 53.4 | Clean | | 64.5 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 80/ | 50/ | | |
| Design Temp. °F | | 150 | 400 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-23.0 | 25.0 | | |
| | Out | 1-23.0 | 23.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 6298 | OD 0.750 in | Thk 0.065 | Length 12.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 82.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | Type VERT- SEG | %Cut 12.4 (Area) | | Spacing-cc 24.0 | |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 1,391 | Bundle Entrance | 1,525 | Bundle Exit | 2,034 |
| Gasket-Shellside | Tubeside | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | Bundle | | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-------------------------------|------------------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Compressor Interstage Cooling | | Item No | H-300B | |
| Size 47x 120 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 3435 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 3435 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | 2nd Stage Syngas | | Cooling water | |
| Total Fluid Entering | lb/hr | 232,600 | | 1,639,500 | |
| Vapor | | 232,600 | | 0 | |
| Liquid | | 0 | | 1,639,500 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ 0.000/0.000 | | 62.000/62.000 | |
| Liquid Viscosity | | cP 0.000 | | 0.762 | |
| Liquid Specific Heat | | Btu/lb-F 0.000 | | 1.000 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.363 | |
| Vapor Mol. Weight (In/Out) | | 16.26/16.26 | | 0.0/0.0 | |
| Vapor Viscosity | | cP 0.0162 | | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F 0.470 | | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.050 | | 0.000 | |
| Temperature (In/Out) | | °F 350.0/110.0 | | 80.0/100.0 | |
| Operating Pressure | | psi(Abs) 84.000 | | 65.000 | |
| Velocity | | ft/sec 119.731 | | 1.938 | |
| Pressure Drop (Allow/Calc) | | psi 5.000/3.994 | | 5.000/0.664 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.001000 | | 0.002000 | |
| Heat Exchanged | 32,790,000 Btu/hr | mtd (corr) | | 103.761 °F | |
| Transfer Rate, Service | 92.0 | Clean | | 134.2 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 100/ | 80/ | | |
| Design Temp. °F | | 400 | 150 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-25.0 | 15.0 | | |
| | Out | 1-23.0 | 15.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 1808 | OD 0.750 in | Thk 0.065 | Length 10.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 47.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | Type VERT- SEG | %Cut 37.2 (Area) | | Spacing-cc 58.0 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 2,286 | Bundle Entrance | 3,535 | Bundle Exit | 3,995 |
| Gasket-Shellside | Tubeside | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | Bundle | | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|-------------------------------|----------------------------|------------------------|--------------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Compressor Interstage Cooling | | Item No | H-300C | |
| Size 51x 120 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 4368 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 4368 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubewise | |
| Fluid Name | | Cooling water | | 3rd Stage Syngas | |
| Total Fluid Entering | | lb/hr | | 225,800 | |
| Vapor | | 0 | | 225,800 | |
| Liquid | | 1,384,500 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 2,710 | |
| Liquid Density (In/Out) | | lb/ft ³ | | 0.000/62.250 | |
| Liquid Viscosity | | cP | | 0.558 | |
| Liquid Specific Heat | | Btu/lb-F | | 1.038 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | | 0.368 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 16.21/16.21 | |
| Vapor Viscosity | | cP | | 0.0164 | |
| Vapor Specific Heat | | Btu/lb-F | | 0.468 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | | 0.051 | |
| Temperature (In/Out) | | °F | | 349.0/110.0 | |
| Operating Pressure | | psi(Abs) | | 220.000 | |
| Velocity | | ft/sec | | 26.531 | |
| Pressure Drop (Allow/Calc) | | psi | | 5.000/0.747 | |
| Fouling resistance | | hr-ft ² -F/Btu | | 0.001000 | |
| Heat Exchanged | | 27,690,000 Btu/hr | | mtd (corr) 92.157 °F | |
| Transfer Rate, Service | | 68.8 | | Clean 88.3 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | | Tubewise | |
| Design/Test Pres. psi | | 80/ | | 245/ | |
| Design Temp. °F | | 150 | | 400 | |
| No. Passes per Shell | | 1 | | 1 | |
| Corrosion Allow. in | | 0.0625 | | 0.0625 | |
| Connections | | In | | 19.0 | |
| Size & | | Out | | 17.0 | |
| Rating | | Intermediate | | 0 | |
| Sketch | | | | | |
| Tube No | 2350 | OD 0.750 in | Thk 0.065 | Length 10.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 51.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | | YES |
| Baffles Cross | | Type VERT- SEG | %Cut 18.9 (Area) | Spacing-cc | 24.0 |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | | U-Bend | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint Type | | | | | |
| Rho-V2 Inlet Nozzle | 1,584 | Bundle Entrance | 1,413 | Bundle Exit | 2,336 |
| Gasket-Shellside | | Tubeside | | Floating Head | |
| Code Requirement | | ASME Section 8, Division 1 | | TEMA Class R | |
| Weight/Shell | | Filled with Water | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | | |
|---|-------------------------------|------------------------------------|------------------------|---------------------------------|-----------------------|--------|
| | | | Job No. | | | |
| Customer | NREL | | Ref No. | LP Syngas Case | | |
| Address | | | Proposal No. | | | |
| Plant Location | | | Date | Rev. 0 | | |
| Service of Unit | Compressor Interstage Cooling | | Item No | H-300D | | |
| Size 42x 120 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series | |
| Surf/Unit (Eff) | 2934 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 2934 ft ² | |
| PERFORMANCE OF ONE UNIT | | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | | |
| Fluid Name | | Cooling water | | 4th Stage Syngas | | |
| Total Fluid Entering | lb/hr | 910,500 | | 223,200 | | |
| Vapor | | 0 | | 223,200 | | |
| Liquid | | 910,500 | | 0 | | |
| Steam | | | | | | |
| Noncondensable | | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 670 | | |
| Liquid Density (In/Out) | | lb/ft ³ 62.000/62.000 | | 0.000/62.210 | | |
| Liquid Viscosity | | cP 0.762 | | 0.580 | | |
| Liquid Specific Heat | | Btu/lb-F 1.000 | | 1.036 | | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.363 | | 0.367 | | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 16.2/16.2 | | |
| Vapor Viscosity | | cP 0.0000 | | 0.0160 | | |
| Vapor Specific Heat | | Btu/lb-F 0.000 | | 0.470 | | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.000 | | 0.049 | | |
| Temperature (In/Out) | | °F 80.0/100.0 | | 277.0/110.0 | | |
| Operating Pressure | | psi(Abs) 65.000 | | 450.000 | | |
| Velocity | | ft/sec 3.281 | | 17.909 | | |
| Pressure Drop (Allow/Calc) | | psi 5.000/3.891 | | 5.000/0.750 | | |
| Fouling resistance | | hr-ft ² -F/Btu 0.002000 | | 0.001000 | | |
| Heat Exchanged | 18,210,000 Btu/hr | mtd (corr) 79.340 °F | | | | |
| Transfer Rate, Service | 78.2 | Clean | | 104.5 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | | |
| | | Shellside | | Tubeside | | Sketch |
| Design/Test Pres. psi | | 80/ | | 500/ | | |
| Design Temp. °F | | 150 | | 330 | | |
| No. Passes per Shell | | 1 | | 1 | | |
| Corrosion Allow. in | | 0.0625 | | 0.0625 | | |
| Connections | | In 1-12.0 | | 15.0 | | |
| Size & Rating | | Out 1-12.0 | | 15.0 | | |
| Rating | | Intermediate 0 | | 0 | | |
| Tube No | 1594 | OD 0.750 in | Thk 0.065 | Length 10.00 ft | Pitch 0.93750 / 30.0° | |
| Tube Type | PLAIN | | Material | | | |
| Shell | I.D 42.00 OD in | | Shell Cover | | INT | |
| Channel or Bonnet | Channel Cover | | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | | |
| Floating Head Cover | | | Impingement Protection | | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 19.2 (Area) | | Spacing-cc 19.2 | | |
| Baffles-Long | Seal Type | | | | | |
| Supports-Tube | U-Bend | | Type | | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | | |
| Expansion Joint | Type | | | | | |
| Rho-V2 Inlet Nozzle | 1,673 | Bundle Entrance | 1,289 | Bundle Exit | 2,454 | |
| Gasket-Shellside | Tubeside | | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | | |
| Weight/Shell | Filled with Water | | | Bundle | | |
| Remarks: | | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|-------------------------|-----------------------------|---------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | ZnO Preheater | | Item No | H-420 ZnO Preheater | |
| Size 90x 96 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 14480 ft ² | Shells/Unit | 1 Surface/Shell (Effective) | | 14480 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Flue Gas fr. Tar Regen | | Sweet Syngas | |
| Total Fluid Entering | lb/hr | 248,400 | | 127,000 | |
| Vapor | | 248,400 | | 127,000 | |
| Liquid | | 0 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 0.000/0.000 | | 0.000/0.000 | |
| Liquid Viscosity | cP | 0.000 | | 0.000 | |
| Liquid Specific Heat | Btu/lb-F | 0.000 | | 0.000 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 27.57/27.57 | | 10.99/10.99 | |
| Vapor Viscosity | cP | 0.0256 | | 0.0182 | |
| Vapor Specific Heat | Btu/lb-F | 0.286 | | 0.659 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.024 | | 0.076 | |
| Temperature (In/Out) | °F | 935.0/190.0 | | 114.0/750.0 | |
| Operating Pressure | psi(Abs) | 14.500 | | 440.000 | |
| Velocity | ft/sec | - | | - | |
| Pressure Drop (Allow/Calc) | psi | 1.000/- | | 5.000/0.287 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.001000 | |
| Heat Exchanged | 52,900,000 Btu/hr | mtd (corr) | 122.52.15 °F | | |
| Transfer Rate, Service | 29.82 | Clean | Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. | psi | 30/ | 480/ | | |
| Design Temp. | °F | 990 | 800 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. | in | 0.0625 | 0.0625 | | |
| Connections | In | 1-35.0 | 10.0 | | |
| Size & | Out | 1-31.0 | 12.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 12160 | OD 0.750 in | Thk 0.065 | | |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 96.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 49.0 (Area) | Spacing-cc | 50 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | Bundle Entrance | | Bundle Exit | | |
| Gasket-Shellside | Tubeside | | Floating Head | | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | Bundle | | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------|----------------------------|------------------------------------|--------------------------------|----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | | | ZnO Syngas Cooler/BFW Preheat | Item No | H-421 |
| Size | 64x 144 | Type | BEM - HORZ Connected in 1 Parallel | | 1 Series |
| Surf/Unit (Eff) | 6915 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 6915 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr ZnO Bed | | BFW | |
| Total Fluid Entering | | lb/hr | 127,000 | 114,306 | |
| Vapor | | 127,000 | | 0 | |
| Liquid | | 0 | | 114,306 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 58.509/46.533 | |
| Liquid Viscosity | | cP | 0.000 | 0.139 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.340 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.359 | |
| Vapor Mol. Weight (In/Out) | | 10.99/10.99 | | 0.0/0.0 | |
| Vapor Viscosity | | cP | 0.0196 | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | 0.660 | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.082 | 0.000 | |
| Temperature (In/Out) | | °F | 750.0/265.0 | 240.0/546.5 | |
| Operating Pressure | | psi(Abs) | 425.000 | 1,295.000 | |
| Velocity | | ft/sec | 27.606 | - | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/2.034 | 5.000/0.399 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.002000 | |
| Heat Exchanged | | 40,570,000 Btu/hr | mtd (corr) | 85.130 °F | |
| Transfer Rate, Service | | 68.9 | Clean | 90.2 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 470/ | 1,360/ | | |
| Design Temp. °F | | 800 | 600 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | | In 1-15.0 | 4.0 | | |
| Size & | | Out 1-13.0 | 6.0 | | |
| Rating | | Intermediate 0 | 0 | | |
| Tube No | | 3364 | OD 0.750 in | | |
| Tube Type | | PLAIN | | Material | |
| Shell | | I.D 64.00 OD in | | Shell Cover INT | |
| Channel or Bonnet | | | | Channel Cover | |
| Tubesheet-Stationary | | | | Tubesheet-Floating | |
| Floating Head Cover | | | | Impingement Protection YES | |
| Baffles Cross | | Type VERT- SEG | %Cut 18.6 (Area) | Spacing-cc 24.0 | |
| Baffles-Long | | | | Seal Type | |
| Supports-Tube | | U-Bend | | Type | |
| Bypass Seal Arrangement | | | | Tube-Tubesheet Joint | |
| Expansion Joint | | | | Type | |
| Rho-V2 Inlet Nozzle | | 2,297 | Bundle Entrance | 611 | Bundle Exit 3,020 |
| Gasket-Shellside | | Tubeside | | Floating Head | |
| Code Requirement | | ASME Section 8, Division 1 | | TEMA Class R | |
| Weight/Shell | | Filled with Water | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|---------------------------|------------------------|---------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | ZnO Syngas Cooler | | Item No | H-422 | |
| Size 30x 96 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 1190 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 1190 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Syngas fr H-421 | | Cooling Water | |
| Total Fluid Entering | | lb/hr | 127,000 | 593,000 | |
| Vapor | | 127,000 | | 0 | |
| Liquid | | 0 | | 593,000 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ | 0.000/0.000 | 62.850/62.283 | |
| Liquid Viscosity | | cP | 0.000 | 0.734 | |
| Liquid Specific Heat | | Btu/lb-F | 0.000 | 1.027 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F | 0.000 | 0.363 | |
| Vapor Mol. Weight (In/Out) | | 10.99/10.99 | | 0.0/0.0 | |
| Vapor Viscosity | | cP | 0.0140 | 0.0000 | |
| Vapor Specific Heat | | Btu/lb-F | 0.645 | 0.000 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F | 0.062 | 0.000 | |
| Temperature (In/Out) | | °F | 265.0/120.0 | 80.0/100.0 | |
| Operating Pressure | | psi(Abs) | 420.000 | 65.000 | |
| Velocity | | ft/sec | 54.190 | 1.566 | |
| Pressure Drop (Allow/Calc) | | psi | 5.000/4.440 | 5.000/0.420 | |
| Fouling resistance | | hr-ft ² -F/Btu | 0.001000 | 0.002000 | |
| Heat Exchanged | 11,860,000 Btu/hr | mtd (corr) | | 88.210 °F | |
| Transfer Rate, Service | 113.0 | Clean | | 184.6 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 465/ | 80/ | | |
| Design Temp. °F | | 315 | 150 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-13.0 | 10.0 | | |
| Size & | Out | 1-12.0 | 10.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 802 | OD 0.750 in | Thk 0.065 | Length 8.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 30.00 OD in | | Shell Cover | INT | |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | | | Impingement Protection | NO | |
| Baffles Cross | Type VERT- SEG | %Cut 32.3 (Area) | Spacing-cc | 24.0 | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 2,469 | Bundle Entrance | 3,979 | Bundle Exit | 4,341 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|------------------------------------|-------------------------|---------------------------------|---------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | MeOH Compressor Interstage Cooling | | Item No | H-500A | |
| Size 24x 72 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 511 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 511 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Cooling water | | Syngas | |
| Total Fluid Entering | lb/hr | 553,000 | | 127,000 | |
| Vapor | | 0 | | 127,000 | |
| Liquid | | 553,000 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 62.000/62.000 | | 0.000/0.000 | |
| Liquid Viscosity | cP | 0.762 | | 0.000 | |
| Liquid Specific Heat | Btu/lb-F | 1.000 | | 0.000 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.363 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 10.99/10.99 | |
| Vapor Viscosity | cP | 0.0000 | | 0.0155 | |
| Vapor Specific Heat | Btu/lb-F | 0.000 | | 0.655 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.068 | |
| Temperature (In/Out) | °F | 80.0/100.0 | | 333.0/200.0 | |
| Operating Pressure | psi(Abs) | 65.000 | | 1,000.000 | |
| Velocity | ft/sec | 4.182 | | 25.131 | |
| Pressure Drop (Allow/Calc) | psi | 5.000/2.552 | | 5.000/0.721 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.002000 | | 0.001000 | |
| Heat Exchanged | 11,060,000 Btu/hr | mtd (corr) | 170.297 °F | | |
| Transfer Rate, Service | 127.1 | Clean | 215.4 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 80/ | 1,050/ | | |
| Design Temp. °F | | 150 | 385 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-10.0 | 12.0 | | |
| Size & | Out | 1-10.0 | 10.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 476 | OD 0.750 in | Thk 0.065 | Length 6.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 24.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | | | Impingement Protection | YES | |
| Baffles Cross | Type VERT- SEG | %Cut 23.4 (Area) | | Spacing-cc | 16.3 |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 1,279 | Bundle Entrance | 1,349 | Bundle Exit | 2,039 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|------------------------------------|------------------------|--------------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | MeOH Syngas Preheat | | Item No | H-501 | |
| Size 73x 168 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 12712 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 12712 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Steam | | Syngas to MeOH Rxn | |
| Total Fluid Entering | lb/hr | 18,830 | | 127,000 | |
| Vapor | | 18,830 | | 127,000 | |
| Liquid | | 0 | | 0 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 18,830 | | 0 | |
| Liquid Density (In/Out) | | lb/ft ³ 0.000/52.387 | | 0.000/0.000 | |
| Liquid Viscosity | | cP 0.148 | | 0.000 | |
| Liquid Specific Heat | | Btu/lb-F 1.120 | | 0.000 | |
| Liquid Thermal Conductivity | | Btu/hr-ft-F 0.404 | | 0.000 | |
| Vapor Mol. Weight (In/Out) | | 18.02/18.02 | | 10.99/10.99 | |
| Vapor Viscosity | | cP 0.0161 | | 0.0170 | |
| Vapor Specific Heat | | Btu/lb-F 0.492 | | 0.659 | |
| Vapor Thermal Conductivity | | Btu/hr-ft-F 0.020 | | 0.074 | |
| Temperature (In/Out) | | °F 487.0/324.0 | | 239.0/460.0 | |
| Operating Pressure | | psi(Abs) 100.000 | | 1,160.000 | |
| Velocity | | ft/sec 4.726 | | 2.192 | |
| Pressure Drop (Allow/Calc) | | psi 5.000/0.548 | | 5.000/0.492 | |
| Fouling resistance | | hr-ft ² -F/Btu 0.005000 | | 0.001000 | |
| Heat Exchanged | 18,450,000 Btu/hr | mtd (corr) | | 60.365 °F | |
| Transfer Rate, Service | 24.0 | Clean | | 28.3 Btu/hr-ft ² -F | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | | Shellside | Tubeside | Sketch | |
| Design/Test Pres. psi | | 100/ | 1,220/ | | |
| Design Temp. °F | | 540 | 515 | | |
| No. Passes per Shell | | 1 | 1 | | |
| Corrosion Allow. in | | 0.0625 | 0.0625 | | |
| Connections | In | 1-8.0 | 10.0 | | |
| Size & | Out | 1-2.0 | 12.0 | | |
| Rating | Intermediate | 0 | 0 | | |
| Tube No | 5242 | OD 0.750 in | Thk 0.065 | Length 14.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 73.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | | | Channel Cover | | |
| Tubesheet-Stationary | | | Tubesheet-Floating | | |
| Floating Head Cover | | | Impingement Protection | | NO |
| Baffles Cross | Type VERT- SEG | %Cut 10.4 (Area) | | Spacing-cc 14.5 | |
| Baffles-Long | | | Seal Type | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | | | Tube-Tubesheet Joint | | |
| Expansion Joint | | | Type | | |
| Rho-V2 Inlet Nozzle | 1,228 | Bundle Entrance | 1,623 | Bundle Exit | 1,384 |
| Gasket-Shellside | | | Tubeside | | Floating Head |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | | | Filled with Water | | Bundle |
| Remarks: | | | | | |

| Heat Exchanger Specification sheet | | | | | |
|---|----------------------------|-------------------------|---------------------------------|---------------------------|-----------------------|
| | | | Job No. | | |
| Customer | NREL | | Ref No. | LP Syngas Case | |
| Address | | | Proposal No. | | |
| Plant Location | | | Date | Rev. 0 | |
| Service of Unit | Blowdown Cooler | | Item No | H-601 | |
| Size 12x 48 | Type | BEM - HORZ Connected in | | 1 Parallel | 1 Series |
| Surf/Unit (Eff) | 89 ft ² | Shells/Unit | 1 | Surface/Shell (Effective) | 89 ft ² |
| PERFORMANCE OF ONE UNIT | | | | | |
| Fluid Allocation | | Shellside | | Tubeside | |
| Fluid Name | | Blowdown | | Cooling water | |
| Total Fluid Entering | lb/hr | 3,164 | | 30,465 | |
| Vapor | | 0 | | 0 | |
| Liquid | | 3,164 | | 30,465 | |
| Steam | | | | | |
| Noncondensable | | | | | |
| Fluid Vaporized or Condensed | | 0 | | 0 | |
| Liquid Density (In/Out) | lb/ft ³ | 56.607/62.000 | | 62.000/62.000 | |
| Liquid Viscosity | cP | 0.311 | | 0.762 | |
| Liquid Specific Heat | Btu/lb-F | 1.059 | | 1.000 | |
| Liquid Thermal Conductivity | Btu/hr-ft-F | 0.382 | | 0.363 | |
| Vapor Mol. Weight (In/Out) | | 0.0/0.0 | | 0.0/0.0 | |
| Vapor Viscosity | cP | 0.0000 | | 0.0000 | |
| Vapor Specific Heat | Btu/lb-F | 0.000 | | 0.000 | |
| Vapor Thermal Conductivity | Btu/hr-ft-F | 0.000 | | 0.000 | |
| Temperature (In/Out) | °F | 298.0/110.0 | | 80.0/100.0 | |
| Operating Pressure | psi(Abs) | 65.000 | | 65.000 | |
| Velocity | ft/sec | 0.170 | | 0.561 | |
| Pressure Drop (Allow/Calc) | psi | 5.000/0.111 | | 5.000/0.536 | |
| Fouling resistance | hr-ft ² -F/Btu | 0.001000 | | 0.002000 | |
| Heat Exchanged | 609,300 Btu/hr | mtd (corr) | 89.027 °F | | |
| Transfer Rate, Service | 76.9 | Clean | 104.4 Btu/hr-ft ² -F | | |
| CONSTRUCTION OF ONE SHELL | | | | | |
| | Shellside | Tubeside | Sketch | | |
| Design/Test Pres. psi | 80/ | 80/ | | | |
| Design Temp. °F | 350 | 150 | | | |
| No. Passes per Shell | 1 | 1 | | | |
| Corrosion Allow. in | 0.0625 | 0.0625 | | | |
| Connections | In 1-1.0 | 2.0 | | | |
| Size & Rating | Out 1-1.0 | 2.0 | | | |
| | Intermediate 0 | 0 | | | |
| Tube No | 116 | OD 0.750 in | Thk 0.065 | Length 4.00 ft | Pitch 0.93750 / 30.0° |
| Tube Type | PLAIN | | Material | | |
| Shell | I.D 12.00 OD in | | Shell Cover | | INT |
| Channel or Bonnet | Channel Cover | | | | |
| Tubesheet-Stationary | Tubesheet-Floating | | | | |
| Floating Head Cover | Impingement Protection YES | | | | |
| Baffles Cross | Type VERT- SEG | %Cut 10.1 (Area) | Spacing-cc 2.3 | | |
| Baffles-Long | Seal Type | | | | |
| Supports-Tube | U-Bend | | Type | | |
| Bypass Seal Arrangement | Tube-Tubesheet Joint | | | | |
| Expansion Joint | Type | | | | |
| Rho-V2 Inlet Nozzle | 459 | Bundle Entrance | 10 | Bundle Exit | 268 |
| Gasket-Shellside | Tubeside | | | Floating Head | |
| Code Requirement | ASME Section 8, Division 1 | | | TEMA Class R | |
| Weight/Shell | Filled with Water | | | Bundle | |
| Remarks: | | | | | |

| | | | | | |
|---|------------------|--|-------------|-------------------|---------------------------|
| COMPRESSOR NUMBER | | K-100 | | | |
| SERVICE | | Combustion Air | | | |
| GAS HANDLED | | Air | | | |
| NORMAL FLOW | SCFM | 51,965 | | | |
| NORMAL FLOW | LB/HR | 235,200 | | | |
| DESIGN FLOW | SCFM | | | | |
| MOL. WT. | | 28.63 | | | |
| C_p/C_v | Value | 1.4 | | | |
| | @ F / PSIA | 90 / 14.7 | | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | PSIA | 14.7 | | | |
| COMPR. FACTOR @ SUCTION | | 0.999 | | | |
| FLOW AT SUCTION | ACFM | 54,910 | | | |
| ORIGIN | PSIA | | | | |
| TEMPERATURE | F | 90 | | | |
| LINE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (1, 2) | | | | |
| CONTINGENCY | PSI | | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | PSIA | 20 | | | |
| DISCH. TEMPERATURE | F (2) | 157 | | | |
| COMPR. FACTOR @ DISCH. | | 0.999 | | | |
| DELIVERY | PSIA | | | | |
| LINE LOSS | PSI (2) | | | | |
| EXCHANGER LOSS | PSI (2) | | | | |
| HEATER LOSS | PSI (2) | | | | |
| CONTROL VALVE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (2) | | | | |
| CONTINGENCY | PSI (2) | | | | |
| TOTAL LOSSES | PSI (2) | | | | |
| COMPRESSION RATIO | | 1.36 | | | |
| EFFICIENCY | (2) | 0.75 | | | |
| BHP | (2) | 1600 | | | |
| COMPRESSOR TYPE | | | | | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | H ₂ O | 3.1 | | | |
| | O ₂ | 20.3 | | | |
| | Ar | 0.9 | | | |
| | N ₂ | 75.7 | | | |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: Low Pressure Syngas Case (BLC Gasifier) | | | |
| | | | | JOB NO | NREL Contract ACO-5-44027 |
| | | | | DRAWING NO | REV |

| COMPRESSOR NUMBER | | K-300A - Stage 1 | K-300B - Stage 2 | K-300C - Stage 3 | K-300D - Stage 4 | |
|--|--|--|---------------------------|---------------------------|---------------------------|----------|
| SERVICE | | Syngas Compressor Stage 1 | Syngas Compressor Stage 2 | Syngas Compressor Stage 3 | Syngas Compressor Stage 4 | |
| GAS HANDLED | | Syngas | Syngas | Syngas | Syngas | |
| NORMAL FLOW | SCFM | 120,208 | 90,448 | 88,044 | 87,158 | |
| NORMAL FLOW | LB/HR | 317,371 | 232,617 | 225,773 | 223,220 | |
| DESIGN FLOW | | | | | | |
| MOL WT. | | 16.7 | 16.26 | 16.21 | 16.2 | |
| C _p /C _v | Value | 1.36 | 1.374 | 1.379 | 1.39 | |
| | @ F / PSIA | 157 / 15.88 | 110 / 30 | 110 / 79 | 110 / 215 | |
| SUCTION CONDITIONS | | | | | | |
| SUCTION PRESSURE | | PSIA | 15.88 | 30 | 79 | 215 |
| COMPR. FACTOR @ SUCTION | | | 0.9979 | 0.999 | 0.9985 | 0.9972 |
| FLOW AT SUCTION | | ACFM | 131,756 | 48,531 | 17,936 | 6,513 |
| ORIGIN | | PSIA | | | | |
| TEMPERATURE | | F | 157.1 | 110 | 110 | 110 |
| LINE LOSS | | PSI (2) | | | | |
| OTHER LOSSES | | PSI (1, 2) | | | | |
| CONTINGENCY | | PSI | | | | |
| DISCHARGE CONDITIONS | | | | | | |
| DISCH. PRESSURE | | PSIA | 35 | 84 | 220 | 450 |
| DISCH. TEMPERATURE | | F (2) | 344.2 | 349.6 | 349.1 | 277 |
| COMPR. FACTOR @ DISCH. | | | 0.9982 | 1.001 | 1.003 | 1.005 |
| DELIVERY | | PSIA | | | | |
| LINE LOSS | | PSI (2) | | | | |
| EXCHANGER LOSS | | PSI (2) | | | | |
| HEATER LOSS | | PSI (2) | | | | |
| CONTROL VALVE LOSS | | PSI (2) | | | | |
| OTHER LOSSES | | PSI (2) | | | | |
| CONTINGENCY | | PSI (2) | | | | |
| TOTAL LOSSES | | PSI (2) | | | | |
| COMPRESSION RATIO | | | 2.204 | 2.8 | 2.78 | 2.093 |
| EFFICIENCY | | (2) | 0.75 | 0.75 | 0.75 | 0.75 |
| BHP | | (2) | 11,248 | 10,251 | 10,251 | 7,036 |
| COMPRESSOR TYPE | | | | | | |
| DRIVER TYPE | | | | | | |
| GAS COMPOSITION: Vol. % | | | | | | |
| | H ₂ | | 39.79 | 52.87 | 54.32 | 54.88 |
| | CO ₂ | | 12.36 | 16.42 | 16.87 | 17.04 |
| | CO | | 18.42 | 24.48 | 25.15 | 25.41 |
| | H ₂ O | | 27.97 | 4.28 | 1.67 | 0.66 |
| | CH ₄ | | 1.19 | 1.58 | 1.62 | 1.64 |
| | C ₂ H ₂ | | 0.02 | 0.02 | 0.02 | 0.02 |
| | C ₂ H ₄ | | 0.02 | 0.22 | 0.23 | 0.23 |
| | C ₂ H ₆ | | 0 | 0.00001 | 0.00002 | 0.00002 |
| | Benzene (C ₆ H ₆) | | 0 | 0.000006 | 0.000006 | 0.000007 |
| | Tar (C ₁₀ H ₈) | | 0 | 0.00001 | 0.000001 | 0.000001 |
| | Ammonia (NH ₃) | | 0.01 | 0.01 | 0.01 | 0.01 |
| | H ₂ S | | 0.03 | 0.04 | 0.04 | 0.04 |
| | N ₂ | | 0.06 | 0.08 | 0.08 | 0.08 |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER | | | | | | |
| (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT | |
| | | NREL BIOMASS GASIFICATION: Low Pressure Syngas Case (BCL Gasifier) | | | | |
| | | | | JOB NO | NREL Contract ACO-5-44027 | |
| | | | | DRAWING NO | | |
| | | | | REV | | |

| | | | | | |
|--|------------------|--|-------------|-------------------|---------------------------|
| COMPRESSOR NUMBER | | K-420 | | | |
| SERVICE | | Flue Gas Blower | | | |
| GAS HANDLED | | Flue Gas | | | |
| NORMAL FLOW | SCFM | 56,988 | | | |
| NORMAL FLOW | LB/HR | 248,400 | | | |
| DESIGN FLOW | SCFM | | | | |
| MOL. WT. | | 27.57 | | | |
| C_p/C_v | Value | 1.367 | | | |
| | @ F / PSIA | 176 / 14.3 | | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | PSIA | 14.3 | | | |
| COMPR. FACTOR @ SUCTION | | 0.9982 | | | |
| FLOW AT SUCTION | ACFM | 71,490 | | | |
| ORIGIN | PSIA | | | | |
| TEMPERATURE | F | 175.8 | | | |
| LINE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (1, 2) | | | | |
| CONTINGENCY | PSI | | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | PSIA | 14.7 | | | |
| DISCH. TEMPERATURE | F (2) | 182 | | | |
| COMPR. FACTOR @ DISCH. | | 0.9982 | | | |
| DELIVERY | PSIA | | | | |
| LINE LOSS | PSI (2) | | | | |
| EXCHANGER LOSS | PSI (2) | | | | |
| HEATER LOSS | PSI (2) | | | | |
| CONTROL VALVE LOSS | PSI (2) | | | | |
| OTHER LOSSES | PSI (2) | | | | |
| CONTINGENCY | PSI (2) | | | | |
| TOTAL LOSSES | PSI (2) | | | | |
| COMPRESSION RATIO | | 1.028 | | | |
| EFFICIENCY | (2) | 0.75 | | | |
| BHP | (2) | 177 | | | |
| COMPRESSOR TYPE | | | | | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | CO ₂ | 0.03 | | | |
| | H ₂ O | 3.1 | | | |
| | O ₂ | 20.29 | | | |
| | Ar | 0.91 | | | |
| | N ₂ | 75.67 | | | |
| <p>(1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN</p> | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: Low Pressure Syngas Case (BCL Gasifier) | | | |
| | | | | JOB NO | NREL Contract ACO-5-44027 |
| | | | | DRAWING NO | REV |

| COMPRESSOR NUMBER | | K-500A | K-500B | | |
|--|--|--|-------------------------|---------------------------|--------|
| SERVICE | | MeOH Compressor Stage 1 | MeOH Compressor Stage 2 | | |
| GAS HANDLED | | Treated Syngas | Treated Syngas | | |
| NORMAL FLOW | SCFM | 73,055 | 73,055 | | |
| NORMAL FLOW | LB/HR | 127,035 | 127,035 | | |
| DESIGN FLOW | | | | | |
| MOL. WT. | | 10.99 | 10.99 | | |
| C _p /C _v | Value | 1.418 | 1.424 | | |
| | @ F / PSIA | 115 / 415 | 200 / 995 | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | | PSIA | 415 | 995 | |
| COMPR. FACTOR @ SUCTION | | | 1.006 | 1.021 | |
| FLOW AT SUCTION | | ACFM | 2,881 | 1,400 | |
| ORIGIN | | PSIA | | | |
| TEMPERATURE | | F | 110 | 200 | |
| LINE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (1, 2) | | | |
| CONTINGENCY | | PSI | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | | PSIA | 1,000 | 1,160 | |
| DISCH. TEMPERATURE | | F (2) | 326 | 239.3 | |
| COMPR. FACTOR @ DISCH. | | | 1.023 | 1.026 | |
| DELIVERY | | PSIA | | | |
| LINE LOSS | | PSI (2) | | | |
| EXCHANGER LOSS | | PSI (2) | | | |
| HEATER LOSS | | PSI (2) | | | |
| CONTROL VALVE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (2) | | | |
| CONTINGENCY | | PSI (2) | | | |
| TOTAL LOSSES | | PSI (2) | | | |
| COMPRESSION RATIO | | | 2.41 | 1.17 | |
| EFFICIENCY | | (2) | 0.75 | 0.75 | |
| BHP | | (2) | 7,377 | 1,340 | |
| COMPRESSOR TYPE | | | | | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | H ₂ | | 65.45 | 65.45 | |
| | CO ₂ | | 1.63 | 1.63 | |
| | CO | | 30.3 | 30.3 | |
| | H ₂ O | | 0.26 | 0.26 | |
| | CH ₄ | | 1.96 | 1.96 | |
| | C ₂ H ₂ | | 0.03 | 0.03 | |
| | C ₂ H ₄ | | 0.28 | 0.28 | |
| | C ₂ H ₆ | | 0.00002 | 0.00002 | |
| | Benzene (C ₆ H ₆) | | 0.000008 | 0.000008 | |
| | Tar (C ₁₀ H ₈) | | 0.000001 | 0.000001 | |
| | NH ₃ | | 0.01 | 0.01 | |
| | N ₂ | | 0.095 | 0.095 | |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER | | | | | |
| (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: Low Pressure Syngas Case (BCL Gasifier) | | | |
| | | JOB NO | | NREL Contract ACO-5-44027 | |
| | | DRAWING NO | | REV | |

| COMPRESSOR NUMBER | | M-601A | M-601B | | |
|--|--|--|------------------------------------|---------------------------|--------|
| SERVICE | | Steam Turbine - Extraction Stage 1 | Steam Turbine - Extraction Stage 2 | | |
| GAS HANDLED | | Steam | Steam | | |
| NORMAL FLOW | SCFM | 88,402 | 81,815 | | |
| NORMAL FLOW | LB/HR | 251,800 | 232,900 | | |
| DESIGN FLOW | | SCFM | | | |
| MOL. WT. | | 18.02 | 18.02 | | |
| C _p /C _v | Value | 1.384 | 1.336 | | |
| | @ F / PSIA | 1000 / 1265 | 564.8 / 165 | | |
| SUCTION CONDITIONS | | | | | |
| SUCTION PRESSURE | | PSIA | 1265 | 100 | |
| COMPR. FACTOR @ SUCTION | | | 0.9332 | 0.977 | |
| FLOW AT SUCTION | | ACFM | 2,691 | 21,390 | |
| ORIGIN | | PSIA | | | |
| TEMPERATURE | | F | 1000 | 487 | |
| LINE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (1, 2) | | | |
| CONTINGENCY | | PSI | | | |
| DISCHARGE CONDITIONS | | | | | |
| DISCH. PRESSURE | | PSIA | 100 | 50 | |
| DISCH. TEMPERATURE | | F (2) | 487 | 376 | |
| COMPR. FACTOR @ DISCH. | | | 0.977 | 0.9833 | |
| DELIVERY | | PSIA | | | |
| LINE LOSS | | PSI (2) | | | |
| EXCHANGER LOSS | | PSI (2) | | | |
| HEATER LOSS | | PSI (2) | | | |
| CONTROL VALVE LOSS | | PSI (2) | | | |
| OTHER LOSSES | | PSI (2) | | | |
| CONTINGENCY | | PSI (2) | | | |
| TOTAL LOSSES | | PSI (2) | | | |
| COMPRESSION RATIO | | | - | - | |
| EFFICIENCY | | (2) | 0.75 | 0.75 | |
| kW Generated | | (2) | 16,067 | 3,343 | |
| Turbine TYPE | | | Steam | Steam | |
| DRIVER TYPE | | | | | |
| GAS COMPOSITION: Vol. % | | | | | |
| | H ₂ | | | | |
| | CO ₂ | | | | |
| | CO | | | | |
| | H ₂ O | 100% | 100% | | |
| | CH ₄ | | | | |
| | C ₂ H ₂ | | | | |
| | C ₂ H ₄ | | | | |
| | C ₂ H ₆ | | | | |
| | Benzene (C ₆ H ₆) | | | | |
| | Tar (C ₁₀ H ₈) | | | | |
| | NH ₃ | | | | |
| | N ₂ | | | | |
| (1) INCLUDES ALLOWANCE FOR SUCTION OR DISCHARGE SNUBBER | | | | | |
| (2) VALUE TABULATED IS ESTIMATED AND MUST BE VERIFIED BY FINAL MECHANICAL DESIGN | | | | | |
| | | | | | |
| | | | | | |
| NO | DATE | REVISIONS | PROC | PROJ. | CLIENT |
| | | NREL BIOMASS GASIFICATION: Low Pressure Syngas Case (BCL Gasifier) | | | |
| | | | JOB NO | NREL Contract ACO-5-44027 | |
| | | | DRAWING NO | REV | |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|---|-------------------------------|-------------------------------------|---------------------------|--|----------------------------------|-----------------------|-------------|---------------------|-------------|
| Site Location | (Note: Four (4) parallel cyclones) | | | | Date | | | Rev. | | |
| SERVICE OF LOW PRESSURE UNIT S-100 and S-101 | | | | | | | | | | |
| Inlet Conditions | | Flow | Viscosity | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | lb/ft-sec | lb/ft3 | lb/mole | | acfm | °F | | |
| Gas (Split into four parallel flows) | | 316,369.00 | 2.35 x 10 ⁻⁵ | 0.03500 | 18.7 | | 150,652.00 | 1,598 | | |
| Particulate | | 40,407.00 | | 62.40 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 33.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 32.64 | | | | | | | | |
| Pressure Drop, Max Allow. (" .WC.) | | 10.48 | | | | | | | | |
| Design/Test Pressure Psig | | 33.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-100 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | Overall Height (ft) | |
| Connections Size & Rating | In | 48 | 58 | Upper Shell | 82 | 84 | 1 | ASME VIII | 35 | |
| | Out | 36 | 46 | Inner Tube | 36 | | | | | |
| | Bottom | TBD | | Cone | | | 1 | ASME VIII | | |
| | | | | Refractory | 74 | | 4 | | | |
| Component Data | | | | | Cyclone Body Materials of Construction | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 1598 | | | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 1598 | | | | CerCast™ | MS | CerCast™ | MS | CerCast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, Ky | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| <i>Recommendation: Replace S-100 and S-101 with 4 cyclones operated in parallel using split air flow:</i> | | | | | | | | | | |
| Four (4) XQ120-48M cyclone assemblies each with the following Features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius CerCast 3300 castable refractory | | | | | |
| 3/8" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| 40"Ø gas inlet flange | | | | | Design pressure (psig) | | 33 | | | |
| 48"Ø verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 7 ftØ x 35 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | 37.663 | | Specific Gravity | | 1.000 | | | | |
| Density (lbm/ft3) | | 0.035 | | Dust Loading (Grains/acf) | | 31.3 | | | | |
| Viscosity (lbm/ft-sec) | | 2.53E-05 | | | | | | | | |
| Inlet Velocity (ft/sec) | | | | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | | | |
| No load pres. drop (in.W.C.) | | 12.6 | | Dia.(microns) | | Weight % | | | | |
| Full load pres. Drop (in. W.C.) | | 10.02 | | 3 | | 7.37 | | | | |
| | | | | 3.5 | | 16.3 | | | | |
| | | | | 4 | | 21.44 | | | | |
| | | | | 4.5 | | 26.75 | | | | |
| | | | | 5 | | 32.07 | | | | |
| | | | | 5.5 | | 37.27 | | | | |
| | | | | 6.5 | | 42.27 | | | | |
| | | | | 7.5 | | 51.48 | | | | |
| | | | | 8.5 | | 59.48 | | | | |
| | | | | 9.5 | | 66.29 | | | | |
| | | | | 10.5 | | 71.99 | | | | |
| | | | | 13 | | 82.36 | | | | |
| | | | | 17 | | 89.12 | | | | |
| | | | | 24 | | 94.36 | | | | |
| | | | | 34 | | 97.39 | | | | |
| | | | | 89 | | 99.83 | | | | |
| Price (2005 U.S.\$) | | \$ 1,225,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|--------------------------------|--------------------------------------|--|---|--|---|------------------------------|--------------------|----------------------------|-------------|
| Site Location | | | | | | | Date | | | Rev. |
| SERVICE OF LOW PRESSURE UNIT S-102 | | | | | | | | | | |
| Inlet Conditions | | Flow | Viscosity | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | BTU/lb°F | lb/ft ³ | lb/mole | | acfm | °F | | |
| Gas | | 328,979.00 | 2.78E-05 | 0.34470 | 16.7 | | 150,612.01 | 1,598 | | |
| Particulate | | 40,407.00 | | 62.40 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 33.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 32.64 | | | | | | | | |
| Pressure Drop, Max Allow. (" .WC.) | | 10.00 | | | | | | | | |
| Design/Test Pressure Psig | | 33.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-102 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | Overall Height (ft) | |
| Connections Size & Rating | In | 34 | 44 | Upper Shell | 58 | 60 | 1 | ASME VIII | 25 | |
| | Out | 26 | 36 | Inner Tube | 34 | | | | | |
| | Bottom | | | Cone | | | 1 | ASME VIII | | |
| | | | | Refractory | 50 | | 4 | | | |
| Component Data | | | | Cyclone Body Materials of Construction | | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 1598 | 20.4 | 15 | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 1598 | | | | Cercast™ | MS | Cercast™ | MS | Cercast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, Ky | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| Recommendation: Quote Pending | | | | | | | | | | |
| Four (4) XQ120-48M cyclone assemblies each with the following Features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius Cercast 3300 castable refractory | | | | | |
| 3/8" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| 40"Ø gas inlet flange | | | | | Design pressure (psig) | | 460 | | | |
| 48"Ø verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 5 ftØ x 25 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | 15.906 | | Specific Gravity | | 1.000 | | | | |
| Density (lbm/ft ³) | | 0.3447 | | Dust Loading (Grains/acf) | | 7.33 | | | | |
| Viscosity (lbm/ft-sec) | | 2.78E-05 | | | | | | | | |
| Inlet Velocity (ft/sec) | | | | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | | | |
| No load pres. drop (in.W.C.) | | 73.64 | | Dia.(microns) | | Weight % | | | | |
| Full load pres. Drop (in. W.C.) | | 63.69 | | 2.5 | | 4.91 | | | | |
| | | | | 3.5 | | 12.88 | | | | |
| | | | | 4.5 | | 22.89 | | | | |
| | | | | 5 | | 28.13 | | | | |
| | | | | 5.5 | | 33.31 | | | | |
| | | | | 6 | | 38.34 | | | | |
| | | | | 7 | | 47.7 | | | | |
| | | | | 8 | | 55.93 | | | | |
| | | | | 9 | | 63 | | | | |
| | | | | 10 | | 68.97 | | | | |
| | | | | 11 | | 73.98 | | | | |
| | | | | 13 | | 81.64 | | | | |
| | | | | 17 | | 88.65 | | | | |
| | | | | 24 | | 94.08 | | | | |
| | | | | 34 | | 97.25 | | | | |
| | | | | 74 | | 99.67 | | | | |
| Price (2005 U.S.\$) | | \$ 370,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

| Cyclone Specification Sheet | | | | | | | | | | |
|---|--------------------------------|--------------------------------------|--|--|--|---|------------------------------|--------------------|----------------|----------------------------|
| Site Location | | | | | | | Date | | | Rev. |
| SERVICE OF LOW PRESSURE UNIT S-103 | | | | | | | | | | |
| Inlet Conditions | | Flow | Viscosity | Density | Molecular Weight (Ave.) | Particle Size (mm) (Stokes' MMD) | Volumetric Flowrate | Temperature | | |
| | | lb/h | lb/ft-sec | lb/ft3 | lb/mole | | acfm | °F | | |
| Gas | | 248,368.00 | 2.87E-05 | 0.03501 | 27.6 | | 7,289.00 | 1,798 | | |
| Particulate | | 40,407.00 | | 1.00 | | 60 | | | | |
| Gas Inlet Pressure (psia) | | 33.00 | | | | | | | | |
| Gas Discharge Pressure (psig) | | 32.64 | | | | | | | | |
| Pressure Drop, Max Allow. (" WC.) | | 10.00 | | | | | | | | |
| Design/Test Pressure Psig | | 33.00 | | | | | | | | |
| Design Particulate Cutpoint | | 50 | | | | | | | | |
| Design Separation Efficiency at Cutpoint (%) | | 98 | | | | | | | | |
| Emery Design Calculations Summary for S-103 (for Reference Only) | | | | | | | | | | |
| Mechanical Sizing | | Inside Diam (in) | Uninsulated Outside Diam (in) | | ID (in) | OD (in) | Thickness (in) | Designation | | Overall Height (ft) |
| Connections Size & Rating | In | 26 | 36 | Upper Shell | 46 | 48 | 1 | ASME VIII | | 25 |
| | Out | 18 | 28 | Inner Tube | 18 | | 4 | | | |
| | Bottom | | | Cone | | | 1 | ASME VIII | | |
| | | | | | Refractory | 38 | | 4 | | |
| Component Data | | | | | Cyclone Body Materials of Construction | | | | | |
| | Design Temperature (°F) | Solids Removal Flowrate (CFM) | Differential Design Pressure (psig) | Type | Upper Section | | Lower Conical section | | Nozzles | |
| Rotary Air Lock | 938 | 20.4 | 15 | | Inner Wall | Outer Shell | Inner Wall | Outer Shell | Inner Wall | Outer Shell |
| Level Indicator | 938 | | | | Cercast™ | MS | Cercast™ | MS | Cercast™ | MS |
| | | | | | Inner Tube | | | | | |
| | | | | | MS | | | | | |
| Vendor/Supplier Specifications and Price Quote | | | | | | | | | | |
| Fisher-Klosterman, Inc | | | | | (Refer to Vendor Communications and Data Sheets) | | | | | |
| Ryan Bruner, Sales Manager | | | | | | | | | | |
| P.O. Box 11190 | | | | | | | | | | |
| Louisville, Ky | | | | | | | | | | |
| Ph: 502-572-4000 ext 213 | | | | | | | | | | |
| Email: rab@fkinc.com | | | | | | | | | | |
| Recommendation: Quote Pending | | | | | | | | | | |
| Four (4) XQ120-48M cyclone assemblies each with the following Features: | | | | | | | | | | |
| Design, fabricated, tested, and stamped as an ASME vessel | | | | | Interior surfaces to be lined with 4" of Vesuvius Cercast 3300 castable refractory | | | | | |
| 3/8" plate carbon steel construction | | | | | All welding per FKI Class 3 procedures with 100% penetration | | | | | |
| Dust receiver section with flanged discharge | | | | | Exterior to be sandblasted and painted with high temperature aluminum paint | | | | | |
| 40"Ø gas inlet flange | | | | | Design pressure (psig) | | 460 | | | |
| 48"Ø verticle gas outlet flange | | | | | Design Temperature (F) | | 650 | | | |
| Approximate Overall Dimensions: | | | | | 4 ft.Ø x 17 ft tall | | | | | |
| Gas Conditions at Inlet: | | | | | Particulate Conditions at Inlet: | | | | | |
| Volume per cyclone (acfm) | | 7.289 | | Specific Gravity | | 1.000 | | | | |
| Density (lbm/ft3) | | 0.5679 | | Dust Loading (Grains/acf) | | 16 | | | | |
| Viscosity (lbm/ft-sec) | | 2.87E-05 | | | | | | | | |
| Inlet Velocity (ft/sec) | | 72.29 | | Fraction Efficiencies: Stokes Equiv. % Efficiency | | | | | | |
| No load pres. drop (in.W.C.) | | 120.63 | | Dia.(microns) | | Weight % | | | | |
| Full load pres. Drop (in. W.C.) | | 99.82 | | 2.5 | | 8.46 | | | | |
| | | | | 3 | | 13.57 | | | | |
| | | | | 3.5 | | 19.29 | | | | |
| | | | | 4 | | 25.27 | | | | |
| | | | | 4.5 | | 31.27 | | | | |
| | | | | 5 | | 37.1 | | | | |
| | | | | 5.5 | | 42.64 | | | | |
| | | | | 6 | | 47.84 | | | | |
| | | | | 7 | | 57.08 | | | | |
| | | | | 8 | | 64.8 | | | | |
| | | | | 9 | | 71.14 | | | | |
| | | | | 10 | | 76.31 | | | | |
| | | | | 12 | | 83.89 | | | | |
| | | | | 16 | | 90.07 | | | | |
| | | | | 21 | | 94.11 | | | | |
| | | | | 31 | | 97.52 | | | | |
| | | | | 101 | | 99.93 | | | | |
| Price (2005 U.S.\$) | | \$ 250,000.00 | | | | | | | | |
| Remarks: Inlet and outlet manifolding is not included in Fisher-Klosterman quote for these four cyclones. Estimated cost of splitter and collection is \$25,000. Refer to supplier data sheet for Vesuvius CERCAST™ 3300 Castable refractory. | | | | | | | | | | |

D.1 INTRODUCTION

The first task undertaken by the team was to examine commercial technologies that are suitable for synthesis gas cleanup for biomass gasification. Currently, there are various types of technologies available dependent upon the specific cleanup requirements. For example, the clean-up required for syngas that will ultimately be fed to a reciprocating engine is much less than for syngas used in chemical synthesis. This study examined all technologies that could be required for syngas that will be used for Fischer-Tropsch (FT) liquids and alcohol synthesis.

The gas cleanup configuration for a system is generally determined by the composition of the syngas exiting the gasifier, the cleanup requirements for the intended use of the syngas, and economic considerations. Technologies such as cyclone separators, barrier filters, and electrostatic precipitators are routinely used for solid particulate removal. Catalytic tar crackers are employed to destroy tars and nitrogen contaminants. Wet scrubbers are used to remove a number of contaminants such as particulates, alkali species, halides, soluble gases, and condensable liquids. Acid gas removal technologies encompass a large selection of processes including amine-based, physical solvent, liquid phase oxidation, and catalytic absorbent. Each section focuses on the operating size ranges and conditions, materials of construction, and cleanup parameters for each technology considered.

D.2 PARTICULATE REMOVAL TECHNOLOGIES

D.2.1 INTRODUCTION

During the gasification process, the mineral matter contained in the biomass feedstock will form inorganic ash, and the unconverted biomass will form char. These particulates are entrained in the syngas stream as it exits the gasifier. The concentration of particulates produced is often influenced by the gasifier design. These particulates can present emissions problem and can cause abrasion to downstream equipment. Therefore, the particulates concentration must be reduced using various technologies discussed in the following paragraphs.

Cyclone Separators

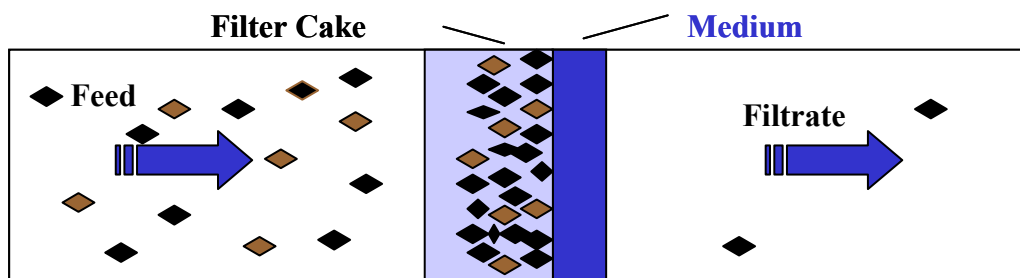
Cyclones use centrifugal forces to separate the bulk of large size particulates from a gas stream. In gasification systems, cyclones are normally used as the first step in the gas cleanup process. They are relatively inexpensive to manufacture and easy to operate which translate to low capital and maintenance costs. In general, 90-98% of particulates 10 μm or larger in diameter can be removed, but the removal efficiency decreases significantly for smaller particulates¹³. The removal efficiency also decreases as the operating temperatures increases. Cyclones are capable of handling operating temperatures up to 2000°F and can be designed to operate at pressures normally encountered in gasifiers. Cyclones are usually made from carbon steel and are refractory lined to withstand high temperature environments. A flow range from 300 to 13,000 CFM is typical for cyclones. This flow range is within the parameter of the syngas flow rate specified by NREL for this project.

¹³ Donaldson Co., Inc. "Cyclone Dust Collectors," July 2003, <<http://www.donaldson.com/en/industrialair/literature/000984.pdf>

D.2.2 BARRIER FILTERS

Barrier filters remove particulates by capturing the particulates on the filter surfaces as the gas stream passes through the filter medium. The particulates accumulated on the filter surfaces form a cake, which can be dislodged by initiating a blowback flow. The blowback gas flows in the reverse direction of normal process flow and dislodges the filter cake, which is then removed from the system. The operating principle of barrier filters is illustrated in Figure D-1. Barrier filters include high-temperature filters, such as ceramic and metal candle filters, and low-temperature filters, such as baghouse filters.

FIGURE D-1 PRINCIPLE OF BARRIER FILTERS



Ceramic Candle Filters

Ceramic filters are designed to remove particulate matter from gas streams at elevated temperatures. Ceramic filters can be designed for any flow requirement and can remove 90% of particulates larger than $0.3 \mu\text{m}$ ¹⁴. In theory, the ceramic filter elements, normally made of aluminosilicate or silicon carbide powder with a sodium aluminosilicate binder, have exceptional physical and thermal properties, and should be able to withstand high temperature operations of up to 1800°F. However, commercial operations using ceramic filters at this temperature range have not been successful due to the susceptibility of the filter elements to cracking. Advances in composite filter element materials that have resistance to crack propagation at high temperatures are being developed and tested¹⁵. At temperatures below 850°F, ceramic filters have demonstrated satisfactory operational reliability.

In operations where tars are formed in the gasifier, ceramic filters should be operated at temperatures above the dew point of the tars (usually about 700-750°F) to avoid tar condensation. Condensed tar accumulates on filter surfaces and leads to plugging which will reduce the lifetime of the filter and impact process flowrates.

Metal Candle Filters

Metal filters are used in high temperature cleanup systems to remove particulate matter and can achieve filtration level as low as $1 \mu\text{m}$. They can be designed to meet any flow requirement and can operate over a wide range of temperatures depending on the material of construction. Metal

¹⁴ Pall Corp., "Syngas Filter Proposal," 26 January 2005, office communication

¹⁵ Jay E. Lane, Jean-Francois LeCostaouec, "Ceramic Composite Hot Gas Filter Development," <http://www.netl.doe.gov/publications/proceedings/98/98ps/pspb-5.pdf>

filters made from stainless steel can be used in cleanup systems for temperatures below 650°F while Inconel or alloy HR filters are suitable for operating temperatures up to 1100°F. At even higher temperatures, Fercalloy can withstand temperatures up to 1800°F¹⁶, although commercial operation at this temperature has not been demonstrated. Commercial operation of metal filters operating at a maximum temperature of 915°F has been successful at a few gasification facilities in Europe¹⁷.

Some operational considerations for metal filters are the corrosion rate and tar deposition on filter elements. Under similar stream compositions and conditions, the corrosion rate of metal filter elements is ten times that of the surrounding piping; thus, a regular maintenance schedule is essential to ensure operational reliability. Additionally, in operations where filter elements are subjected to frequent cleaning cycles due to tar deposition, the lifetime of the filter will be reduced. Therefore, it is recommended that the filter be operated at a temperature above the dew point of the tars in the syngas stream to avoid tar condensation and deposition.

Baghouse Filters

Baghouse filters are made of a woven fabric or felted (non-woven) material to remove particulate matter from an air or gas stream and can remove particulates down to 2.5 μm ¹⁸. For woven fabric filters, the removal efficiency increases as the thickness of filter cake increases; thus, the removal efficiency of these systems is constantly changing. Felted filter systems have a constant removal efficiency that does not depend on the thickness of the filter cake¹⁹. Baghouse filters are modular in design and thus can accommodate a wide flow range from 1,500 to 150,000 CFM. The air-to-cloth ratio, or ratio of the volumetric flow to cloth area, sets the size of a baghouse unit. The bag fabric can be made from various materials including polyester, acrylic, NOMEX, Teflon, Ryton, and fiberglass²⁰. The operating temperature range of an application influences the selection of bag material. For example, materials such as polyester or acrylic are suitable for applications with operating temperatures below 300°F, while NOMEX, Teflon, Ryton, or fiberglass is recommended for temperatures up to 500°F. Due to the temperature limits of the filter fabric, baghouse filters are only used in the low-temperature cleanup systems. They are often used downstream of the cyclones so that the particulate loading on the filters can be reduced.

Disadvantages of baghouse filters include the need for periodic bag replacement that can result in high maintenance costs and the potential for bag fire or explosion. A spark detection and extinguishment system, along with bag grounding strips, are recommended safety measures to mitigate the fire potential. Additionally, the performance of the filter fabrics degrades drastically with tar deposition on the fabric surface, so fabric surface treatments such as Teflon coating and pre-coating with limestone or other compatible filter aids is recommended. Such pre-coats can

¹⁶ Mott Corp., "Fiber Metal. The High-Flow, Low-Pressure Drop Alternative," June 2003, <http://www.mottcorp.com/resource/pdf/PSFIBERfinal.pdf>

¹⁷ Mike Wilson, Mott Corp., "Fercalloy Metal Filters," 2 February 2005, Vendor input

¹⁸ Donaldson Co., Inc. "Dalamatric Dust Collectors," December 2002, <http://www.donaldson.com/en/industrialair/literature/000983.pdf>

¹⁹ EPA, "Air Pollution Technology Fact Sheet-Fabric Filter – Pulse-Jet Cleaned Type," http://www.macrotek.net/pdf/FS_Pulse_Clean_Dust_Collector.pdf

²⁰ Ducon, "Baghouse Filter," 2003, <http://www.ducon.com/bag-house-filter.php>

also be used to adsorb mercury and other contaminants.. Industry experience suggests that either ceramic or metal filters should be used in place of baghouse filters in high temperature operations.

D.2.3 ELECTROSTATIC PRECIPITATORS (ESPs)

ESPs are commonly used in large power plants to control fly ash emissions. ESPs consist of discharge electrodes centered between positively grounded collection plates. As the gas stream laden with particulates passes through the ESP, the discharge electrodes provide a negative charge to the particulates. The positively grounded collection plates act as a magnet for the negatively charged particulates, which collect on the plates. The collected particulates are transported into the collection hopper by the rapper or vibrator system.

ESPs are classified as either wet or dry processes. In wet ESPs, a water quench is applied either intermittently or continuously to the collection plates. The purpose of the water quench is to prevent possible fires that have occasionally resulted from the use of dry ESPs. The wastewater from wet ESPs must be treated prior to disposal.

For dry ESPs, the removal efficiency decreases for particulates with a high electrical resistivity since these particulates can introduce positive ions into the gas space resulting in reduced attraction of the negatively charged particulates to the collection plates. Particulates with a high resistivity are commonly produced from combustion of low-sulfur coals. Flow ranges of 10,000 – 300,000 CFM are typical for dry ESPs. Dry ESPs operate in the pressure range from vacuum conditions up to 150 psi and can operate at temperatures up to 750°F²¹.

Wet ESPs can achieve 99.9% removal of sub-micron particulates down to 0.01 µm. Particulate resistivity does not affect removal efficiency of wet ESPs since the humid operating environment often reduces the resistivity of particulates. These systems are generally designed for gas flow range from 1,000 to 100,000 CFM. Gas streams with particulate sizes larger than 2 µm or with an exceptionally high particulate loading should be pretreated to reduce the load on the ESP. Wet ESPs operate in the pressure range from vacuum conditions up to 150 psi, with operating temperatures limited to 170-190°F^{22,23}.

The type of ESP selected for an application is largely influenced by the operating parameter and the type of particulates to be removed. However, the use of ESPs is limited in gasification systems due to the significant capital costs compared to other systems. Additionally, the removal efficiency of ESPs is sensitive to fluctuations in process conditions, such as changes in temperatures and pressures, gas compositions, and particulate loading. Therefore, ESPs are not suitable for biomass gasification applications that have highly variable syngas compositions from different feedstocks.

²¹ Gerry Graham, "Controlling Stack Emissions in the Wood Products Industry," <http://www.ppcesp.com/ppcart.html>

²² Ducon, "Wet & Dry Electrostatic Precipitators," 2003, <http://www.ducon.com/wet-dry-precipitators.php> (24 January 2005)

²³ EPA, "Air Pollution Technology Fact Sheet-Wet Electrostatic Precipitator (ESP)-Wire-Pipe Type," <http://www.p2pays.org/ref/10/09890.pdf> (25 January 2005)

D.3 TAR REMOVAL TECHNOLOGIES

D.3.1 INTRODUCTION

Following NREL guidelines for the purpose of this project, tar is defined as C10+ hydrocarbons. Tar in syngas products can cause serious operational problems when the syngas stream cools below the dew point of the tars (usually about 700-750°F) and tar deposition occurs on downstream equipment and piping. Thus, tar removal is critical when there is tar present in the syngas. Tar can be removed either by physical or chemical processes. The most common physical process involves cooling the syngas stream to condense the tar into fine droplets and removing these droplets by wet scrubbing. Chemical process involves catalytic steam reforming of tars to lighter gases.

D.3.2 WET SCRUBBERS

Wet scrubbing is generally used to remove water-soluble contaminants from the syngas by absorption into a solvent. Tar components are water-soluble can be removed by this method. Additionally, wet scrubbing is also often used to remove a number of other contaminants such as particulates, alkali species, halides, soluble gases, and condensable liquids. In wet scrubbing, water is a common solvent choice. Wet scrubbers with the venturi design are frequently used in gas cleanup applications to achieve sub-micron particulate removal requirements. As the gas stream enters the venturi scrubber, the scrubbing liquid is sprayed into the gas stream. The two streams are thoroughly mixed by the turbulence in the venturi throat section where fine particles are impacted and agglomerate into liquid droplets. The liquid droplets are separated from the gas stream in a separator unit consisting of a cyclone separator or a mist eliminator.

Venturi scrubbers can achieve 99.9% removal efficiency of sub-micron particulates. Flow range for a single-throat venturi is 500-100,000 SCFM. Flows above this range require either multiple venturi scrubbers in series or a multiple-throat venturi²⁴. Venturi scrubbers with a quench section can accommodate high temperature gas streams up to 450°F, and they can operate over a wide range of pressures²⁵.

The standard material of construction for venturi scrubbers is carbon steel. For corrosive or high temperature applications, stainless steel or special alloys such as FRP (fiberglass reinforced plastic) and Inconel are used.

The disadvantages of scrubbers include high pressure drop, the need to treat the wastewater effluent prior to disposal, and the loss of sensible heat of the syngas due to quenching. In power generation applications, the loss of sensible heat reduces the energy content of the gas and thus is undesirable; however, it is less of a concern in biomass refinery applications. Nevertheless, sensible heat loss will result in reduced overall system efficiency.

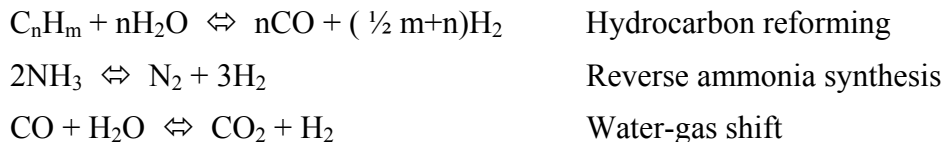
²⁴ EPA, "Air Pollution Technology Fact Sheet-Venturi Scrubber" <http://www.macrotek.net/pdf/FS_Venturi_Scrubber.pdf

²⁵ Envitech, Inc., "Venturi Scrubber," <<http://www.envitechinc.com/scrubber.zhtml>

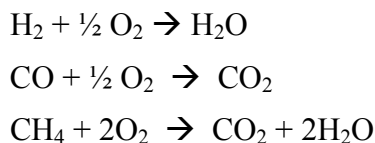
D.3.3 CATALYTIC TAR REFORMING

Catalytic reforming of biomass tars is a developing technology for tar removal from syngas streams. The concept of this technology is to reform tar in a fluidized reactor bed, or tar cracker, into lighter gases using a proprietary catalyst. In addition to tar, light hydrocarbons (C1 to C5), benzene, and ammonia are also removed. A few large-scale biomass gasification facilities, such as Carbona in Denmark and the FERCO gasifier in Vermont, have demonstrated a novel catalyst in their tar crackers since commercial catalysts are too friable for this application²⁶. The FERCO tar cracker removed 90% of the tar in the syngas stream using a novel catalyst known as DN34²⁷. In both of these processes, a wet scrubber was used downstream of the tar cracker to remove residual tars and impurities.

A tar cracker known as the Reverse Flow Tar Cracking (RFTC) reactor developed by BTG uses the steam reforming process with a commercial nickel catalyst²⁸. The nickel catalyst is very sensitive to sulfur impurities; therefore, a syngas stream containing sulfur contaminants has to be desulfurized prior to entering the RFTC reactor. Due to the cooling requirement for the desulfurization process, the syngas is fed to the reactor at a temperature from 660 -1200°F and is heated to the reaction temperature of 1650 -1740°F in the reactor entrance section. The heated gas passes through a bed of nickel catalyst where tar, light hydrocarbons, and ammonia are removed by steam reforming. The main reactions of the RFTC reactor are:



A small amount of the syngas is combusted to counterbalance the endothermic tar reforming reactions:



The typical conversion for the RFTC reactor is as follows:

| <u>Components</u> | <u>Conversion</u> |
|-------------------|-------------------|
| Benzene | 82 |
| Napthalene | 99 |
| Phenol | 96 |
| Total Aromatic | 94 |
| Total Phenols | 98 |
| Total Tar | 96 |
| Ammonia | 99 |

²⁶ Don J. Stevens, "Hot Gas Conditioning: Recent Progress with Larger-Scale Biomass Gasification Systems," prepared by Pacific Northwest National Laboratory for NREL, August, 2001

²⁷ Mark A. Paisley, Mike J. Welch, "Biomass Gasification Combined Cycle Opportunities Using the Future Energy *Silva* Gas Gasifier Coupled to Alstrom's Industrial Gas Turbines," ASME Turbo Expo Land, Sea, and Air, Georgia World Congress Center, June 16-19, 2003

²⁸ BTG Biomass Technology Group, "Tar & Tar Removal," 22 March 2004, <http://www.btgworld.com/technologies/tar-removal.html>

The partial oxidation reaction (POx) was also investigated as a possible process for tar and hydrocarbons removal. In this process, the syngas enters the POx reactor and mixes with oxygen that is at about 300°F. Partial oxidation and reforming reactions occur in a combustion zone where tar, methane, light hydrocarbons, and benzene are converted to CO and H₂. The reformed gas exits the reactor at about 2500°F.

The main disadvantage of POx is a reduction of the product gas heating value. In order to achieve destruction of the tars and oils, a high temperature reactor is required. While it is possible to crack the tars and oils at moderate temperatures, it is very difficult to selectively react methane. However at high temperatures oxidation of CO and H₂ also occur. As a result, the gas composition will be shifted toward a lower H₂:CO ratio.

In order to improve the efficiency of POx, a catalyst can be used to lower the temperature, and hence also the amount of oxidizer required to destroy the tars and oils. A catalytic auto-reformer technology may provide a solution to biomass tar and oil elimination. Such an application would only apply to a particulate-free gas since any particulate in the gas could shortly blind the catalytic reactor. As shown in Table D-1 below, an auto-thermal reformer is essentially a hybrid between POx and steam reforming.

TABLE D-1 COMPARISON OF SYNGAS REFORMING PROCESS TECHNOLOGY

| Gas Reforming Process | Typical H ₂ /CO ratio | Comments |
|-------------------------------------|----------------------------------|---|
| Tar Cracking/Reforming | wide range | Developing technology. Operating information not widely available. |
| Steam (Methane) Reforming SR or SMR | 3-4 | Dominant technology for industrial H ₂ production Typically high efficiency |
| Partial Oxidation (POx) | 1.7-1.8 | Used in refining to upgrade heavy liquid fuels Low efficiency May generate coke or soot |
| Auto-thermal Reforming (ATR) | 2.4-4 | Hybrid of POx and SR |

D.4 ACID GAS REMOVAL TECHNOLOGIES

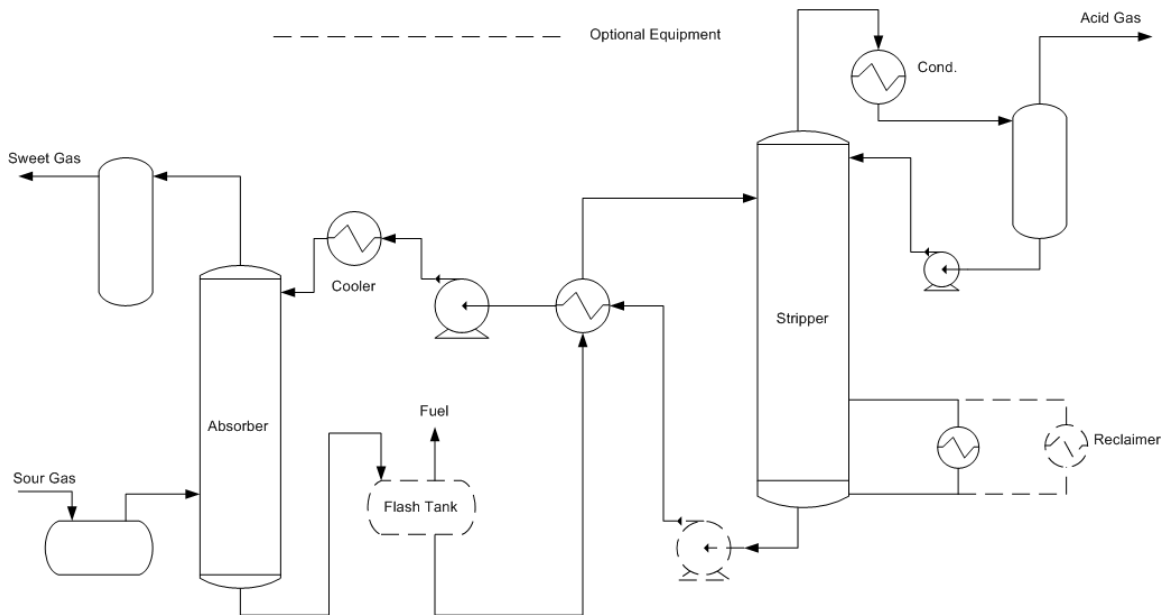
D.4.1 INTRODUCTION

Sulfur contaminants such as H₂S, COS, CO₂, mercaptans, and HCN poison catalysts used in liquid fuel synthesis. Therefore, the syntheses of methanol and FT liquids from syngas require that the sulfur be removed from the syngas to a residual level of 0.10 ppm or less. The syngas considered for this study contains approximately 400 ppmv of H₂S; therefore, acid gas removal is critical in the gas cleanup process. Acid gas removal technologies can be categorized as amine-based, physical solvent, liquid phase oxidation, or catalytic absorbent processes. The type of technology selected is largely influenced by the system operating conditions, the sulfur level in the syngas stream, and the desired purity of the treated syngas. Brief descriptions to explain the overall process for each system are given in the following paragraphs.

D.4.2 AMINE-BASED SYSTEM

Amine processes are proven technologies for the removal of H₂S and CO₂ from gas streams by absorption. Amine systems generally consist of an absorber, a stripper column, a flash separator, and heat exchangers. This is a low-temperature process in which the gas to be treated usually enters the absorber at approximately 110°F. In the absorber, acid gases are removed from the gas stream by chemical reactions with the amine solution. The sweet gas stream exits at the top of the absorber. Regeneration of the rich amine is accomplished through the flash separator to remove absorbed hydrocarbons followed by a stripper column to remove the H₂S and CO₂ from the amine solution. The lean amine solution is cooled and returned to the absorber. The stripped acid gas stream is cooled to recover water and then sent to a sulfur recovery unit. A typical amine system is shown in Figure D-2.

FIGURE D-2 TYPICAL AMINE SYSTEM FLOW DIAGRAM



Amine systems normally operate in the low to medium pressure range of 70-360 psi, although higher pressures can be accommodated with a specific amine solvent. However, in applications where the partial pressure of acid gases is high, the economy of an amine system declines in comparison to other systems. Amine systems can be designed to meet specific flow range and sulfur removal requirements. A sulfur removal level as low as 1 ppm can be achieved but at the expense of operating cost due to the large solvent circulation rate required²⁹.

There are a variety of amine solutions available. Each offers distinct advantages based on the specific treating condition. Commercially available amine solutions include³⁰:

²⁹ Input from GTI, "Gas Cleanup Technologies Discussion," 3 February 2005, office communication

³⁰ GPSA

MEA – Monoethanolamine removes both H₂S and CO₂ from gas streams and is generally used in low-pressure systems and in operations requiring stringent sulfur removal.

DGA – Diglycolamine is used when there is a need for COS and mercaptan removal in addition to H₂S. DGA can hydrolyze COS to H₂S; thus, a COS hydrolysis unit is not needed in the cleanup system.

DEA - Diethanolamine is used in medium- to high-pressure systems (above 500 psi) and is suitable for gas stream with a high ratio of H₂S to CO₂.

MDEA - Methyldiethanolamine has a higher affinity for H₂S than CO₂. MDEA is used when there is a low ratio of H₂S to CO₂ in the gas stream so that the H₂S can be concentrated in the acid gas effluent. If a Claus plant is used for sulfur recovery, a relatively high concentration of H₂S (>15%) in the acid gas effluent is required for optimal Claus operation.

After prolonged use, MEA, DGA, and MDEA solutions accumulate impurities that reduce the H₂S removal efficiency of the solutions. A reclaim unit is needed to remove the impurities in order to improve system efficiency.

One major operating concern for amine systems is corrosion. In water, H₂S dissociates to form a weak acid while CO₂ forms carbonic acid. These acids attack and corrode metal. Therefore, equipment in the amine systems may be clad with stainless steel to improve equipment life.

D.4.3 PHYSICAL SOLVENT SYSTEM

This acid gas removal technology uses an organic solvent to remove acid gases from gas streams by physical absorption without chemical reaction. The driving force of this process is the high solubility of acid gases in the organic solvent. In most cases, solubility increases as the temperature decreases and the pressure increases. Thus, physical absorption is a low-temperature, high-pressure process, with high partial pressure of acid gases required for the economy and efficiency of this process. The temperature of the solvent should be as low as possible while the temperature of the gas to be treated usually enters the absorber at about 100°F. Physical solvent systems normally operate at pressures above 150 psi³¹.

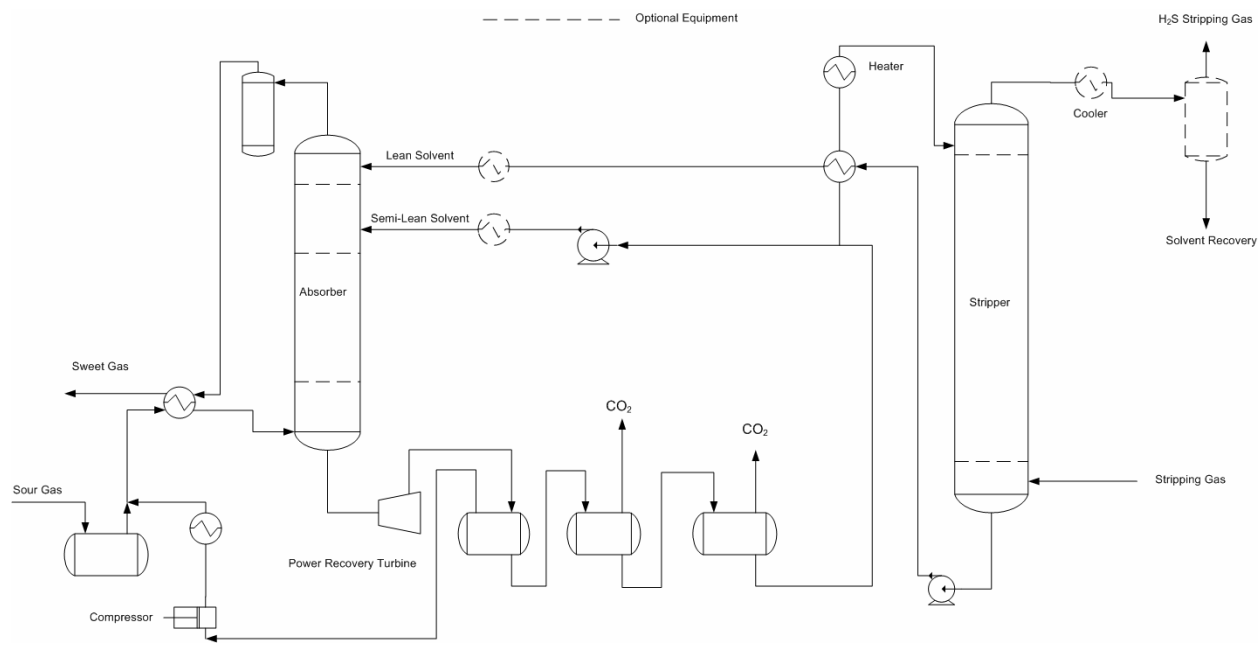
In general, physical solvent systems consist of an absorber, a stripper column, a series of flash separators, and heat exchangers. In the absorber, acid gases in the syngas stream are absorbed into the solvent solution. The sweet syngas stream exits the top of the absorber. Regeneration of the rich solvent stream is accomplished through a series of flash separators at reduced pressures to remove absorbed hydrocarbons followed by the stripper column to remove the acid gases from the solvent. The lean solvent solution is cooled and returned to the absorber. The stripped acid gas stream is cooled to recover water and then sent to a sulfur recovery unit. A typical physical solvent system is shown in Figure D-3.

³¹ Gerhard Ranke, "Advantages of the Rectisol-Wash Process in Selective H₂S Removal from Gas Mixtures," 1973, office communication, 30 January 2005

The two common physical systems are Rectisol and Selexol. The Rectisol process, which uses methanol at temperatures $< 32^{\circ}\text{F}$, can achieve a sulfur removal level as low as 0.1 ppm. The Selexol process, which uses mixtures of dimethyl ethers of polyethylene glycol, can achieve a sulfur removal level of 1 ppm³².

Selection of material of construction depends on the solvent used. For example, stainless steel is required for much of the Rectisol process equipment, contributing to a significant capital cost. In the Selexol process, carbon steel is the standard material of construction, except for those areas with high severity where stainless steel will be used.

FIGURE D-3 TYPICAL PHYSICAL SOLVENT SYSTEM FLOW DIAGRAM



D.4.4 LIQUID PHASE OXIDATION PROCESS -- LO-CAT™

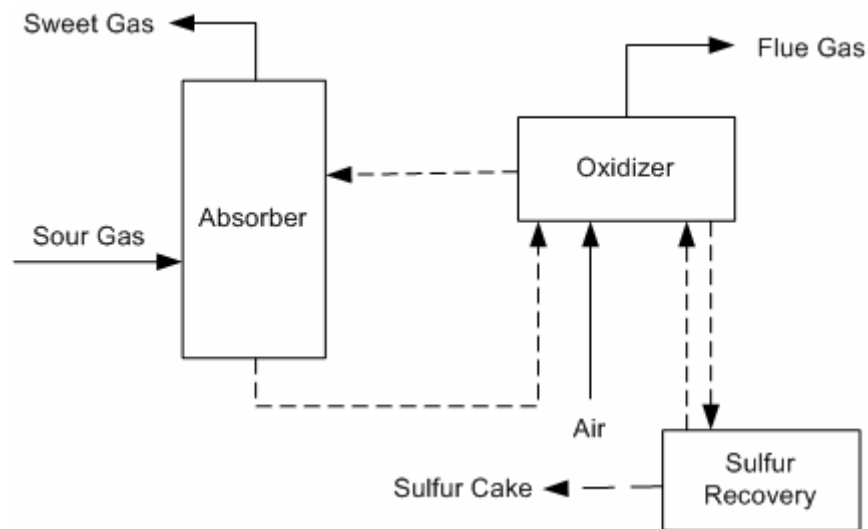
LO-CAT™ is an oxidation process that uses iron catalyst held in a chelating agent to oxidize H_2S to elemental sulfur. H_2S is the only acid gas being removed in this process but a high CO_2 concentration in the feedgas requires caustic for pH adjustment. A LO-CAT™ process consists of 3 sections that include an absorber, an oxidizer for catalyst regeneration, and a sulfur handling unit. Figure D-4 illustrates a typical LO-CAT™ unit. When the gas stream comes in contact with the LO-CAT™ solution in the absorber, H_2S in the gas stream is converted to elemental sulfur. The spent catalyst along with the elemental sulfur exit the absorber, then enter the oxidizer where the spent catalyst is regenerated by contact with oxygen in air, and the elemental sulfur is concentrated into a sulfur slurry. The sulfur slurry moves to the sulfur handling unit where it is washed to recover any entrained catalyst. The sulfur recovered from a LO-CAT™

³² D.J. Kubek, E. Polla, F.P. Wilcher, "Purification and Recovery for Gasification," Gasification Technologies Conference, October 1996, San Francisco, CA.

process contains a small amount of entrained residual catalyst and is considered low-value sulfur that is suitable for agricultural purposes but is undesirable as a chemical feedstock.

The LO-CAT™ process is suitable for small-scale applications that require less than 20 TPD of sulfur recovery capacity, making the LO-CAT™ a candidate process for this study, which has less than 5 TPD of sulfur recovery. This process can achieve 99.9%+ of H₂S removal efficiency³³. This process can operate over a wide range of pressures from atmospheric up to 600 psi, but most are low-pressure applications in amine acid gas service. The operating temperature is normally maintained at about 110°F since high temperatures degrade the LO-CAT™ solution that can affect removal efficiency. Advantages of this process include the ability to treat a wide range of gas compositions, a significant turndown flexibility, and less capital costs in comparison to the Claus process with the associated tail gas treating unit.

FIGURE D-4 TYPICAL LO-CAT™ SYSTEM FLOW DIAGRAM



Since LO-CAT™ only removes H₂S, a COS hydrolysis unit upstream of the LO-CAT™ is needed to hydrolyze any COS in the gas stream to H₂S. Other acid gases, such as HCN and mercaptans, would have to be removed by wet scrubbing.

The standard material used for LO-CAT™ systems is stainless steel. Under certain conditions where there is build-up of chloride ions from the feed gas, FRP (fiberglass reinforced plastic) material is used to provide added stability for the stainless steel components³⁴.

D.4.5 CATALYTIC ABSORBENT—ZnO

ZnO is often used as a polishing step for sulfur removal in gas streams where the sulfur level is below 20 ppmv. In a traditional purification system, illustrated in Figure D-5, ZnO is used in

³³ Douglas L. Heguy, Gary J. Nagl, "The State of Iron Redox Sulfur Plant Technology New Developments to an Established Technology," <http://www.gtpmerichem.com/support/technical_papers/state_of_iron_redox.html> (25 January 2005)

³⁴ GTP-Merichem, "FAQ's About Sulfur Removal and Recovery Using the LO-CAT System," <<http://www.gtp-merichem.com/support/faq.html>> (25 January 2005)

conjunction with hydrogenation catalysts based on cobalt, molybdenum and nickel. This system involves the hydrogenation of sulfur compounds such as mercaptans to H₂S, and halides such as chlorides to HCl. These compounds are then reacted with the ZnO absorbent where H₂S is converted to zinc sulfide, and HCl forms a stable chloride. Additionally, ZnO also removes COS by hydrolysis to form H₂S which is then adsorbed to form zinc sulfide. The general reactions are summarized below³⁵:

Hydrogenation reactions:



Reaction with ZnO:

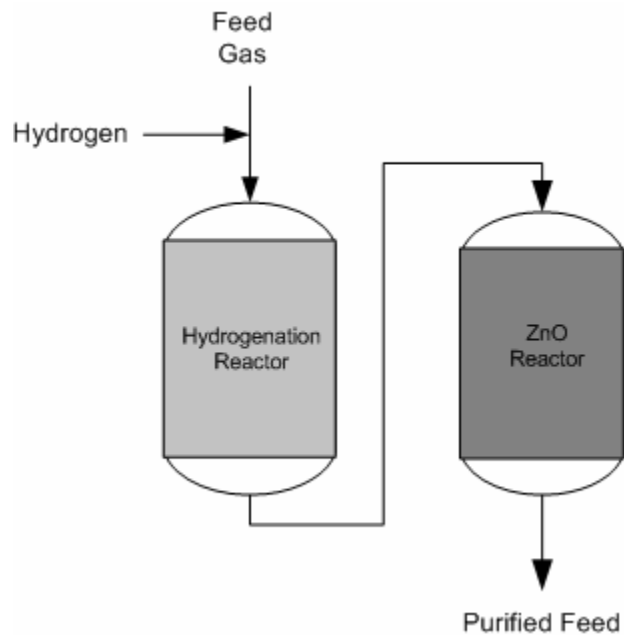
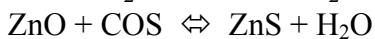


FIGURE D-5 TRADITIONAL ZNO PURIFICATION SYSTEM

A sulfur removal below 50 ppb is attainable with ZnO³⁶. Since the sulfur specifications for alcohols and FT liquids are 0.10 ppm or less, ZnO will be used to achieve these requirements. However, a hydrogenation reactor will not likely be required since the syngas stream given by NREL does not contain halogens or any other sulfur compounds other than H₂S.

³⁵ Johnson Matthey Group, "Purification Catalysts and Absorbents for Hydrogen Production," available at <http://www.jmcatlysts.com> (25 January 2005)

³⁶ Johnson Matthey Group, "Absorbent for Sulphur Polishing," available at <http://www.jmcatlysts.com> (25 January 2005)

ZnO is active over a wide range of temperatures from ambient to 750°F; however, operating temperatures range between 660°F and 750°F are normally used to maximize absorption efficiency. Operating pressure limits are not a concern for the use of ZnO absorbent. The ZnO reactor is normally constructed from carbon steel clad with stainless steel to prevent corrosion caused by acid gases.

One drawback of this process is the significant operating costs contributed by frequent replacement and disposal of ZnO absorbent since it cannot be regenerated.

D.4.6 COS HYDROLYSIS

COS can be removed simultaneously with H₂S and other acid gases in some of the acid gas removal processes described above. In chemical absorption processes, the degree of COS removal is dependent upon the reactivity of the solvent solution with COS. For example, DGA can remove virtually all of the COS whereas MDEA has little reactivity with COS. In physical absorption processes, the solubility of COS in the physical solvent and the COS partial pressure determine the level of removal. A COS level of 0.1 ppm is attainable with the Rectisol process while the Selexol process can achieve 10 ppm COS³⁷. In the ZnO process, approximately 80% of the COS can be removed by hydrolysis.

When COS cannot be effectively removed by the conventional acid gas removal processes, a COS hydrolysis reactor is required and is placed upstream of the acid gas removal unit. COS removal is accomplished by hydrolysis of COS on a catalyst to form H₂S which is sent to the downstream acid gas removal unit. Activated alumina catalysts are often used in these applications. COS removal to 0.1 ppm or below can be achieved³⁸. COS hydrolysis reactors can operate over a wide range of pressures with temperatures in the range of 100°F – 450°F. The COS hydrolysis reactor is normally constructed from carbon steel clad with stainless steel to prevent corrosion caused by acid gases.

D.4.7 SULFUR RECOVERY UNIT (SRU)

In the sulfur recovery unit, the acid gas stream from the amine or physical solvent unit is recovered to elemental sulfur. In operations where the sulfur recovery is more than 20 TPD, a Claus SRU is generally an economical approach. However, since the amount of sulfur in the syngas for this study is small (< 5 TPD), a Claus operation would not be a cost-effective solution. For a low sulfur recovery capacity, a LO-CAT SRU would be a more suitable process.

D.5 AMMONIA, ALKALI, AND OTHER CONTAMINANTS

D.5.1 AMMONIA REMOVAL

Two methods for removing ammonia include catalytic tar reforming and wet scrubbing. Tar cracker catalysts have been demonstrated to be effective at reducing ammonia in the syngas stream by conversion to N₂ and H₂. A tar cracker can be used to remove ammonia followed by

³⁷ Robert Chu, Senior Design Engineer, Nexant, "COS Removal," office communication, 17 February 2005

³⁸ United Catalysts Inc., "UCI COS Hydrolysis Catalysts," 22 June 1992, and office communication, 17 February 2005

gas cooling and a wet scrubber to remove residual ammonia. This cleanup configuration should achieve complete removal of ammonia.

D.5.2 ALKALI REMOVAL

Alkali removal is normally accomplished by cooling the syngas stream below 1100°F to allow condensation of alkali species followed by barrier filtration or wet scrubbing. Corrosion potential should be taken into consideration when using metal or ceramic candle filters due to possible reactions between the alkali and filter materials at high temperatures. Several demonstration facilities had used barrier filters to remove alkali along with other impurities. For example, ceramic filters were used at the Lahti facility in Finland and Varnamo in Sweden^{39, 40}. The Varnamo facility experienced breakage of the ceramic filter elements and replaced them with sintered metal filters, which operated successfully. Baghouse filters were used in Lahti's low-pressure gasification system and the FERCO facility in Vermont.

Alkali can easily be removed by wet scrubbing, thus it is often the preferred method for alkali removal. Descriptions of operating and cleanup parameters for barrier filters and wet scrubbing are given earlier in this Appendix.

D.5.3 REMOVAL OF OTHER CONTAMINANTS

Contaminants such as halides or metals (i.e. nickel or iron) are not typical, but may exist in syngas produced from biomass gasification. If present, these impurities can be removed by wet scrubbing or purification by hydrogenation and ZnO absorption.

³⁹ OPET Finland, OPET Report 4 "Review of Finnish Biomass Gasification Technologies," May 2002

⁴⁰ Krister Stahl, et al. "Biomass IGCC at Varnamo, Sweden-Past and Future," GCEP Energy Workshop, 27 April 2004, Stanford University, CA.

REPORT DOCUMENTATION PAGE

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|---|------------------------------------|---|--|--|--|
| 1. REPORT DATE (DD-MM-YYYY) May 2006 | | 2. REPORT TYPE Subcontract Report | | 3. DATES COVERED (From - To) | |
| 4. TITLE AND SUBTITLE Equipment Design and Cost Estimation for Small Modular Biomass Systems, Synthesis Gas Cleanup, and Oxygen Separation Equipment; Task 2: Gas Cleanup Design and Cost Estimates – Wood Feedstock | | | 5a. CONTRACT NUMBER DE-AC36-99-GO10337 | | |
| | | | 5b. GRANT NUMBER | | |
| | | | 5c. PROGRAM ELEMENT NUMBER | | |
| 6. AUTHOR(S) Nexant Inc. | | | 5d. PROJECT NUMBER NREL/SR-510-39945 | | |
| | | | 5e. TASK NUMBER BB06.3710 | | |
| | | | 5f. WORK UNIT NUMBER | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Nexant Inc. 101 Second St., 11 th Floor San Francisco, CA 94105 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER ACO-5-44027 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393 | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) NREL | |
| | | | | 11. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/SR-510-39945 | |
| 12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161 | | | | | |
| 13. SUPPLEMENTARY NOTES NREL Technical Monitor: Kelly Ibsen | | | | | |
| 14. ABSTRACT (Maximum 200 Words) As part of Task 2, Gas Cleanup and Cost Estimates, Nexant investigated the appropriate process scheme for treatment of wood-derived syngas for use in the synthesis of liquid fuels. Two different 2,000 metric tonne per day gasification schemes, a low-pressure, indirect system using the gasifier, and a high-pressure, direct system using gasification technology were evaluated. Initial syngas conditions from each of the gasifiers was provided to the team by the National Renewable Energy Laboratory. Nexant was the prime contractor and principal investigator during this task; technical assistance was provided by both GTI and Emery Energy. | | | | | |
| 15. SUBJECT TERMS biomass; Nexant; small modular; synthesis gas; syngas; fluidized catalytic cracking; steam methane reforming; natural gas liquids expanders; scaling; wood; National Renewable Energy Laboratory; NREL | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT UL | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT Unclassified | b. ABSTRACT Unclassified | c. THIS PAGE Unclassified | | | 19b. TELEPHONE NUMBER (Include area code) |

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18