# FINAL REPORT

## U.S. Department of Energy (DOE)
## National Energy Technology Laboratory (NETL)

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**PROJECT TITLE**

# Enabling Staged Pressurized Oxy-Combustion: Improving Flexibility and Performance at Reduced Cost

**WORK PERFORMED UNDER AGREEMENT**

DE-FE0029087

**SUBMITTED BY**

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Submission Date: July 31, 2019

Project Period of Performance: October 1, 2016 – April 30, 2019

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| Abbreviation | Meaning | Abbreviation | Meaning |
|---|---|---|---|
| AACE | Association for the Advancement of Cost Engineering International | LCOE | levelized cost of electricity |
| AL | Air Liquide, Inc. | LHV | lower heating value |
| ASME | American Society of Mechanical Engineers | LOx | liquid oxygen |
| ASU | air separation unit | LP | low pressure |
| BAC | booster air compressor | MAC | main air compressor |
| BEC | bare erected cost | MCR | maximum continuous rating |
| BFW | boiler feedwater | NETL | National Energy Technology Laboratory |
| BOP | balance-of-plant | NFPA | National Fire Protection Agency |
| CAPEX | capital expenditure | OC | operating costs (FIX – fixed, VAR – variable) |
| CCF | capital charge factor | O&M | operations and maintenance |
| CCS | carbon capture and storage | OEM | original equipment manufacturer |
| CEPCI | Chemical Engineering Plant Cost Index | OPEX | operational expenditure |
| CF | capacity factor | PC | pulverized coal |
| CFD | computational fluid dynamics | PCC | post-combustion capture |
| COE | cost of electricity | PM | particulate matter |
| CPU | $CO_2$ compression and purification unit | PRB | Powder River Basin (sub-bituminous coal) |
| DCC | direct-contact cooler | PSFM | Power Systems Financial Model |
| DOE | Department of Energy | PV | pressure vessel |
| DBL | Doosan Babcock Limited | QGESS | Quality Guidelines for Energy System Studies |
| EAF | equipment availability factor | R&D | research and development |
| ELPI | Electrical Low-Pressure Impactor | SC | supercritical |
| EOR | enhanced oil recovery | SLPM | standard litre per minute |
| EPC | engineering, procurement, and construction | SMPS | Scanning Mobility Particle Sizer |
| EPRI | Electric Power Research Institute, Inc. | SPOC | Staged, Pressurized Oxy-combustion |
| FC | fixed costs | SR | stoichiometric ratio |
| FGR | flue gas recycle | TAG | Technical Assessment Guide |
| GAN | gaseous nitrogen | TASC | total as-spent capital |
| GOx | gaseous oxygen | TGA | thermogravimetric analysis |
| HHV | higher heating value | TOC | total overnight costs |

| Abbreviation | Meaning | Abbreviation | Meaning |
|---|---|---|---|
| HP | high pressure | TPC | total plant costs |
| ID | induced draft | TPD | tonnes per day |
| IGCC | integrated gasification combined cycle | T&S | transportation and storage |
| IOU | Investor-owned utility | WUSTL | Washington University in St. Louis |
| IP | intermediate pressure | | |

## Units

| Quantity | S.I. (cgs) | Description | English | Description |
|---|---|---|---|---|
| Length | m | metre | ft | foot |
| | mm | millimetre | in | inch |
| Area | $m^2$ | square metre | $ft^2$ | square foot |
| Volume | $m^3$ | cubic metre | $ft^3$ | cubic foot |
| | $Nm^3$ | normal $m^3$ (at 0°C/1atm) | SCF | standard cubic foot |
| Temperature | °C | degrees Celsius | °F | degrees Fahrenheit |
| Mass | kg | kilogram | lb | pound mass |
| | tonne | metric tonne (1000 kg) | ton | Short tonne (2000 lb) |
| Pressure | bara | bar absolute (0.1 MPa) | psia | pounds force per square inch |
| Energy | kJ | kilojoule | Btu | British thermal unit |
| Energy Flow | W | Watt (Joule/second) | Btu/hr | British thermal unit per hour |
| | kW | 1000 W | MMBtu/hr | Million Btu/hr |
| | MW | 1000 kW | | |
| | GJ/hr | gigajoules/hr | | |
| Properties | kJ/kg | energy content | Btu/lb | energy content |
| | $m^3$/kg | specific volume | $ft^3$/lb | specific volume |
| | kJ/kgK | specific heat content | Btu/lb°F | specific heat content |
| | W/mK | thermal conductivity | Btu/hr ft °F | thermal conductivity |
| | μPa-s | fluid viscosity | lbf-s/$ft^2$ | fluid viscosity |
| Composition | vol % | by volume | | |
| | wt % | by weight (mass) | | |

## Chemical Formula

| Formula | Name | Formula | Name |
|---|---|---|---|
| Ar | argon | $N_2$ | nitrogen |
| CO | carbon monoxide | NOx | nitrogen oxides |
| $CO_2$ | carbon dioxide | $O_2$ | oxygen |
| $H_2O$ | water/steam | SOx | sulfur oxides |

# EXECUTIVE SUMMARY

## Introduction and Objective

The staged pressurized oxy-combustion (SPOC) process, developed by Washington University in St. Louis (WUSTL), is an oxy-combustion carbon capture technology that employs a steam power cycle to generate electricity. As with atmospheric-pressure oxy-combustion processes, carbon dioxide ($CO_2$) capture rates of 90% or higher can be achieved. The staged-combustion approach of the SPOC process, when operated at elevated gas pressure, allows for near elimination of flue gas recycle (FGR) and leads to significant improvements in efficiency and reduced costs.

The primary goal of this project was to investigate the potential for SPOC for flexible operation beyond the capabilities of conventional coal-fired power plants, particularly those employing carbon capture and storage (CCS). Oxy-combustion differs from conventional coal combustion in that the combustion of coal is carried out using oxygen as opposed to air. The resultant flue gas is a mixture of primarily $CO_2$ and water, greatly simplifying $CO_2$ capture. As SPOC does the oxy-combustion process under pressure, it is higher efficiency and lower cost than atmospheric oxy-combustion.

The project was led by the Electric Power Research Institute, Inc., with the assistance of WUSTL, Doosan Babcock (DBL – boiler plant original equipment manufacturer), and Air Liquide (AL – air separation experts). The specific objectives of the project were to:

- Evaluate the SPOC concept and develop a risk-based approach to the heating surface layout ensuring that performance (gas and steam side), manufacturing, transportation, and plant erection considerations were fully accounted for in the system design.
- Improve the technology to ensure its performance and cost potential are substantially better than today's baseline pulverized coal power plant with post-combustion capture (PCC) or atmospheric oxy-combustion, and show progress toward performance commensurate with projected commercial operation, including 90% or more $CO_2$ capture.
- Address critical technology gaps and improving overall system performance for the technology.
- Perform combustion tests at scale under commensurate pressure to the commercial operating system validate combustor and advance the SPOC combustion modeling tools that will facilitate full-scale design.

## SPOC Concept Evolution

The SPOC concept has undergone significant evolution throughout the execution of this project, following review of the constructability of the SPOC boiler stages, its ability to operate at part loads, and strategies for flexible pressurized oxygen delivery. A two-pass pressure vessel (PV) arrangement for each stage allows for road transportation to be feasible at the 400 MWth scale. This allows a 4-stage SPOC system to deliver 550 MWe with a high degree of modular factory manufacture, ensuring economic efficiency in the manufacture and construction process is attainable at this scale due to lower people hours and improved quality control over onsite construction methods.

Additionally, conventional heat transfer methods have been applied to the convective stages to ensure that heat is delivered to each of the water/steam circuits in appropriate proportions throughout the load range. Allowing bypassing of stages ensures that a significant degree of turndown is achievable on the steam turbine without incurring stage combustion turndown beyond 50%. Testing of the SPOC combustion showed that ultra-low firing rates are also possible, introducing the possibility of being able to sustain stages in a warm-standby condition in readiness for rapid ramping.

## Combustion Testing

The 100 kWth pilot scale combustion testing facility has undergone significant modifications to facilitate up to 15 barg pressure SPOC testing to be carried out. This system represents a single SPOC stage using synthetic FGR and a down-fired, co-axial low-mixing flow design. The system is designed to replicate the environment that coal particles would experience in the first 5 seconds of the full-scale SPOC boiler arrangement, where the main combustion reactions occur. Sampling techniques were developed to allow pressurized samples to be drawn from multiple locations in the reactor to allow for evaluation of coal particle composition throughout the combustion process and the final carbon-in-ash levels at the outlet. The sampling lines were heated to avoid moisture and acid gas condensation. The sampling allowed for comparison with the predicted computational fluid dynamic results to verified when complete combustion was achieved.

Another requirement of the testing was to verify the heat flux generated from the SPOC flame, as this informs the full-scale design regarding boiler-tube arrangement and appropriate water-side mass fluxes needed to keep the tubes appropriately cooled. Testing was initially carried out at atmospheric pressure with methane to ensure that all systems were correctly operating. Following this, the testing then proceeded to moderate pressure operation at 4 bara, where different stoichiometric conditions were used across an extended heat input range, showing that a stable flame could be maintained. Testing then proceeded at 10 and 15 bara where it was shown that the ignition system needed to be replaced at these operating conditions. When testing recommenced, a similar stable flame shape was achieved, without any methane support, and the full 100 kWth coal oxy-combustion was demonstrated. Heat flux measurements showed 400 $kW/m^2$ (0.126 $MMBtu/hr\text{-}ft^2$) from the flame, within the 450 $kW/m^2$ (0.142 $MMBtu/hr\text{-}ft^2$) preferred limit defined by DBL for the full-scale design case. Carbon monoxide and carbon-in-ash measurements showed that complete combustion was possible with ultra-low excess oxygen at 1 vol % in the product flue gas. This allowed the full-scale models to be calculated based on this level of excess oxygen, improving the performance of the system as lower feed oxygen is produced in the air separation unit (ASU), saving auxiliary power.

## Full-Scale Design

The full-scale design is sized to deliver 550 MWe net electrical power output to allow direct comparison with the National Energy Technology Laboratory (NETL) baseline cases using the same Montana Powder River Basin (PRB) fuel. The cases used for direct comparison are: Case S12A (supercritical [SC] coal without $CO_2$ capture), Case S12B (SC coal with PCC at 90% $CO_2$ capture, and Case S12F (atmospheric oxy-combustion SC coal with 90% $CO_2$ capture). The SPOC stages were configured to be identical arrangements, allowing for a more straightforward design, construction, and control strategy. As a result, all stages were configured to deliver sufficient oxygen to match the firing rate with only a small excess oxygen level being present and the produced gases are split with the majority feeding the next stage and the balance being passed to a collection duct that gathers the exhaust from each stage. A portion of the accumulated flue gas produced is recycled to the first stage to maintain similar combustion conditions as of the other stages.

Each stage consists of two PVs, the first being the combustor PV module and the second being the convective PV module. The combustor module is the tallest vessel, with local coal feeding equipment and the burner FGR and oxygen plenums at the top and ash management at the bottom. The combustor module is effectively an open cross section with membrane tubes around the circumference – this unobstructed slender profile ensures that the relatively slower burnout mechanism needed for the low-speed turbulent mixing burner can proceed unimpeded and that molten ash will not attach to any surfaces at an angle to the predominant flue gas flow.

Upon reaching the bottom of the combustor PV module the flue gas is sufficiently cooled to below the ash initial deformation temperature that flow direction changes will only yield ash particle deposition and not solid growth. The gas can therefore be passed horizontally to the upward flowing convective PV module where cross flow heat exchange banks are located to deliver heat to the steam/water circuits. The steam turbine used in the SPOC design is essentially the same unit utilized in the atmospheric oxy-combustion case except the degree of heat recovery possible allows the low-pressure (LP) feedwater heater train to be eliminated. This is a result of being able to capture the latent heat of evaporation of the moisture produced in the combustion (normally lost to the stack). A comparison to the NETL baseline cases is shown in Table 1.

The SPOC system outperforms the NETL atmospheric oxy-combustion baseline case by 3.3% points and the PCC case by 7.5% points. This performance increase is mainly a result of the improved heat recovery possible from the product flue gas and from the reduced auxiliary power consumption from the ASU and the $CO_2$ compression and purification unit over the atmospheric equivalent. Another substantial saving is delivered from the reduced duty of the recycle fan (or induced draft fan) where the volume of gas being recycled in the SPOC case is substantially lower than is the case for the atmospheric oxy-combustion case. The combination of these savings in auxiliary power are added to by incremental reductions in fuel processing and cooling water systems leading to a gross power generation requirement that is 25.6 MWe lower than the atmospheric case.

**Table 1**
**Comparison of SPOC with NETL Baseline Cases**

| Parameter Case | S12A | S12B | S12F | SPOC |
|---|---|---|---|---|
| Total Gross Power, MWe | 582.7 | 673.0 | 748.3 | 724.0 |
| $CO_2$ Capture/Removal Auxiliaries, kWe | - | 22,900 | 94,710 | 124,607 |
| $CO_2$ Compression, kWe | - | 49.000 | 64,740 | 21,774 |
| Balance of Plant (BOP), kWe | 32,670 | 51,040 | 38,840 | 27,607 |
| Total Auxiliaries, MWe | 32.67 | 122,940 | 198.29 | 174.0 |
| Net Power, MWe | 550.0 | 550.1 | 550.0 | 550.0 |
| Net Plant Efficiency, % higher heating value (HHV) | 38.7 | 27.0 | 31.2 | 34.5 |
| Net Plant Heat Rate, kJ/kWh HHV | 9307 | 13,330 | 11,532 | 10,426 |
| Thermal Input, MWth HHV | 1422.0 | 2036.7 | 1761.9 | 1593.0 |
| Boiler Efficiency, % HHV | 85.7 | 85.8 | 88.7 | 87.5 |
| Heat to Steam, MWth | 1219.3 | 1748.1 | 1564.1 | 1412 |
| High-pressure (HP) Heat Recovery, MWth | - | - | - | 35.7 |
| LP Heat Recovery, MWth | - | - | 64.46 | 197.8 |
| As-Received Coal Feed, kg/hr | 256,992 | 368,084 | 318,415 | 287,892 |

A bituminous check coal, Illinois No. 6, was also applied to the SPOC baseline design. Illinois No. 6 contains significantly lower moisture content at 11.12 wt % than the design coal, Montana PRB, at 25.77 wt %, resulting in a drier flue gas produced from the SPOC stages. Although this reduced moisture mass lowers the thermal losses in the SPOC boiler system (due to a reduced latent heat from evaporation of water in the fuel), the opportunity to recover latent heat from the flue gas is subsequently reduced.

Where the low-temperature feedwater heating target temperature is fully met in the design case, the Illinois No.6 case heat recovery was reduced by 22.5%, requiring a significant increase in the deaerator heating duty. Additionally, due to an overall reduced flue gas flowrate, the HP feedwater heating duty was lower by 16.6%. The reduction of these heat recovery duties resulted in a net increase in the steam turbine heat rate of 2.2%.

The combined improvement in boiler efficiency and reduction in the steam turbine heat rate resulted in a net improvement in the overall plant efficiency by 0.61%, to 35.6% on a HHV basis. This relatively small improvement in plant efficiency between sub-bituminous and bituminous coals shows the value of useful moisture latent heat recovery offered by the SPOC system when using low rank fuels.

## Flexibility and Turndown

The SPOC system has inherent high turndown capabilities because of a demonstrated high range of combustion stability and the ability to bypass stages, thereby reducing steam generation rates proportionally without altering firing rates in operating stages. ASU units do not generally offer significant turndown opportunities as they are limited by the performance of the compression plant. The baseline SPOC design has a 2-train ASU configuration, needed to be able to meet the 10,500 tonnes per day duty, that can deliver efficient turndown points between 85–100% load with both trains operating, and at 45–50% load with a single train operating. Outside these operating points, the flexibility and efficiency are limited and may be uncompetitive at loads below 45% as the ASU systems are unable to turndown beyond 85% for the base case and 70% for the flexible case. The ASU cold box for the flexible case was designed to operate at loads between 40-100%, below this operating range the purity of the produced oxygen cannot be guaranteed, resulting in additional load for the CPU equipment. The additional power consumption of these cases yields an uneconomic operating condition with poor efficiency when operating at low loads such as 25% and 12%, as shown in Table 2, which are typical of operating in a condition of readiness prior to an expected demand signal (when renewable generators are expected to lose generating capabilities).

**Table 2**
**SPOC Baseline Load Cases**

| **Load Case** | **Fuel Heat Input** MWth | **Heat to Steam** MWth | **Gross Power** MWe | **Net Export Power** MWe | **Net Efficiency** % HHV |
|---|---|---|---|---|---|
| 100% | 1593 | 1412 | 724 | 550 | 34.53 |
| 75% | 1219 | 1080 | 552 | 412 | 33.85 |
| 50% | 827 | 731 | 382 | 275 | 33.24 |
| 25% | 509 | 455 | 224 | 137 | 26.99 |
| 12% | 354 | 313 | 153 | 66 | 18.63 |

To address this flexibility constraint, AL evaluated how the ASU configuration could be altered to deliver efficient oxygen supply over the load range. This involved integrating the compressor duties across both ASU trains into a shared duty arrangement with multiple compressors, strategically sized to deliver the duty required across all load ranges between 40–100% by enabling different combinations of the main air compressors and the booster air compressors. The oxygen purity cannot be guaranteed below 40% load for each train – the power consumption at 25% and 12% loads were estimated based on the multi-compressor configuration at maximum turndown as these load cases were not considered in the flexible ASU design. With a different cold box configuration, i.e. number of trains, the entire load range could be delivered within oxygen purity specifications.

Although there is a small efficiency reduction at full load, there are significant improvements in overall plant performance during low-load operation, as shown in Table 3. The exact ASU configuration needed will therefore be dependent on the expected operating profile of the unit.

**Table 3**
**SPOC Flexible ASU Load Cases**

| **Load Case** | **Fuel Heat Input** MWth | **Heat to Steam** MWth | **Gross Power** MWe | **Net Export Power** MWe | **Net Efficiency** % HHV |
|---|---|---|---|---|---|
| 100% | 1595 | 1415 | 726 | 550 | 34.47 |
| 75% | 1219 | 1080 | 552 | 412 | 33.85 |
| 50% | 819 | 724 | 379 | 275 | 33.57 |
| 25% | 446 | 396 | 196 | 137 | 30.83 |
| 12% | 268 | 235 | 111 | 66 | 24.62 |

## Economic Analysis

Cost estimates for the baseline and the flexible cases were developed using NETL baseline case data for common BOP items and an Association for the Advancement of Cost Engineering International Class 5 (conceptual/screening study) assessment of key components unique to the SPOC system. The capital, operating, and maintenance costs were assessed along with the first-year power cost, levelized cost of electricity, and $CO_2$ captured and avoided cost for the SPOC cases were compared against the relevant NETL baseline cases in January 2019 dollars.

The first-year power costs, broken down into their components, for the NETL baseline cases and the SPOC baseline and flexible cases, are shown in Figure 1. Both SPOC cases achieve a lower cost that the alternative NETL baseline cases (with the flexible SPOC case being slightly higher than the baseline SPOC case due to the compounded impact of higher capital costs and lower efficiency at full load). Figure 2 shows the cost of $CO_2$ captured for all capture cases compared against NETL baseline case S12A.

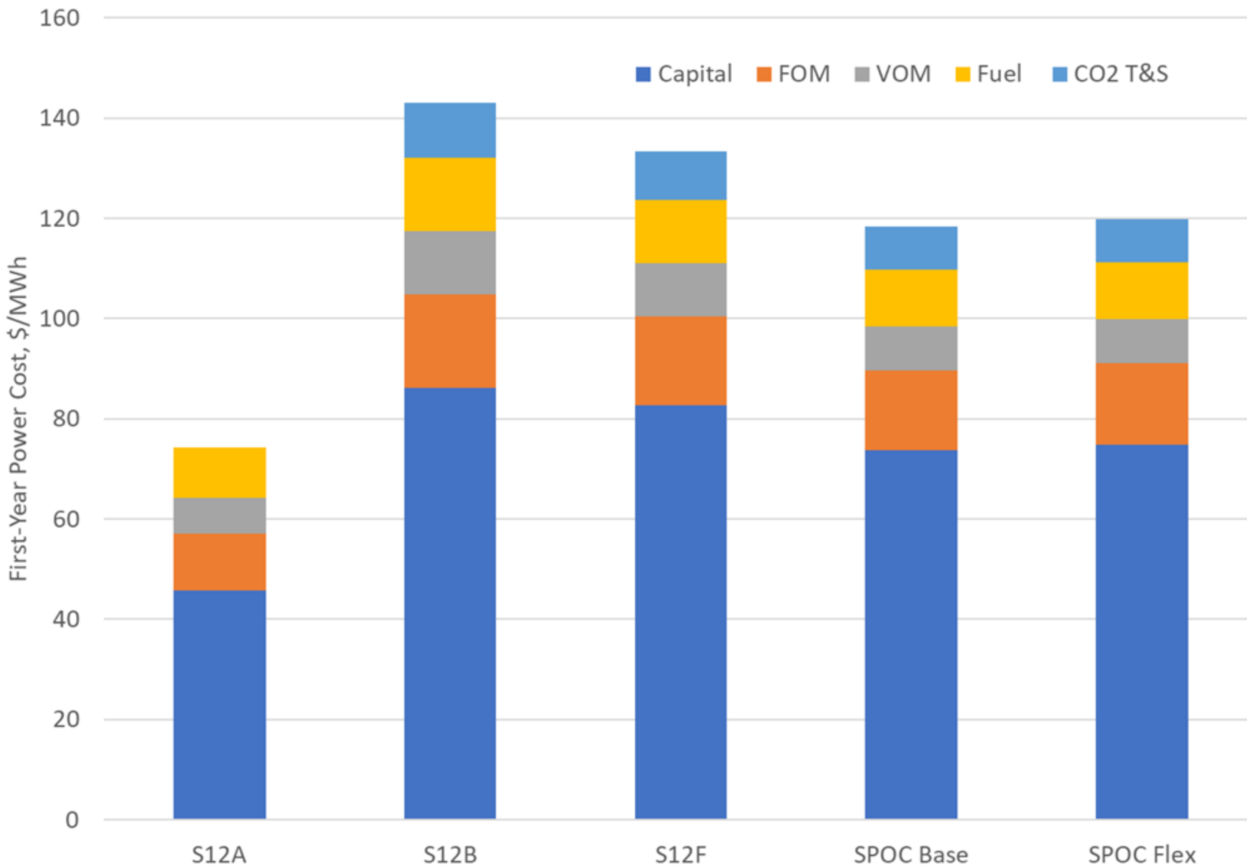



**Figure 1**
**First-Year Power Costs for All Cases**

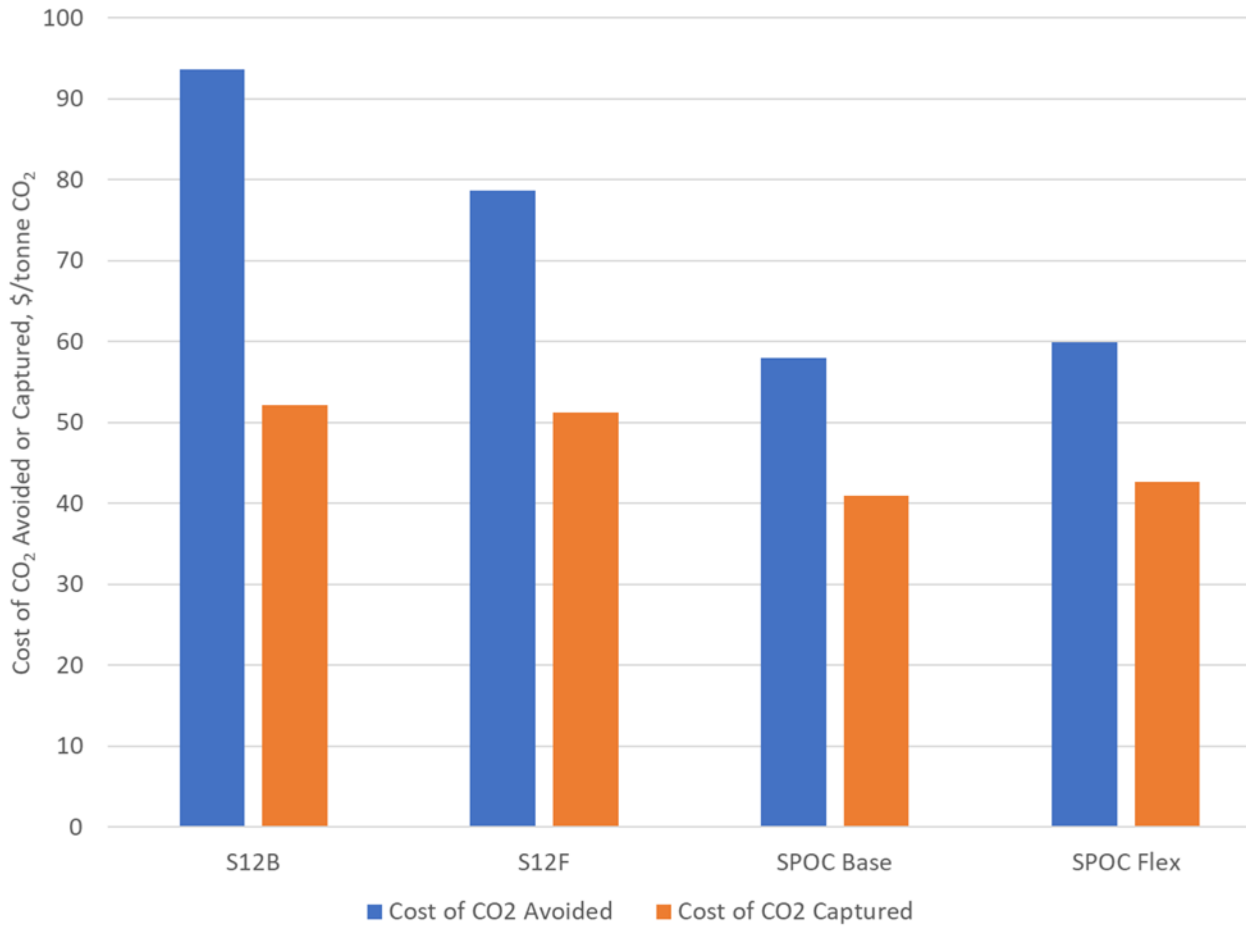



**Figure 2**
**$CO_2$ Avoided and Captured Costs for All Capture Cases**

The SPOC cases deliver a lower cost of $CO_2$ avoided than the NETL baseline cases due to greater efficiency in generating low-carbon power. However, the cost of $CO_2$ captured is higher because the higher efficiency of the SPOC process generates less $CO_2$, hence less needs to be captured, resulting in a high capital cost being shared over a reduced $CO_2$ quantity.

The flexible ASU adds 1.6% overall to the plant cost in comparison to the baseline case, but the efficiency improvements at loads below 50% are significant. Subsequently, depending on the plant load-profile expectation, the flexible ASU would be beneficial if the plant spends a significant portion of its operating life below 50% load.

This kind of operating profile is likely to be required for all fossil plants when more renewable electricity generators are installed on the local grid, particularly solar power that can be predicted ahead of time, allowing for appropriate pricing signals to be incorporated into the diurnal cycle.

## R&D Recommendations

SPOC, while a promising technology, is a relatively recent concept and, as such, operability issues of combustor design and steam-side integration for such systems at a scale relevant to commercial deployment have not been evaluated. WUSTL has conducted extensive small pilot-scale (100 kWth) research to understand and advance pressurized oxy-combustion processes, including investigation of combustion and flame characteristics, radiative heat flux, burner operability, turn down, char burnout, ash characteristics, water-wash column operation, etc. for pressurized oxy-combustion systems. Nonetheless, at this stage in the development of the SPOC process, what is needed is a large-scale pilot plant that can serve to study pressurized oxy-combustion systems and components at a scale commensurate with the maturity of the technology.

A scale of 10 MWth, which includes steam-side integration and two stages would yield essential information with respect to heat transfer characteristics both in the radiative and convective sections of the pressure vessels, and the ability to operate the fuel staging process. In addition, while modeling results indicate that combustion and flame characteristics improve with scale, direct studies of the combustor at this scale will ensure that the models can be relied upon for scale up to commercial scale. Furthermore, a detailed analysis must be performed to understand the scaling aspects of key components and systems.

# 1
# INTRODUCTION

## Background

Coal-fired power plants are being driven to reduce greenhouse gas emissions through efficiency improvements and carbon dioxide ($CO_2$) abatement. Existing technologies for carbon capture and storage (CCS) are expensive and energy intensive. Thus, to ensure a stable and reliable future energy mix, second-generation technologies that can capture $CO_2$ at lower energy penalty and cost are critically needed. Staged pressurized oxy-combustion (SPOC), developed at the Washington University in St. Louis (WUSTL), is a promising candidate technology to address this need.

## Project Objectives

The primary goal of this project is to investigate the potential for SPOC for flexible operation beyond the capabilities of conventional coal-fired power plants, particularly those employing CCS. SPOC is a form of oxy-combustion whereby coal is combusted with oxygen (produced by a cryogenic air separation unit [ASU]) and recirculated flue gas, as opposed to air. The resultant flue gas is a mixture of primarily $CO_2$ and water, greatly simplifying $CO_2$ capture. As the oxy-combustion process is conducted under pressure in the SPOC process, it has a higher efficiency and lower cost than traditional oxy-combustion, which is conducted at atmospheric pressure.

The specific objectives of the project were to:

- Evaluate the SPOC concept and develop a risk-based approach to the heating surface layout ensuring that performance (gas and steam side), manufacturing, transportation, and plant erection considerations were fully accounted for in the system design.
- Improve the technology to ensure its performance and cost potential are substantially better than today's baseline pulverized coal (PC) power plant with post-combustion capture (PCC) or atmospheric oxy-combustion, and show progress toward performance commensurate with projected commercial operation, including 90% or more $CO_2$ capture.
- Address critical technology gaps and improving overall system performance for the technology.
- Perform combustion tests conducted at scale under commensurate pressure to the commercial operating system to validate combustor and advance the SPOC combustion modeling tools that will facilitate full-scale design.

The ultimate outcome of this project is an economically-optimized conceptual design for a commercial-scale, pressurized oxy-combustion coal power plant that has been scrutinized by leading vendors of coal power and ASU technology.

The Electric Power Research Institute, Inc. (EPRI) is the prime contractor for this project with WUSTL, Doosan Babcock Limited (DBL), and Air Liquide (AL) as subcontractors.

In addition to project management and reporting done in Task 1, five tasks were scheduled for the project technical work:

- **Task 2 –** Develop a design basis for the full-scale design and carry out an original equipment manufacturer (OEM) review of the SPOC process.
- **Task 3 –** Develop the 550 MWe SPOC baseline case with full integration between the boiler system, steam turbine feedwater heating train, the ASU, and the $CO_2$ compression and purification unit (CPU).
- **Task 4 –** Assess SPOC system flexibility and update ASU configuration to achieve efficient turndown capability.
- **Task 5 –** Carry out testing at WUSTL using 100 kWth SPOC pilot plant to verify combustion performance, assess heat flux profiles and particle burnout.
- **Task 6 –** Develop the cost estimate for the SPOC full-scale 550 MWe plant and compare to the existing National Energy Technology Laboratory (NETL) baseline cases in 2019 U.S. dollars.

## Report Structure

The goal of this report is to summarize all the work performed in this project:

- Chapter 2 provides the design basis specifications for the SPOC system, including the selected base cases that were used for comparison.
- Chapter 3 details the OEM assessment of the SPOC system, a risk assessment of the system, and a proposed design that aims to mitigate the identified risks.
- Chapter 4 presents the testing activities, detailing the testing plan, pilot plant upgrades, instrumentation, and test execution and results.
- Chapter 5 covers the baseline 550 MWe SPOC design and the integration methodology of the SPOC boiler system, steam turbine integration, and the oxy-combustion auxiliaries heat recovery.
- Chapter 6 explores the SPOC configuration during turndown operation and the flexible oxygen supply options.
- Chapter 7 provides the methodology applied to the economic analysis and the comparison of the SPOC system against the NETL baseline cases.
- Chapter 8 summarizes the results, conclusions, and recommendations.

# 2
# DESIGN BASIS

To allow a direct comparison with existing NETL baseline cases, the full-scale SPOC design was sized to delivery 550 MWe net with 90% $CO_2$ capture. The key NETL cases identified are based on firing Montana Powder River Basin (PRB) sub-bituminous coal using a conventional supercritical (SC) single reheat steam cycle, as detailed in Table 2-1.[1,2]

**Table 2-1**
**NETL Baseline Cases**

| Case | Boiler | Fuel | Steam Cycle barg/°C/°C (psig/°F/°F) | $CO_2$ Separation / Purification Technology |
|---|---|---|---|---|
| S12A | SC PC | PRB | 241/593/593 (3500/1100/1100) | None |
| S12B | SC PC | PRB | 241/593/593 (3500/1100/1100) | PCC (Econamine) |
| S12F | SC Oxy-combustion | PRB | 241/593/593 (3500/1100/1100) | Cryogenic Distillation |

For reference, the heat-and-material flow diagrams have been included in Appendix B.

## General Criteria

The plant was located on a greenfield site, and hence no existing plant infrastructure is available to be utilized. The site characteristics are given in Table 2-2.

**Table 2-2**
**Site Characteristics**

| Parameter | Value |
|---|---|
| Location | Midwestern U.S. |
| Topology | Level |
| Land Available, hectares (acres) | 121.4 (300) (including 0.24 km [0.15 mile] boundary) |
| Fuel, Ash and Utility Transportation | Rail or Highway |
| Ash Disposal | Offsite |
| Water Availability | 50% Municipal / 50% Groundwater |

[1] Cost and Performance Baseline for Fossil Energy Plants Volume 3b: Low Rank Coal to Electricity: Combustion Cases DOE/NETL-2011/1463.

[2] Cost and Performance for Low-Rank Pulverized Coal Oxycombustion Energy Plants – Final Report DOE/NETL-401/093010.

### *Battery Limits*

The main battery limits were defined as:

| | |
|---|---|
| Fuel/Ash | Gatehouse where coal trucks or railcars enter / exit |
| Water | Municipal water inlet flange |
| $CO_2$ | High-pressure (HP) $CO_2$ compressor / pump outlet flange |
| Electrical Power | Low-voltage side of step-up transformer to high-voltage grid connection |

### *Meteorological Data*

Table 2-3 defines the site meteorological data used for the performance calculations of the SPOC system.

**Table 2-3**
**Ambient Conditions**

| Parameter | Value |
|---|---|
| Elevation, m (ft) | 1036 (3400) |
| Barometric Pressure, bara (psia) | 0.9 (13.0) |
| Design Ambient Temperature, Dry Bulb / Wet Bulb, °C (°F) | 5.6 (42) / 2.8 (37) |
| Design Ambient Relative Humidity, % | 62 |

### *Environmental Targets*

The environmental targets applied to the NETL baseline cases comply with the New Source Performance Standards, as amended in June 2007, as shown in Table 2-4.

**Table 2-4**
**Plant Emission Limits**

| Pollutant | Emission Limit | Technology (where applicable) |
|---|---|---|
| Particulate Matter (PM) | 6 g/kJ (0.013 lb/MMBtu) | Fabric Filter / Electrostatic Precipitator |
| Sulfur Dioxide ($SO_2$) | 63 g/kJ (0.132 lb/MMBtu) | Dry Flue Gas Desulfurizer |
| Nitrogen Oxides (NOx) | 33 g/kJ (0.07 lb/MMBtu) | Low-NOx Burners / Overfire Air / Selective Catalytic Reduction |
| Hg | 0.29 g/MJ (0.6 lb/TBtu) | Co-benefit Capture / Carbon Injection |

These standards are applicable to Cases 12A and 12B where flue gases are being discharged directly to the atmosphere, however they are also included for the oxy-combustion cases to account for all discharges (for example, from the inerts stack in the CPU). Mercury (Hg) emission limits are based on the facility being designated as a “dry unit,” as most of the areas in Montana receive less than 63.5 cm (25 inches) of rainfall per annum.

### *Capacity Factor*

It is assumed that there is always a demand for power and that the product $CO_2$ can always be exported. The NETL baseline cases worked on the basis that they had an equivalent availability factor (EAF) of 85%. Although unabated coal power plants might be expected to have a lower capacity factor than this due to the impact of non-dispatchable resources in the power grid, a $CO_2$-abated plant would potentially be able to achieve this based on both the need for low-carbon intensity power and demand for the $CO_2$ product.

## Plant Design Criteria

### Plant Scale

To allow for a direct comparison to the NETL baseline cases, the SPOC plant design target was sized to deliver 550 MWe net at maximum output. The power module is considerably larger than that for Case S12A to account for the auxiliary power requirements of the ASU, CPU, and the subsequent compression of the $CO_2$ to the required export pressure requirements.

The rated output is based on the design point ambient conditions and was used for the equipment sizing and plant costing.

### Pressurized System Conditions

As the SPOC system operates at elevated pressure, the combustion envelope and all downstream equipment (convective heat transfer banks, acid gas removal, cooling units, and driers) need to be contained within pressure vessels (PVs) as described in Table 2-5.

**Table 2-5**
**Pressurized Plant Design Criteria**

| Design Criteria | Standard |
|---|---|
| Maximum Allowable Working Pressure, bara (psia) | 16 (232) |
| Vessel Construction Design Code | American Society of Mechanical Engineers (ASME) VIII (2013) |
| Safety Valves | Mandatory – 110% of Maximum Allowable Working Pressure;<br>Vent to safe area, plant trip on actuation |
| Boiler Components | ASME Section I / II<br>Rules for Construction of Power Boilers |
| Combustion Systems | National Fire Protection Agency (NFPA)-85: Boiler and Combustion Systems Hazards Code (2019) |

As these PVs need to be transportable, the maximum sizes available are constrained to that of typical shipping limits. Generally, such vessels are limited to approximately 4.2 m (14 ft) diameter to allow for economic shipping by road or rail; however, vessels of 7 m (23 ft) and greater in diameter are routinely transported (although this can add significant cost). The sizing of the vessels has therefore taken into consideration both the economics and performance to establish the optimum design.

### Load Cases

Plant performance data generated for the load cases are given in Table 2-6.

**Table 2-6**
**Load Cases and Flexibility Requirements**

| Load | Standard |
|---|---|
| Plant Maximum Continuous Rating (MCR) | Based on generator max |
| Part Load – 75% MCR | |
| Part Load – 50% MCR | |
| Minimum Stable Generation | System lower limit / can be in circulating mode |
| **Flexibility** | |
| Startup Time (excluding ASU/CPU) | Hot (after <2 hours), warm (after 12 hours), and cold (after >36 hours) |
| Ramp Rate | Not determined at design basis* |

** Achievable ramp rate to be determined by the boiler vendor based on conventional practice; oxygen supply system to be developed to facilitate required startup, turndown, and ramping events.*

As there is potential for specific attenuation of the heat balance between superheat and reheating surfaces using the SPOC arrangement, the reheat temperature control is to be maintained to as low a load as is reasonable with minimal reheat attemperation (<1%), subject to steam turbine constraints.

### *Startup System*

From a cold condition, the system will be started up on natural gas or light oil fuel with the combustion enclosure pressure being built by controlled throttling of the purge stream following initial light-off. All SPOC stages will be established and oxygen flow control optimized to deliver a product gas composition that is suitable for CPU admission. Prior to this, the product gases will be depressurized and vented to a safe location.

The combustion volume will be suitably vented prior to light-off or following a shutdown or plant trip as per NFPA-85 requirements.[3]

The steam system was designed to ensure appropriate cooling is maintained on the radiant surfaces by establishing a circulating flow (in subcritical condition) and allowing steam generation to flow through the superheater sections and pipework to ensure appropriate warming. A HP bypass valve allows this steam to also pass to the reheater circuit, providing pipework warming and reheater sections to be actively cooled. When the main steam pipework leading to the turbine stop valve is appropriately heated, steam turbine warming can commence in the usual manner, allowing the HP bypass to be closed.

### *Sparing Philosophy*

To allow for a direct comparison with the baseline cases, the system is designed to have commensurate spare capacity for identical equipment, such as for fuel and ash handling components, electrical switchgear, and auxiliary transformers. Small pumps have 100% spare

[3]NFPA 85: Boiler and Combustion Systems Hazards Code 2019 edition

capacity to facilitate maintenance during operations. The cooling water circulating system has 3 x 50% capacity to ensure appropriate availability is achieved.

For plant components that are unique to the SPOC process, the degree of spares required was determined by industry practice based on delivering an overall plant availability that is anticipated to exceed the baseline case EAF of 85%.

## Feedstocks and Products

### *Coal Properties*

The design coal used is Montana Rosebud PRB with characteristics taken from the NETL Coal Quality Guidelines as shown in Table 2-7 and with corresponding ash quality shown in Table 2-8.

To further explore the implications of coal quality on the SPOC design, a bituminous "check" coal was also considered (Illinois No. 6). This coal has significantly lower moisture content than the design coal, but contains elevated levels of sulfur and chlorine as shown in Table 2-9 and Table 2-10.

The work was carried out exclusively on the design coal, with the check coal being used only to show the potential design differences that would be possible if a bituminous fuel was taken as the design coal (i.e., no performance characteristics were assessed).

**Table 2-7**
**Design Coal Characteristics (Montana Rosebud PRB)**

| **Proximate Analysis** | **Dry Basis, wt %** | **Wet Basis, wt %** |
|---|---|---|
| Moisture | 0.00 | 25.77 |
| Ash | 11.04 | 8.19 |
| Volatile Matter | 40.87 | 30.34 |
| Fixed Carbon | 48.09 | 35.70 |
| *Total* | *100.00* | *100.00* |
| **Heating Value** | **Dry Basis** | **Wet Basis** |
| Higher Heating Value (HHV), kJ/kg (Btu/lb) | 26,787 (11,516) | 19,920 (8564) |
| Lower Heating Value (LHV), kJ/kg (Btu/lb) | 25,810 (11,096) | 19,195 (8252) |
| **Hardgrove Grindability Index** | 57 | |
| **Ultimate Analysis** | **Dry Basis, wt %** | **Wet Basis, wt %** |
| Carbon | 67.45 | 50.07 |
| Hydrogen | 4.56 | 3.38 |
| Nitrogen | 0.96 | 0.71 |
| Sulfur | 0.98 | 0.73 |
| Chlorine | 0.01 | 0.01 |
| Ash | 11.03 | 8.19 |
| Moisture | 0.00 | 25.77 |
| Oxygen (By Difference) | 15.01 | 11.14 |
| *Total* | *100.00* | *100.00* |

**Table 2-8**
**Design Coal Ash Properties (Montana Rosebud PRB)**

| **Mineral Composition** | | **wt %** |
|---|---|---|
| Silica | $SiO_2$ | 38.09 |
| Aluminum Oxide | $Al_2O_3$ | 16.73 |
| Iron Oxide | $Fe_2O_3$ | 6.46 |
| Titanium Oxide | $TiO_2$ | 0.72 |
| Calcium Oxide | CaO | 16.56 |
| Magnesium Oxide | MgO | 4.25 |
| Sodium Oxide | $Na_2O$ | 0.54 |
| Potassium Oxide | $K_2O$ | 0.38 |
| Sulfur Trioxide | $SO_3$ | 15.08 |
| Phosphorous Pentoxide | $P_2O_5$ | 0.35 |
| Barium Oxide | $Ba_2O$ | 0.00 |
| Strontium Oxide | SrO | 0.00 |
| Unknown | | 0.84 |
| | *Total* | *100.00* |
| **Trace Components (fly ash)** | | **ppmd** |
| Mercury | Hg | 0.081 |
| **Ash Fusion Temperatures** | | **°C (°F)** |
| Reducing Atmosphere | Initial Deformation | 1225 (2238) |
| | Softening | 1234 (2254) |
| | Hemispherical | 1243 (2270) |
| | Fluid | 1259 (2298) |
| Oxidizing Atmosphere | Initial Deformation | 1251 (2284) |
| | Softening | 1261 (2301) |
| | Hemispherical | 1271 (2270) |
| | Fluid | 1297 (2298) |

**Table 2-9**
**Check Coal Characteristics (Illinois No. 6 Bituminous)**

| Proximate Analysis | Dry Basis, wt % | Wet Basis, wt % |
|---|---|---|
| Moisture | 0.00 | 11.12 |
| Ash | 10.91 | 9.70 |
| Volatile Matter | 39.37 | 34.99 |
| Fixed Carbon | 49.72 | 44.19 |
| *Total* | *100.00* | *100.00* |
| **Heating Value** | **Dry Basis** | **Wet Basis** |
| HHV, kJ/kg (Btu/lb) | 30,531 (13,126) | 27,135 (11,666) |
| LHV, kJ/kg (Btu/lb) | 29,447 (12,660) | 26,171 (11,252) |
| **Hardgrove Grindability Index** | 60 | |
| **Ultimate Analysis** | **Dry Basis, wt %** | **Wet Basis, wt %** |
| Carbon | 71.73 | 63.75 |
| Hydrogen | 5.06 | 4.50 |
| Nitrogen | 1.41 | 1.25 |
| Sulfur | 2.82 | 2.51 |
| Chlorine | 0.33 | 0.29 |
| Ash | 10.91 | 9.70 |
| Moisture | 0.00 | 11.12 |
| Oxygen (By Difference) | 7.74 | 6.88 |
| *Total* | *100.00* | *100.00* |

**Table 2-10**
**Check Coal Ash Properties (Illinois No. 6 Bituminous)**

| **Mineral Composition** | | | **%** |
|---|---|---|---|
| Silica | | $SiO_2$ | 45.0 |
| Aluminum Oxide | | $Al_2O_3$ | 18.0 |
| Iron Oxide | | $Fe_2O_3$ | 20.0 |
| Titanium Oxide | | $TiO_2$ | 1.0 |
| Calcium Oxide | | CaO | 7.0 |
| Magnesium Oxide | | MgO | 1.0 |
| Sodium Oxide | | $Na_2O$ | 0.6 |
| Potassium Oxide | | $K_2O$ | 1.9 |
| Sulfur Trioxide | | $SO_3$ | 3.5 |
| Phosphorous Pentoxide | | $P_2O_5$ | 0.2 |
| Barium Oxide | | $Ba_2O$ | 0.0 |
| Strontium Oxide | | SrO | 0.0 |
| Unknown | | | 1.8 |
| | | *Total* | *100.00* |
| **Ash Fusion Temperatures** | | | **°C (°F)** |
| Reducing Atmosphere | Initial Deformation | | 1066 (1950) |
| | Softening | | 1110 (2030) |
| | Hemispherical | | 1171 (2140) |
| | Fluid | | 1177 (2150) |
| Oxidizing Atmosphere | Initial Deformation | | 1232 (2250) |
| | Softening | | 1260 (2300) |
| | Hemispherical | | 1332 (2430) |
| | Fluid | | 1343 (2450) |

## Non-fuel Feedstocks

When desulfurization processes are applied to flue gases, typically limestone or lime is used to react with the acid gases. As the pressurized oxy-combustion process is not anticipated to require this amount of desulfurization (only produced water neutralization), the compositions of these feedstocks are not listed here, but can be found in the NETL Quality Guidelines – Specification for Selected Feedstocks.[4]

[4] Quality Guidelines for Energy System Studies – Specification for Selected Feedstocks, January 2012 DOE/NETL-341/011812.

## $CO_2$ Product Purity

The $CO_2$ product leaving the process will meet the specification detailed in Table 2-11 for export compliance. Monitoring will be provided with provision for diversion and safe venting should these specifications not be attained (e.g., during system startup).

**Table 2-11**
**Product Export Specification**

| Parameter | Limit | Requirement |
|---|---|---|
| Temperature | <35°C (95°F) | Transportation pipeline specification |
| Pressure | 152 barg (2200 psig) | Transportation pipeline specification |
| $CO_2$ | >95 vol % | Minimum miscible pressure for enhanced oil recovery (EOR) |
| $N_2$ | <4 vol % | Minimum miscible pressure for EOR |
| $H_2O$ | dew point <-40°C (-40°F) | Transportation pipeline corrosion / hydrate formation |
| $O_2$ | <40 ppmv | Transportation pipeline corrosion |
| CO | <0.1 vol % | Safety and corrosion |

## Air Separation Unit

The ASU was initially designed as a standard commercial system with no specific upgrades related to improved flexibility. Improved flexibility was subsequently determined by AL. The baseline case specifications are detailed in Table 2-12.

**Table 2-12**
**ASU Parameters**

| Parameter | Requirement |
|---|---|
| Gaseous Oxygen Pressure | 17 bara (247 psia) |
| Gaseous Oxygen Purity | 95.9 $O_2$ vol % |
| Gaseous Oxygen Flowrate | 10,500 tonnes/day (TPD) |
| Oxygen Storage | 8 hours as liquid oxygen (LOx) |
| Nitrogen Supply Pressure | 0.95 bara (13.8 psia) |
| Nitrogen Purity | 99.5 $N_2$ vol % |
| Nitrogen Flowrate | Up to 17,000 TPD |
| Nitrogen Storage | Not required |
| Primary Machine Drive | Electrical |
| Shipping Constraints | No constraint considered |
| ASU Startup Time | Vendor to specify |
| Cooling Water Supply Temperature | 14°C (57°F) |
| Cooling Water Temperature Rise | 10°C (18°F) |
| Cooling Water Pressure Drop | 2 bar (29 psi) |
| Compressed Air Export Flowrate | 4000 $Nm^3$/hr (2536 standard $ft^3$/min) |
| Compressed Air Export Pressure | 11.4 bara (165 psia) |
| Compressed Air Export Temperature | Maximum 54°C (130°F) |

Ambient air purity as specified for the NETL baseline case[3] is detailed in Table 2-13.

**Table 2-13**
**Ambient Air Quality (dry basis)**

| Impurity | Chemical Formula | Quantity (volume basis, vapor) |
|---|---|---|
| Nitrogen | $N_2$ | 78.11% |
| Oxygen | $O_2$ | 20.96% |
| Argon | Ar | 0.93% |
| Carbon Monoxide | CO | <0.6 ppm |
| Carbon Dioxide | $CO_2$ | <480 ppm |
| Methane | $CH_4$ | <8 ppm |
| Ethane | $C_2H_6$ | <0.1 ppm |
| Acetylene | $C_2H_2$ | <0.4 ppm |
| Ethylene | $C_2H_4$ | <0.2 ppm |
| Propylene | $C_3H_6$ | <0.2 ppm |
| Propane | $C_3H_8$ | <0.05 ppm |
| Other Hydrocarbons | $C_4$ + | <0.05 ppm |
| Ammonia | $NH_3$ | <0.01 ppm |
| Nitrous Oxide | $N_2O$ | <0.35 ppm |
| Nitrogen Oxides | NOx | <0.1 ppm |
| Ozone | $O_3$ | <0.1 ppm |
| Sulfur Dioxide | $SO_2$ | <0.1 ppm |
| Chloride | Cl | <0.1 ppm |
| Total Strong Acid | HCl + $NHO_3$ | <0.05 ppm |
| Dust | - | <0.2 mg/$Nm^3$ |

## Economic Analysis

The NETL baseline cases used for comparison to the SPOC process were carried out on a 2007 constant-dollar value basis, which required that the previous baseline data be adjusted to account for inflation.

The 550 MWe net SPOC plant total overnight capital (TOC) estimate was carried out on the overall plant equipment using an Association for the Advancement of Cost Engineering International (AACE) Class 5 basis.[5] This represents less than a 2% level of project definition, using a capacity factored or parametric modeling approach, and delivers a cost estimate between -50% and +100% in accuracy. The TOC can be broken down into lower-cost levels such as the total process capital (TPC) and the bare-erected cost (BEC). The items included in the development of the TOC estimate are detailed in Table 2-14 and consist of the manufacture, shipping, and labor costs to construct the plant.

[5] Recommended Practice 18R-97 of the Association for the Advancement of Cost Engineering International.

**Table 2-14**
**Total Overnight Cost**

| Cost Component | BEC | TPC | TOC |
|---|---|---|---|
| Process Equipment | * | * | * |
| Shipping and Fees (where applicable) | * | * | * |
| Installation Labor | * | * | * |
| Engineering, Procurement, and Construction (EPC) Contractor Services | | * | * |
| Process Contingency (+20 to 35% for unproven technology to +0-10% for commercially mature) | | * | * |
| Project Contingency (+15% to +30% of BEC, EPC fees) and Process Contingency | | * | * |
| Pre-Production Costs (6 months operating labor, 1-month maintenance materials/non-fuel consumables/waste disposal, 25% of one month of fuel, and +2% TPC) | | | * |
| Inventory Capital[6] (+0.5% TPC spares, 60 days of fuel and consumables) | | | * |
| Financing Costs (+2.7% of TPC, excluding interest) | | | * |
| Other Owners Costs (any prepaid royalties +15% of TPC, accounting for the front-end engineering design study, infrastructure improvements, legal fees, permitting costs, owner's engineering, and owner's contingency) | | | * |

The TOC value was used as the basis for the capital charge factor (CCF) that was applied to the cost of electricity (COE) calculations. The baseline cases were assessed using the assumptions in Table 2-15. The SPOC COE was assessed on an equivalent basis.

To ensure a fair comparison with baseline case S12A, all non-SPOC specific plant costs such as the air quality control system and ancillaries were scaled, where applicable, from baseline case S12A costs using the methodology outlined in NETL Capital Cost Scaling Methodology Quality Guidelines for Energy System Studies (QGESS).[7] The scaling parameters were determined from the results of the SPOC cycle model output that achieves a 550 MWe net plant output

**Table 2-15**
**Economic Analysis Assumptions**

| Parameter | Value |
|---|---|
| CCF (low-risk / high-risk Investor Owned Utility) | 0.1165–0.1243 |
| Capital Expenditure Period | 5 years |
| Operational Period | 30 years |
| Capital Cost Escalation during Expenditure Period | 3.6% annual rate |
| Distribution of TOC over Expenditure Period | 5-Years: 10%, 30%, 25%, 20%, 15% |

[6] Technical Assessment Guide (TAG®) Power Generation and Storage Technology Options: 2013 Topics. EPRI, Palo Alto, CA: 2014. 3002001434.

[7] Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology, DOE/NETL-341/013113, January 2013.

The resulting COE was calculated using the CCF and the TOC to account for the installed costs, along with the annual fixed costs (FC) and the variable costs for operations and maintenance (O&M):

$$COE(\$/\mathrm{MW}-\mathrm{hr}) = \frac{TOC * CCF + O\&M + FC}{CF * 8760 * MW_{net}}$$

The COE was expressed in base-year dollars (2017). TOC estimates were developed for the baseline SPOC system and a flexible variant, requiring additional expenditures for the oxygen supply system. The COE for both variants was calculated; however, the value associated with achieving rapid load following was not assessed.

# 3
# SPOC ASSESSMENT

## Introduction

A review of the original modeling and conceptual design work to date by WUSTL was carried out by DBL. The main objective of the concept review was to identify key technical risks associated with the design, in terms of performance and manufacturability, and to confirm the basis of design for the 550 MWe net, once-through, SC, coal-fired SPOC process. The concept review considered the following documents produced or presented by WUSTL:

- "Staged, High-Pressure Oxy-Combustion Technology: Development and Scale-up – Phase I Topical Report," DE-FE0009702, June 2013.
- "Staged, High-Pressure Oxy-Combustion Technology: Development and Scale-up – Final Technical and Economic Report," DE-FE0009702, June 2013.
- "Process Design and Performance Analysis of a Staged, Pressurized Oxy-Combustion (SPOC) Power Plant for Carbon Capture," *Gopan et al.* Applied Energy, 125, 179–188, 2014.
- "Effect of Operating Pressure and Fuel Moisture on Net Plant Efficiency of a Staged, Pressurize Oxy-Combustion Power Plant," *Gopan et al.* International Journal of Greenhouse Gas Control, 39, 390–396, 2015.
- "Control of Radiative Heat Transfer in High-Temperature Environments Via Radiative Trapping – Part I: Theoretical Analysis Applied to Pressurized Oxy-Combustion," *Xia et al.,* Fuel, 172, 81–88, 2016.
- Extract from 2016 NETL Meeting – SPOC Corrosion Test Results, DE-FE0009702.
- "Pressurized Oxy-combustion with Low Flue Gas Recycle: Computational Fluid Dynamic Simulations of Radiant Boilers," *Xia et al.,* Fuel, 181, 1170–1178, 2016.
- "An Approach to Estimating Flame Radiation in Combustion Chambers Containing Suspended-Particles," *Yang et al.,* Fuel, 199, 420–429, 2017.
- "Control of Radiative Heat Transfer and Ash Deposition in Staged, Pressurized Combustion Boiler," *Yang et al.,* Presentation July 2017.
- "Control of Radiative Heat Transfer in High-Temperature Environments Via Radiative Trapping – Part II: Application in Pressurized Oxy-Combustion with Low Flue Gas Recycle," *Xia et al.,* Draft Manuscript, 2017.

- “Staged, Pressurized Oxy-Combustion Boiler with Low Flue Gas Recycle. Part I: Burner Design and Scaling,” *Gopan et al.*, Draft Manuscript, 2017.
- “Staged, Pressurized Oxy-Combustion Boiler with Low Flue Gas Recycle. Part II: Operational Flexibility,” *Gopan et al.*, Draft Manuscript, 2017.

## Original Concept

The SPOC process employs a steam power cycle to generate electricity. As with atmospheric-pressure oxy-combustion processes, $CO_2$ capture rates of 90% or higher can be achieved. The staged-combustion approach of the SPOC process, when operated at an elevated gas pressure of nominally 16 bara (232 psia), allows for substantial reduction of flue gas recycle (FGR) and leads to significant improvements in efficiency and reduced costs.

As shown in Figure 3-1, the concept, as initially proposed by WUSTL,[8] is comprised of four separate downward-fired radiant furnaces connected in series in order of gas flow. Each stage has several design aspects that are like commercial radiant syngas cooler technology as applied to, for example, an integrated gasification combined cycle (IGCC) plant.

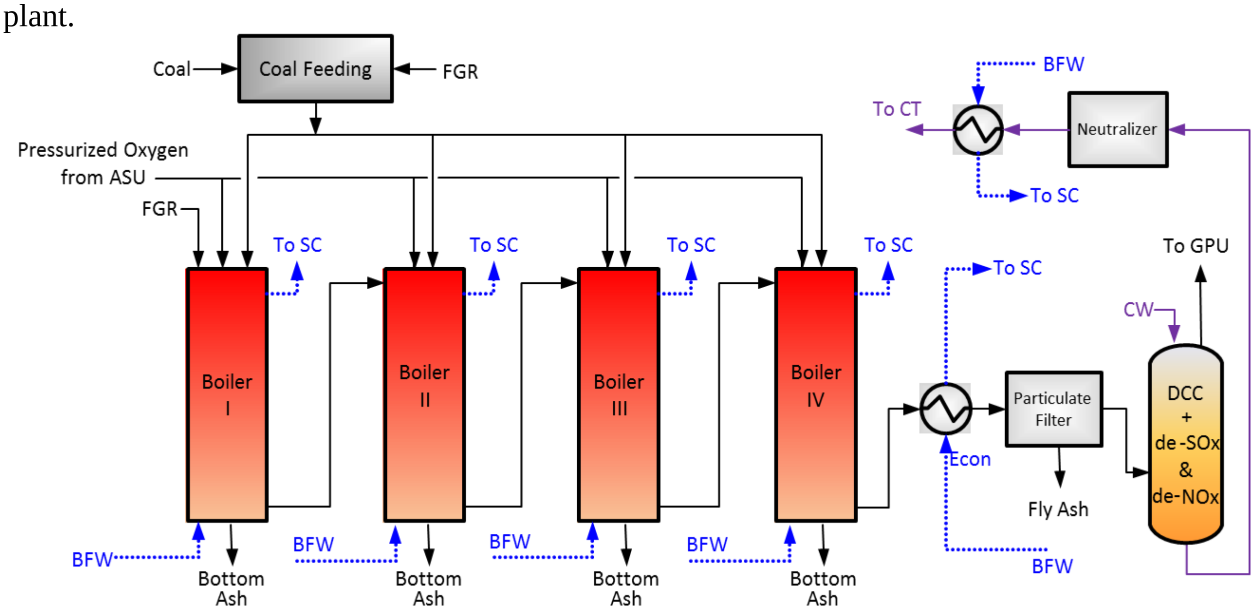



**Figure 3-1**
**Original SPOC Process Concept**

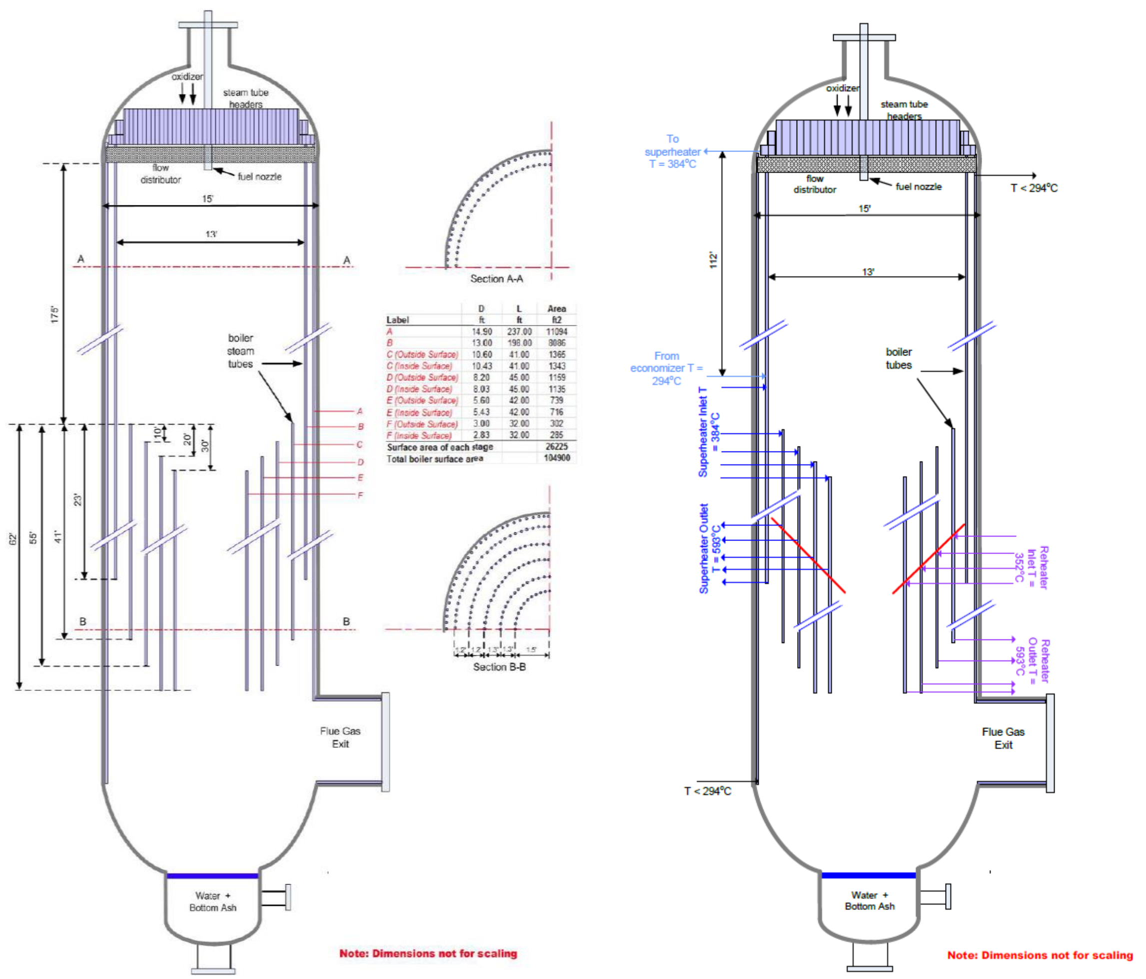
As initially proposed, PC is introduced to the combustion process at each stage, with most of the oxygen required for the entire SPOC process being introduced in the first stage, where it is only partially consumed. Each SPOC stage incorporates radiant and convective heating surfaces to raise steam and limit the exit flue gas temperature

8 Staged, High-Pressure Oxy-Combustion Technology: Development and Scale-up – Phase I Topical Report, DE-FE0009702, June, 2013

progressing to the next SPOC stage, where further fuel and strategic amounts of oxygen are introduced allowing further combustion and heat release.

The fuel staging and dilution from the products of combustion as well as excess oxygen limit the gas temperatures in the SPOC process to levels comparable to those associated with atmospheric oxy-combustion. Also, HP operation leads to radiative trapping that reduces radiative heat flux to the walls. This results in a minimal need for FGR, thereby reducing both the capital and operating costs and the $CO_2$ capture energy penalty due to lower flue gas flow rates and blower power.

The original SPOC boiler concept, shown in Figure 3-2, consisted of a PV with internal membrane wall tubes to provide protection to the shell from incident thermal radiation. The long, narrow combustion zone was surrounded by vertical steam tubes to capture the radiative heat flux. The lower portion of the PV contained additional heating surfaces consisting of vertical steam tubes arranged in concentric circles of differing diameters.




| Label | D ft | L ft | Area ft2 |
|---|---|---|---|
| A | 14.90 | 237.00 | 11094 |
| B | 13.00 | 198.00 | 8086 |
| C (Outside Surface) | 10.60 | 41.00 | 1365 |
| C (Inside Surface) | 10.43 | 41.00 | 1343 |
| D (Outside Surface) | 8.20 | 45.00 | 1159 |
| D (Inside Surface) | 8.03 | 45.00 | 1135 |
| E (Outside Surface) | 5.60 | 42.00 | 739 |
| E (Inside Surface) | 5.43 | 42.00 | 716 |
| F (Outside Surface) | 3.00 | 32.00 | 302 |
| F (Inside Surface) | 2.83 | 32.00 | 285 |
| Surface area of each stage | | | 26225 |
| Total boiler surface area | | | 104900 |

**Figure 3-2**
**Original SPOC Boiler Concept**

## Concept Review

### *Original SPOC Boiler Concept*

The proposed SPOC boiler concept shown in Figure 3-2 presents several challenges. In particular, the arrangement of concentric heating surface would need a significant design effort to ensure the concept can be engineered to deliver structural and mechanical integrity including differential expansion and resistance to vibration. The location and number of headers and penetrations through the PV also increase the design complexity and ultimately impact cost. Although it is anticipated that these design challenges could be overcome, the solutions may require a greater capital expenditure (CAPEX) and increased technical risk compared to alternative designs that could deliver a similar performance.

The total heating surface was investigated during this project utilizing proprietary boiler OEM design tools. The tube pitching (center-to-center distance between the tubes) proposed in the boiler concept was found to be tighter than what would generally be considered acceptable for atmospheric-pressure systems, although the SPOC system operates under pressure. Also, with the proposed arrangement, the propensity for slagging and fouling of the boiler heating surface was deemed a concern. Excessive slagging and fouling would impact the effectiveness of heating surfaces and hence the amount of heating surface area required. In addition, excessive fouling and slagging could lead to significant additional gas-side pressure drops resulting in further operational issues or decreased availability and increased maintenance. It is noted that the anticipated flow regime in the SPOC boiler has been modeled with computational fluid dynamics (CFD) with the results predicting a reduced particle impact rate when compared to a conventional coal boiler plant.[9] The CFD modeling also anticipates that the ash deposition temperatures will be below that of the ash fusion temperature. These results suggest that fouling and slagging will not be a problem. However, this modeling requires further validation to ensure the results are robust, and in the development stage it was deemed prudent to consider design changes that could reduce this risk with no envisioned impact on either CAPEX or operational expenditure (OPEX).

### *Vessel Arrangement and Sizing*

The four stages proposed for the SPOC process concept in Figure 3-1 are capable of operating with near-zero FGR, while maintaining acceptable post-combustion temperatures. Based on the results of previous work carried out by WUSTL,[10] four stages are considered as the maximum number practical due to economics and the complexity that further stages would add, with limited additional benefit. While there may be

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[9] Yang et al. Control of radiative heat transfer and ash deposition in staged, pressurized combustion boiler, Presentation July 2017

[10] "Staged, High-Pressure Oxy-Combustion Technology: Development and Scale-up – Final Technical and Economic Report," DE-FE0009702, June 2013.

advantages to reducing the number of stages, this must be balanced against heating surface area requirements and the overall system flexibility and controllability.

As the SPOC system operates under an elevated pressure of nominally 16 bara, the combustion envelope and all downstream equipment such as convective heat transfer banks need to be fully contained within PVs. These PVs are preferably transportable, requiring the maximum sizes to be constrained to that of typical shipping limits. Figure 3-2 shows the original SPOC boiler concept with a diameter of 4.2 m (14 ft) and height of more than 76.2 m (250 ft). Generally, vessels are limited to approximately 4.2 m (14 ft) diameter and 61 m (200 ft) in length to allow for economic shipping by road or rail.[11,12] While it is possible to construct large vessels on site, it is likely to be more economical to manufacture vessels off-site. Shops for fabrication of large PVs are designed to accommodate the largest vessels that may be transported by rail.

From a manufacturing, sparing, and economics viewpoint, having all boiler stages within the SPOC system concept identical in terms of sizing and heating surface would be beneficial.

### *Burner Design*

An axial-flow burner has been proposed to ensure slower mixing and a more axially-distributed heat release than a swirl-stabilized burner. While swirling flow is required for flame stabilization in air-fired and first-generation oxy-combustion systems, the SPOC system utilizes a novel burner design and elevated oxygen concentration in the oxidizer flows to ensure flame stabilization.

The proposed SPOC concept incorporates a down-fired boiler configuration primarily to avoid bottom ash hitting the burner, as would be the case in an up-fired arrangement. To minimize the impact of buoyancy, which could negatively affect flame shape and wall heat flux, the initial section of the boiler is designed as the frustum of a cone, as shown in Figure 3-3.

A concern with the original SPOC concept is that the burners for each stage must be capable of firing sufficient coal to deliver enough thermal input at the 550 MWe plant scale (approximately 375 MWth per stage for a 4-stage system) but the operating conditions of each stage are different. As full-scale testing of burner performance has not been performed, there is significant uncertainty about burner performance, in particular when targeting low excess oxygen levels, desirable for reducing auxiliary power requirements.

The CFD modeling carried out to date for the SPOC combustor concept with 375 MWth heat input delivers peak wall heat fluxes in the range 400–450 kW/m$^2$ (0.127–0.143 MMBtu/hr-ft$^2$). This range is acceptable for OEM boiler design considerations.

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[11] Staged, High-Pressure Oxy-Combustion Technology: Development and Scale-up – Final Technical and Economic Report, DE-FE0009702, June, 2013

[12] U.S. Department of Transportation Federal Highway Administration, Federal Size Regulations for Commercial Motor Vehicles, https://ops.fhwa.dot.gov/freight/publications/size_regs_final_rpt/

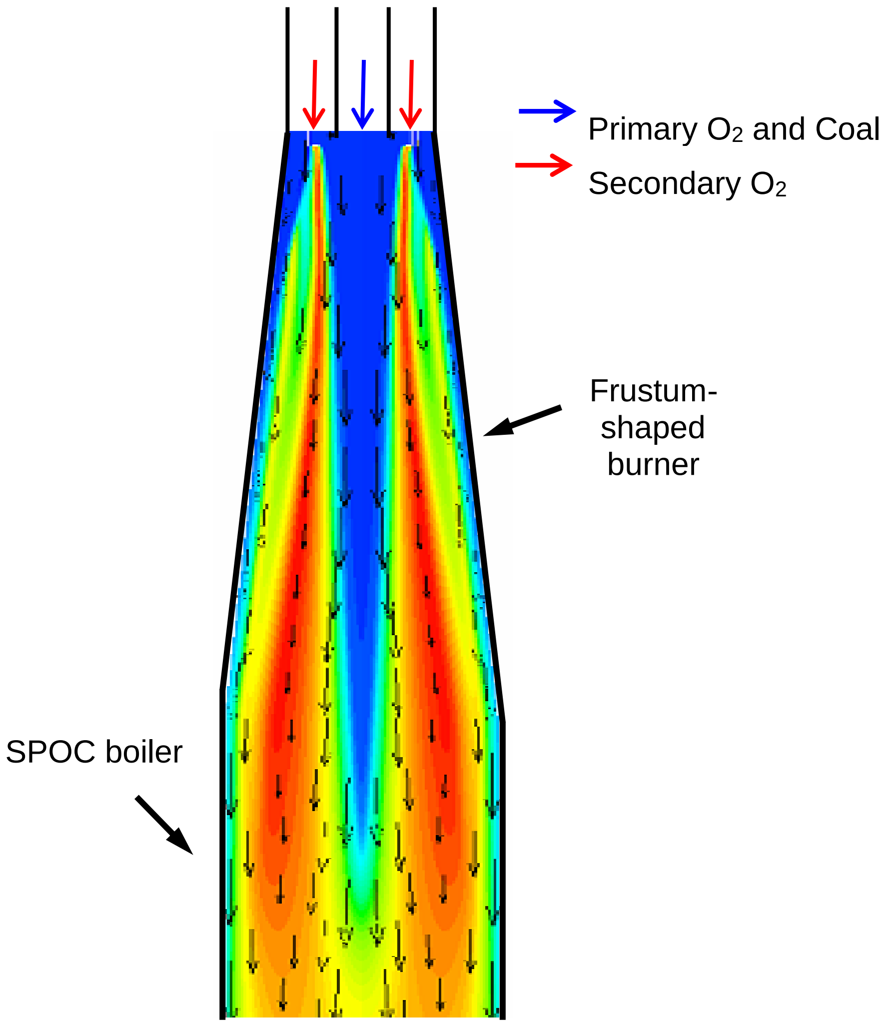


**Figure 3-3**
**Original SPOC Burner Concept**

### *Fuel Selection and Fuel Handling*

The design fuel has been selected as sub-bituminous Montana Rosebud PRB coal,[13] which adds a degree of both technical and commercial risk compared to a higher-rank bituminous coal. The slagging and fouling characteristics of PRB are greater resulting in the need for increased tube pitch and online cleaning systems, which increase PV sizing and hence CAPEX. Additionally, the use of a lower-rank coal has a significant effect on plant sizing due to the additional fuel-firing requirement and the resultant larger flue gas

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[13] Enabling Staged Pressurized Oxy-Combustion: Improving Flexibility and Performance at Reduced Cost: Design Basis DE-FE-0029087 – Design Basis, DOE-EPRI-29087-1, May 2017.

flows required to achieve the same duty in comparison to a higher-rank coal. Compared to a bituminous coal, a plant utilizing PRB will be 7% larger from a heat input perspective alone. This results in additional CAPEX for larger equipment and increased OPEX through increased auxiliary power consumption. Therefore, the base cases selected for comparison use the same PRB fuel.[14,15]

The SPOC fuel delivery concept requires dry-coal feeding using a lockhopper arrangement as this has been shown to yield considerably higher efficiencies than slurry feeding. While HP dry-coal pumps are being developed to deliver dry coal at up to 40 bar without the aid of motive gas, lock-hopper pneumatic dry-feeding systems are commercially available and have a history of proven operation in the gasifier industry.[16] They require a small amount of motive gas for feeding the coal in dense phase. Given the proven performance of the lock-hopper systems and the lower operating pressure required by the SPOC concept compared to gasifier operation, lock-hoppers are used in this design.

The main concern with respect to the proposed SPOC fuel delivery concept is that fuel surface moisture could potentially lead to "clumping" in the feed system. To reduce this risk, the dry nitrogen waste stream from the ASU is utilized for surface drying of the fuel, thereby reducing the possibility of clumping during transport operations.

### *Particulate Removal*

The SPOC system concept proposes the use of candle filters for PM removal. Both metal and ceramic candle filter elements have been utilized in industry but ceramic filters are susceptible to breakage, which would negatively impact performance and availability. Candle filters have been extensively used in the gasifier industry and would have an analogous application in the SPOC system. From an operational point of view, a key concern in utilizing candle filters is the high pressure drop, resulting in an increased CAPEX for compression equipment and OPEX for auxiliary power.

### *Ash Management and Ash Handling*

The SPOC concept proposes the use of wet bottom removal for ash and slag. This process is analogous to gasifier systems where a lock-hopper system is used for removal of bottom ash and slag from pressurized to atmospheric conditions. Failure in the ash handling system would be detrimental to performance, reliability, and availability and the application of this technology to the novel SPOC concept is untested; however, using an established technology reduces the technical risk. The biggest concern in the proposed concept is that flue gas is exposed to concentrically arranged, convective heating surfaces prior to any ash removal, resulting in increased fouling, slagging, and erosion potential.

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[14] Cost and Performance Baseline for Fossil Energy Plants Volume 3b: Low Rank Coal to Electricity: Combustion Cases DOE/NETL-2011/1463.

[15] Cost and Performance for Low-Rank Pulverized Coal Oxycombustion Energy Plants – Final Report DOE/NETL-401/093010.

[16] Gasification - Feed Systems, NETL https://www.netl.doe.gov/research/coal/energy-systems/gasification/feed-systems

If fouling and slagging in the boiler are considered a risk, then each SPOC boiler stage may require the use of online cleaning systems. If no online cleaning is carried out, excessive slagging and fouling would impact the effectiveness of the heating surfaces, increasing the amount of surface needed. In addition, fouling could lead to significant gas-side pressure drops resulting in operational issues that could decrease availability and increase maintenance requirements. The proposed SPOC boiler concept with concentrically arranged heating surface is not conducive to typical PC boiler online cleaning methods, such as steam-driven sootblowers. Nonetheless, pneumatic hammer wrapping systems have successfully been implemented in gasification process applications.[17]

### *Other Possible Risks for the Proposed SPOC Concept*

Several other potential concept risks have been identified through the concept review as it relates to scale up of the process:

<u>Extent of Erosion and Corrosion</u>

The extent of anticipated erosion and corrosion through the SPOC system is not known and could have an adverse effect on both pressure parts and balance-of-plant (BOP) resulting in system performance issues, decreased availability, and increased maintenance. It is noted that some work has been carried out with respect to corrosion testing related to SPOC under a previous award.[18]

<u>Validation of Boiler Performance Modelling</u>

The 100 kWth SPOC test rig has no installed boiler heating surface with which to validate modeled boiler performance predictions. The lack of a means to validate data may result in a significant over- or under-estimate of boiler heating surface requirements.

<u>Concept Scale Up</u>

The design rules for scale up of the SPOC concept from 100 kWth to 550 MWe have not been fully established and the risk is that the design basis for scale-up is not robust enough leading to errors in system design and sizing.

<u>Concept Plant Flexibility</u>

At this stage of concept development, it is not possible to properly assess the pressure part scantlings in terms of maximum allowable ramp rates and allowable operational flexibility against impact on design life.

## Proposed Concept Improvements and Risk Mitigation

This section represents the OEM review on proposed improvements for mitigation of technical risk. Appendix A provides a tabulated summary, in the form of a Risk Matrix,

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[17] Gunter Keintzel and Leszek Gawlowski, "Planung Und Aslegung Der Dampferzeuger Fur Kohle-Kombikraftwerke, VGB Special Conference Buggenum IGCC Demonstration Plant, 1993.

[18] Extract from 2016 NETL meeting – SPOC Corrosion test results, DE-FE0009702

of the perceived key technical issues with suggested proposals for consideration in mitigating the risks and defining the optimized arrangement for the 550 MWe commercial-scale version of SPOC.

### *Layout*

The key concerns with regards to the original layout are associated with the proposed concentric heating surface arrangement; particularly in terms of mechanical design requirements and propensity for fouling and slagging. The proposed mitigation is to consider an alternate SPOC furnace/boiler configuration with each SPOC stage comprising a "two-pass" downward-fired radiant vessel and upward-flow convective boiler arrangement with heating arranged in cross flow as shown in Figure 3-4.

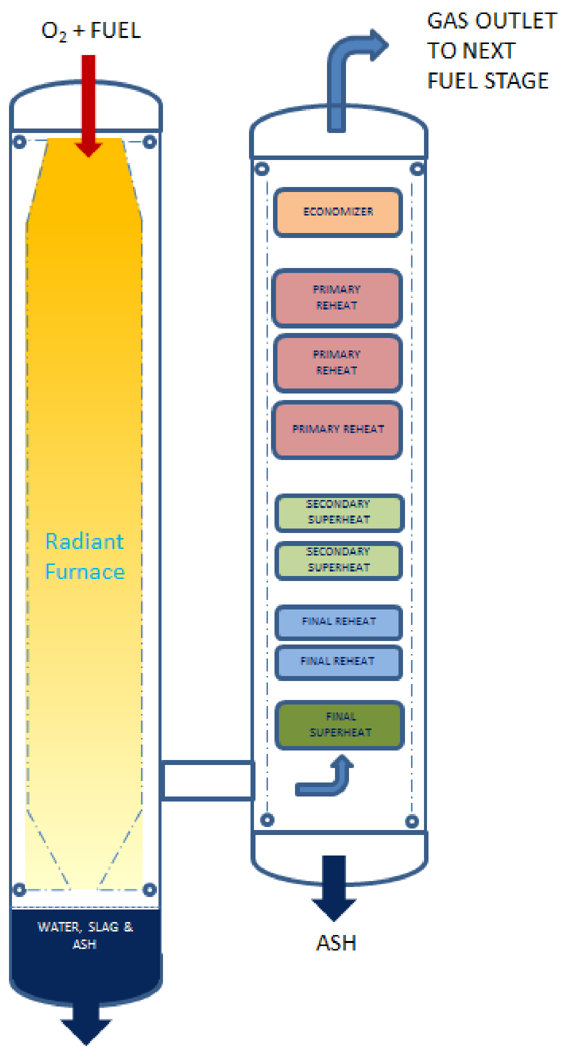



**Figure 3-4**
**Alternative SPOC Boiler Concept**

It should be noted that the heating surface arrangement shown in Figure 3-4 is indicative and a more detailed configuration is presented in Chapter 5.

This alternative SPOC boiler arrangement also provides technical risk mitigation with respect to the potential for excessive slagging and fouling as there can be a degree of ash and slag management (momentum change at the bottom of the Combustor PV) prior to the flue gas contacting the convective heating surface. In addition, OEM design rules will be considered for tube pitching and an allowance for an amount of excess effective heat transfer surface will be made.

### *Vessel Arrangement and Sizing*

The number of SPOC stages required will be driven by both heating surface requirements and vessel sizing economics. Although vessels are generally limited to approximately 4.2 m (14 ft) in diameter, vessels of 7 m (23 ft) and greater in diameter are routinely transported, although this can add significant cost.

In Chapter 3 it was identified that from a manufacturing, sparing, and economics viewpoint, having all boiler stages within the SPOC system concept identical in terms of sizing and heating surface would be beneficial.

### *Burner Design*

Concerns regarding burner design identified in Chapter 3 included uncertainties in the CFD model at scale and the char burnout. The performance of the burner at scale will remain a concept risk until detailed engineering is carried out and there is a practical demonstration at significant pilot plant scale (approximately 10 MWth per stage) of the complete SPOC boiler system to ensure the basis for scale up is robust. To address concerns of combustor performance in the less-oxygenated SPOC stages, combustion testing of anticipated final SPOC stage conditions was carried out as part of this project and requirements for alternative designs were developed as discussed in Chapter 5.

### *Fuel Selection and Fuel Handling*

The SPOC concept design was developed utilizing Montana Rosebud PRB with inference that a higher-rank coal is likely to give improved economics and process performance.

### *Particulate Removal*

The use of candle filters is considered acceptable given their demonstration in the analogous PM removal process done in commercial IGCC units. In the Wabash River Plant IGCC, ceramic candle filters were installed but suffered from filter element breakage. The ceramic candle filters were replaced by a metallic variant that has given a candle element life of 10,000 hours. In some cases, candle filters have been paired with an upstream cyclone separator to optimize cost, removal efficiency, and equipment sizing. To minimize technical risks. the use of metallic filters is recommended for the SPOC concept to improve availability albeit at the expense of increased CAPEX. Further work, beyond the scope of this project, is required to determine the optimum solution that balances CAPEX and OPEX (e.g., auxiliary power vs. direct-contact cooler [DCC] water treatment costs, etc.) vs. removal efficiency and process requirements.

### *Ash Management and Ash Handling*

The proposed concept for ash handling is considered robust given its implementation in the analogous IGCC process. The risk of application to the novel SPOC system concept will be mitigated further by carrying out detailed engineering design and a practical demonstration at pilot scale.

The implementation of the alternative SPOC concept utilizing a “two-pass” arrangement as per Figure 3-4 is conducive to improved ash management with a degree of ash removal prior to the flue gas contacting the convective heating surface. In addition, having the boiler heating surface arranged in a cross flow rather than concentrically allows for cavities in the heating surface to be more easily created, subject to vessel height, providing easier implementation of traditional on-line cleaning methods such as sootblowers, mechanical rapping, or shock-pulse generators.

### *Other Identified Risks for the Proposed SPOC Concept*

Other identified technical risks will be mitigated through application of OEM knowledge and experience, design rules, and design tools to the modified concept design as far as is reasonably practicable given the available SPOC process performance data. To mitigate risks further (outside the scope of this current project), it is recommended that the developed SPOC concept undergoes detailed engineering design with practical demonstration at significant pilot-plant scale, likely in the >1 MWth size range.

## Summary

A review of the original conceptual modeling and design work was undertaken, and several key concept risks and consequences were identified. Following identification, potential mitigation steps were identified with recommendations for design changes to the original SPOC boiler and system concept. The concept risks and high-level ratings and mitigations are summarized in the Risk Matrix presented in Appendix A.

At this stage of conceptual design, the SPOC system seems viable with the potential to deliver flexible performance. Several of the key concerns have been addressed, although ultimately there is still a degree of uncertainty and risk given the scale of process performance testing, lack of boiler surface for validation, and reliance on CFD and modeling. The residual risk could be further mitigated through detailed engineering design with practical demonstration at significant pilot-plant scale.

# 4
# COMBUSTION TESTING

An essential requirement for the development of the SPOC process is a rigorous experimental test program that can validate the combustion process at a scale that is commensurate with the present level of development. This chapter provides details of the pilot-plant upgrade activities, testing objectives, the testing plan, and the testing execution.

## 100 kWth Pilot-Scale Combustion Facility

The pressurized combustion test facility at WUSTL has been designed to operate at up to 16 barg (232 psig) and can fire at 100 kWth input. The system represents a single SPOC stage, and it uses synthetic FGR. Figure 4-1 shows a schematic of the facility. It is comprised of pressurized combustor, gas supply system, coal feeding system, and diagnostic system.

The oxygen and $CO_2$ are both provided by bulk liquid tanks, from which gases are vaporized and delivered to the combustor at 21.7 bara (314.7 psia). Air is supplied by two compressors with one as backup. Methane is used as gaseous fuel for ignition and reactor preheating and is supplied by HP cylinders.

Coal feeding is designed to be a batch process to avoid a complex lock-hopper system. Before operation, coal is charged into a gravimetric screw feeder inside a coal vessel. Then the coal vessel is pressurized to the target operating pressure. During operation, coal is fed into a vibrating feeder, which is mounted inside a transfer pipe. The pressures inside the coal vessel and transfer pipe are equalized. A vibrating feeder provides uniform and steady feeding. Coal particles fall into the burner, mainly by gravity, supplied by a small stream of $CO_2$.

The pressurized combustor is a scaled-down version of a single-stage, commercial-scale SPOC combustor PV, as shown in Figure 4-2. The pilot combustor is approximately 6 m (19.7 ft) long and is mainly comprised of a PV, an internal reactor, a burner, and a water-quench section. The PV is rated at 20 bara (290 psia) and contains multiple sections with access ports for instrumentation. The internal reactor, placed at the center of the PV, is composed of a 0.3 m (1 ft) long, conical-shaped quartz tube at the top, and a 2.7 m (8.9 ft) long refractory tube at the bottom. The quartz tube provides full-view optical access to the flame. The refractory tube has six access ports distributed at three different heights.

Vessel walls surrounding the quartz tube region are lined with cooling water coils to prevent overheating of the walls by radiation coming from the flame. A stream of $CO_2$ purge gas enters the annular space between the reactor and the PV from the top of the vessel and leaves at the bottom of the vessel. The flue gas from the reactor is cooled to less than 120°C (248°F) by water sprays generated by six nozzles in the water-quench section before it goes through the pressure control valve and is vented through the exhaust line. Water level in the quench section is controlled at a fixed level during operation.

The internal reactor design features a down-fired flame and a co-axial, low-mixing flow. This unique design ensures a long and straight flame and hence more axially distributed heat release, which helps prevent excess heat flux on the wall at elevated pressure. A down-fired combustor configuration was chosen over an up-fired for several reasons, the most obvious being that an up-fired burner would be prone to bottom ash hitting the burner. Another benefit of an axisymmetric, axial-flow burner is that radial velocity components, which would cause ash deposition and slagging, are minimized.

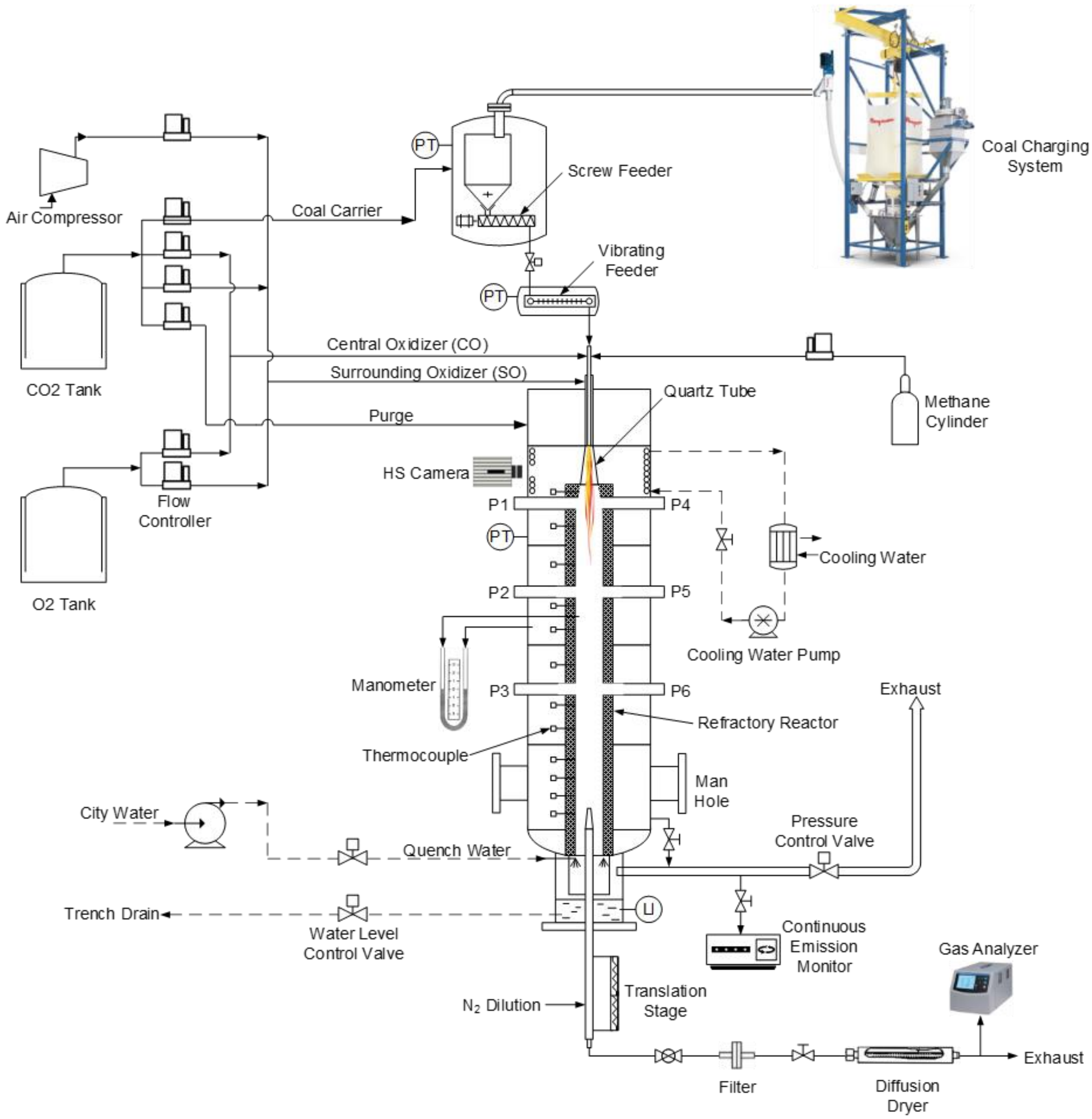



**Figure 4-1**
**Schematic of the 100 kWth SPOC Pilot Testing Facility**

**Figure 4-2**
**Photo of 100 kWth Pressurized Combustor of the SPOC Pilot Testing Facility**

A summary of the combustion diagnostic capabilities of the research facility is provided in Table 4-1. The flame shape and flow patterns are capture by a high-speed, high-resolution camera. The inner wall temperatures of the reactors are measured by type-K thermocouples embedded inside the wall (0.32 cm [1/8 inch] away from the inner wall surface). The flue gas composition in the exhaust line is measured continuously using a continuous emission monitor. An in-house designed pressurized sampling probe was utilized to sample flue gas and fly ash particles. It can move along the centerline of the reactor and take samples at different heights. Another in-house built sampling probe is used to sample fine particles (<10 µm). It is designed with multi-stage dilutions to prevent bias during sampling and depressurization. The sampled gas composition is continuously monitored with an Horiba multi-gas analyzer and, when needed, with Fourier-transform infrared spectroscopy. The sampled fine particles are analyzed by an Electrical Low-Pressure Impactor (ELPI) or Scanning Mobility Particle Sizer (SMPS) to determine particle size distribution. Two types of heat flux measurement can be conducted. One is total heat flux measurement with a heat flux sensor; the other is a narrow-angle radiation measurement with an in-house built narrow angle radiometer.

**Table 4-1**
**Diagnostic Capabilities of the SPOC Research Facility at WUSTL**

| Measurement | Device |
|---|---|
| Visual Observation of Flames | High-resolution, high-speed camera |
| Wall Temperatures | Embedded thermocouples |
| Exhaust Gas Composition | Continuous emissions monitoring system |
| Gas and Particle Sampling | Translatable gas and particle sampling tube<br>In-house built fine-particle sampling probe |
| Sampled Gas Composition | Horiba multi-gas analyzer<br>Fourier-transform infrared spectroscopy |
| Sampled Particle Size Distribution | ELPI and SMPS |
| Ash Composition | Thermogravimetric analysis (TGA) system<br>Energy-dispersive X-ray spectroscopy |
| Ash Morphology | Scanning electron microscope |
| Heat Flux | Medtherm Schmidt-Boelter heat flux sensor<br>In-house designed narrow angle radiometer |

## Pilot Facility Retrofit and Upgrade

For this project, major retrofit and upgrade activities have been carried out. WUSTL also held a process safety review meeting with internal and external experts in combustion processes and oxygen safety to review the pilot facility with respect to potential safety hazards. All recommendations were addressed prior to operating the facility at high pressure. These activities ensured that the facility would operate safely and reliably at target operating conditions.

### *Facility Retrofit*

The retrofit activities included two parts. The first part focused on improving the burner and reactor designs such that the combustor can properly simulate the environment that the coal particles would experience inside a full-scale SPOC boiler. The second part focused on improving optical and physical access for combustion diagnostics.

Figure 4-3 shows the geometries of the burner before and after retrofit. Both burners incorporate a co-axial flow design and operate in a non-premixed combustion mode. The burner before retrofit only included two reactant streams with a central fuel stream surrounded by a oxidizer stream (Figure 4-3a), while the burner after retrofit incorporates three reactant streams with a central oxidizer stream surrounded by a fuel stream in an annulus, which is further surrounded by a surrounding oxidizer stream (Figure 4-3b). This design enhances operating flexibility. The flame length can be easily controlled by adjusting the central and surrounding oxidizer. The oxygen concentration in both central and surrounding oxidizer streams can be varied between 0–100 vol %.

The new burner was tested in a separate facility (30 kWth in size), which operates at atmospheric pressure before being installed in the pressurized facility. In this separate facility, this burner was successfully fired over a wide range of operating conditions, including extreme conditions such as 100% oxygen concentration in the oxidizer. During this testing, the burner design was shown to be very reliable and flexible.

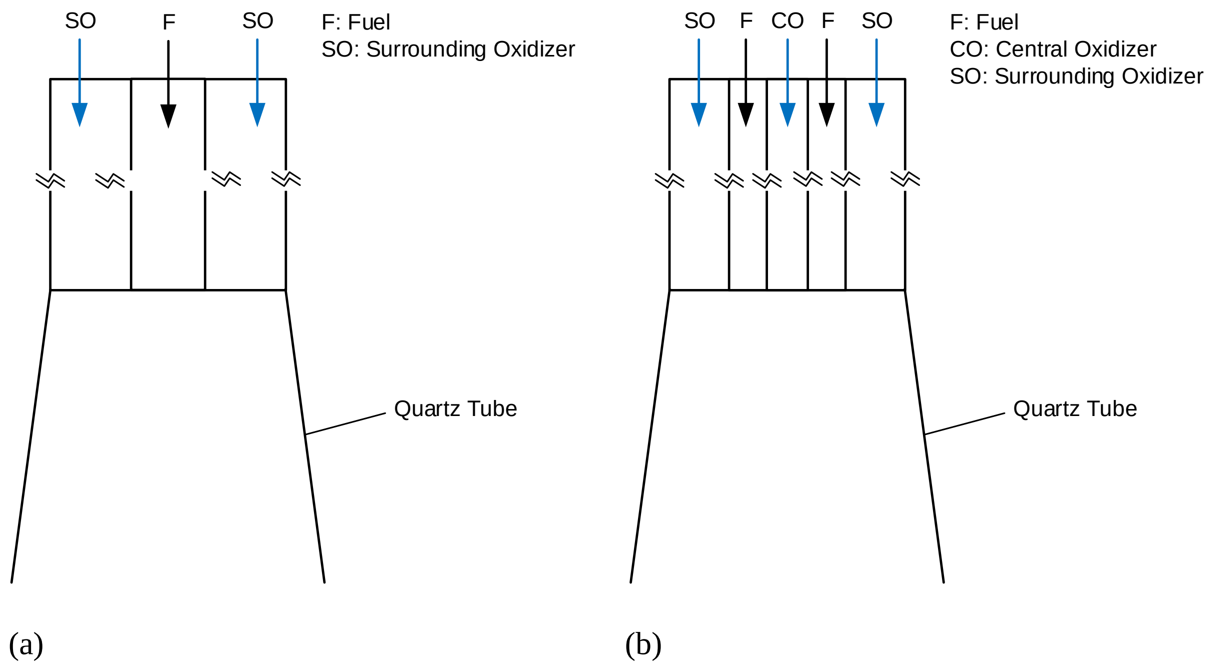



**Figure 4-3**
**Geometries of the Burners (a) Before Retrofit and (b) After Retrofit**

The reactor is composed of a conical-shaped quartz tube and a cylindrically-shaped refractory tube. Before retrofit, the maximum internal diameter of the reactor was 0.14 m (5.5 inches). Initial testing and CFD simulations both indicate that at this size an internal recirculation zone forms below the flame due to buoyancy. This internal recirculation zone can lead to excess ash deposition on the walls adjacent to this zone. After redesign using the CFD model, a new refractory tube was installed with an internal diameter of 0.127 m (5 inches). Testing results after retrofit demonstrated that the internal recirculation zone was successfully removed. The modified reactor also included additional ports for gas and particle sampling and heat-flux measurements.

One of the objectives of this project was to use the pilot-scale combustor to simulate the temperature environment that coal particles would experience in a utility-scale SPOC boiler. Since the residence time (~5 sec) of the pilot-scale combustor is smaller than that of a SPOC boiler (~22 sec), the goal is to have the pilot-scale combustor simulate the early stage (i.e., first ~5 sec) of the SPOC boiler, because this stage is where the main combustion processes occurs. After this stage, the particle burning is complete, leaving only physical processes (the heat of the flue gas is transferred to the water in the boiler walls). This goal required special consideration of the heat transfer characteristics of the reactor walls in the design such that the gas temperature profile inside the reactor can be maintained like that in a full-scale boiler. For this purpose, different types of refractory materials were adopted for different sections of the reactor. Figure 4-4 shows the temperature histories of a 50-µm coal particle in the pilot-scale combustor and a full-scale SPOC boiler predicted by CFD simulations. As shown, the particle temperature history in the pilot-scale combustor matches reasonably well with that of the full-scale SPOC boiler in the first 5 seconds.

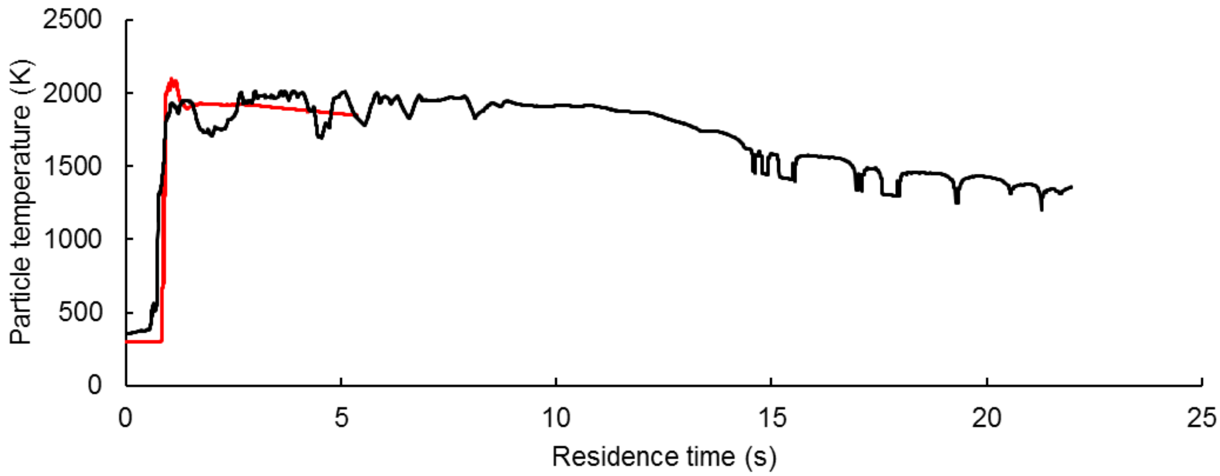



**Figure 4-4**
**Temperature Histories of a 50 μm-Coal Particle in the Pilot-scale Combustor and a Full-scale SPOC Combustor Predicted by CFD Simulation**

To improve the optical access for visually capturing flame shape and flow pattern, a larger conical-shaped quartz tube with ignition and sampling ports was installed shown in Figure 4-5.

This quartz tube served as the top part of the reactor internals and provided significantly improved visual access to the flame for cameras (including high-speed camera) and laser diagnostics. Around the quartz tube, water-cooled coils were installed to cover the internal surface of the PV to prevent overheating and to provide heat loss data from the quartz tube.

A flow control valve was also added to control the $CO_2$ purge flow rate leaving the PV, as shown in Figure 4-1. Since the $CO_2$ purge flow entering the PV is fixed, by adjusting the new added flow control valve at the outlet side, the pressure outside the reactor can be adjusted, ensuring that this pressure is equal or slightly higher than that inside the reactor. In this way, flue gas leakage to the PV can be avoided. The pressure difference between inside and outside of the reactor is measured by a pressurized manometer.

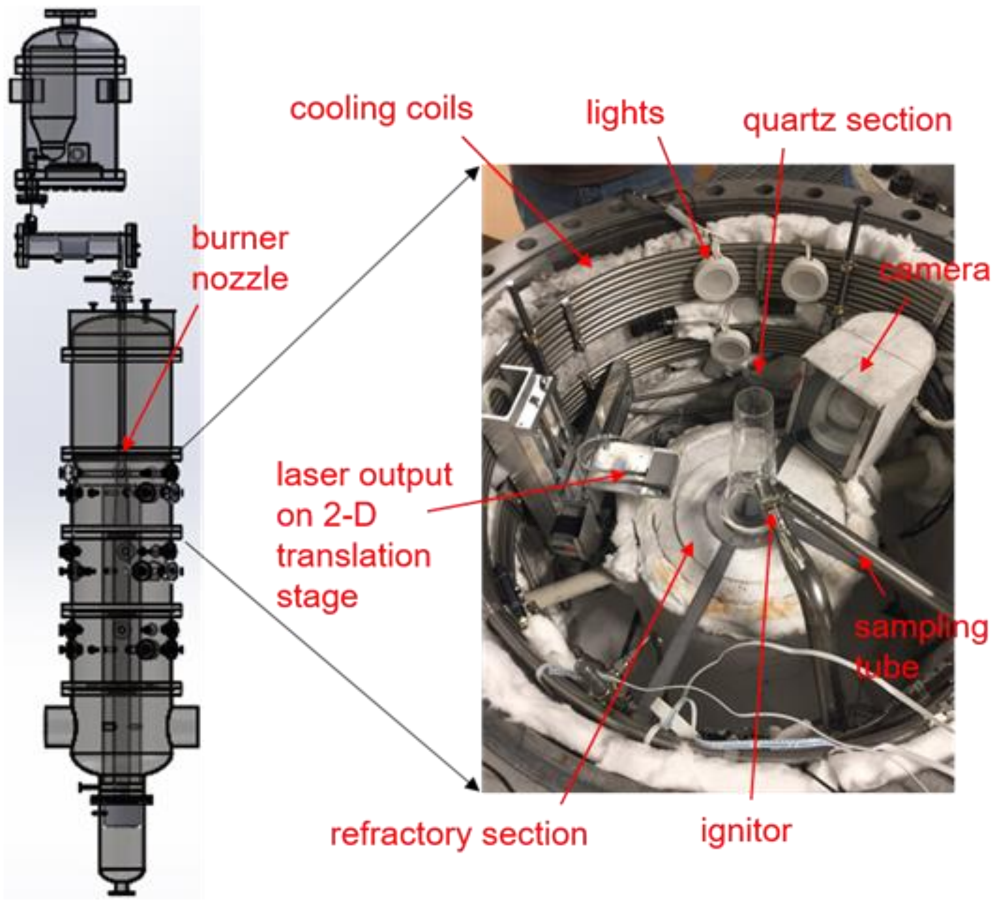



**Figure 4-5**
**Picture of Internals of SPOC Pilot Pressure Vessel**

### *Facility Upgrade*

The facility upgrade focused on two parts: diagnosis instrumentation and system automation. The diagnosis instrumentation upgrade included measurement equipment for fluid flow visualization, gas composition, particle size and composition, and heat transfer. System automation upgrades included hardware and software upgrades.

To evaluate soot formation inside the flame, a laser diagnostic system together with multi-axis translation stages were designed and installed inside the PV along with the quartz tube. The laser diagnostic system incorporated a red-green-blue three-color laser and can provide the particle volume fraction and temperature information. A fiber optic laser output with a cylindrical lens was installed, which produced a laser sheet and was used to detect particles in the flow. This laser is mounted on a 2-D translation stage. The multi-axis translation stages allow for a two-dimensional scanning of the flame through the quartz tube.

A pressurized multi-function sampling probe was designed as shown in Figure 4-6. Both gas and particles can be sampled together by the sampling probe.

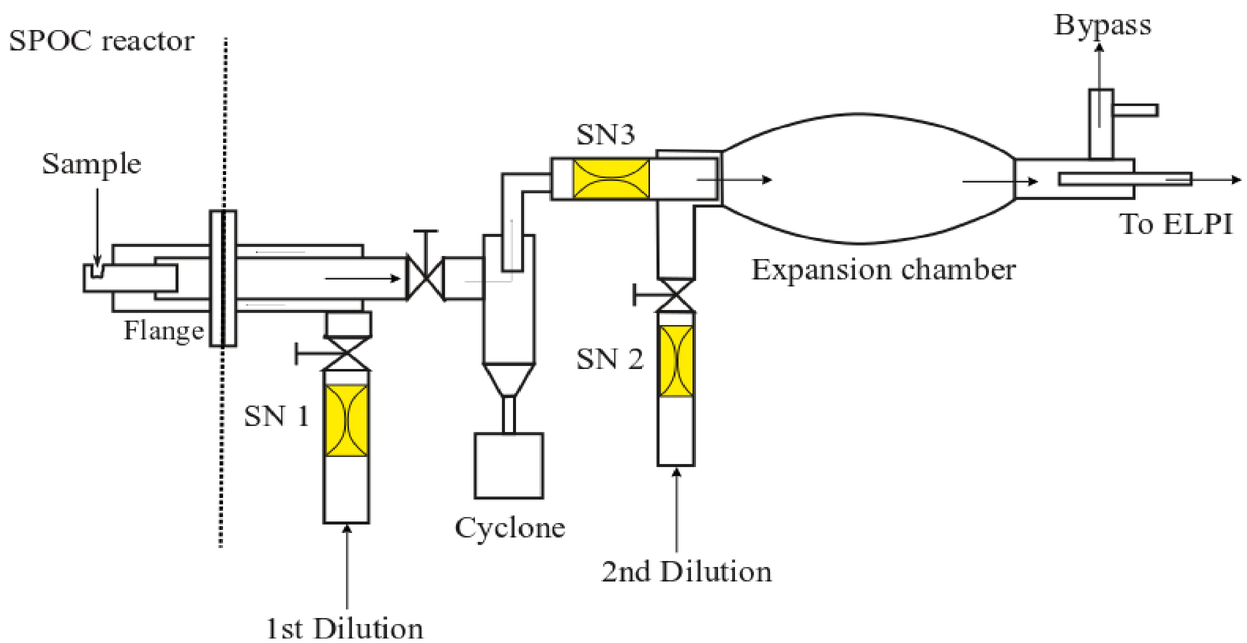



**Figure 4-6**
**Schematic of a Two-stage Dilution Gas and Particle Sampling Probe**

The probe has two-stage nitrogen dilutions. The first-stage dilution is hot at the inlet of the probe, which is used to prevent particle inception and condensation. The second dilution is where the sampled stream is depressurized. It is used to avoid acid and moisture condensation and forms a shield flow around the inner surface of the expander to prevent particle impaction on the expander wall. The two-stage dilution ratios can be accurately adjusted according to the operating pressure and temperature. The coarse particles were captured by an in-house built pressurized cyclone, and the remaining fine particles were fed into a SMPS or the ELPI to measure the particle size distribution.

Another pressurized sampling probe was designed to collect fly-ash particles and gas along the centerline of the reactor as shown in Figure 4-7. The sampling probe draws around 30 standard litre per minute (SLPM [1.06 scfm]) flue gas. The sampled flue gas is diluted by a stream of around 30 SLPM (1.06 scfm) nitrogen. Then the mixed stream passes through a filter, which is used to collect fly-ash particles. After the filter, the stream is depressurized through a needle valve, and then a slip stream of the flue gas (0.4 SLPM [0.01 scfm]) is drawn to a diffusion dryer. After drying out the moisture, this slip stream enters the Horiba portable gas analyzer (Model PG-250), which is used to measure the composition of the dried gas stream.

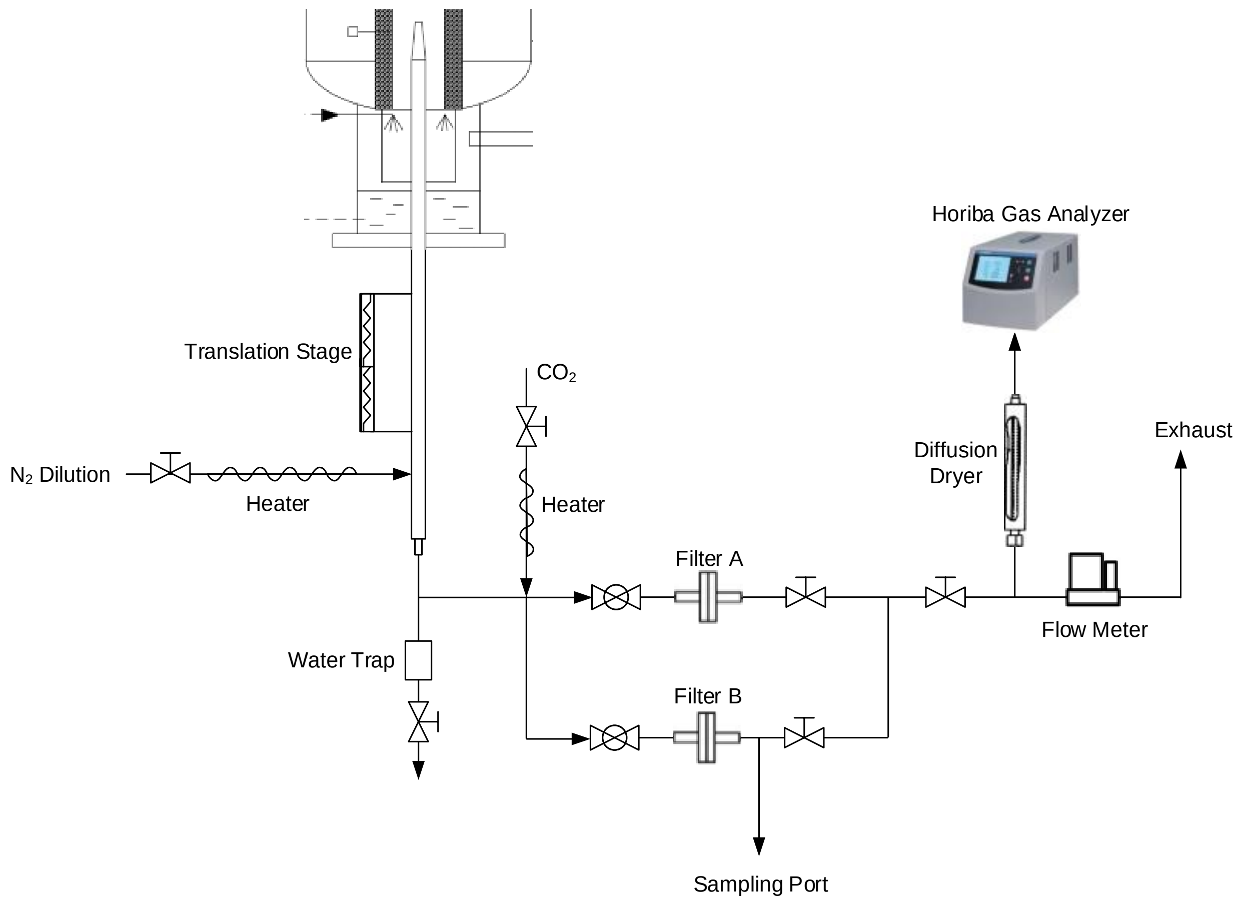



**Figure 4-7**
**Schematic of a One-Stage Dilution Sampling Probe for Collecting Fly Ash and Gas on the Centerline of the Reactor**

To prevent water and acid condensation in the sampling system, the sampled probe is heated to above 300°C (572°F) using heated $CO_2$ flows before taking samples. The outside of the probe is also heated by heat tapes such that the temperature on the whole surface of the probe is maintained above 300°C (572°F).

Figure 4-8 shows a sketch of the radiometer design, which was built in-house by WUSTL. The radiometer comprises an optical lens, an aperture, a thermopile, and a metal housing. During measurement, the radiometer was placed at the outside of one quartz window port. The port size is 3.8-cm (1.5") inner diameter. On the opposite side of the chamber, there is another port with a cold quartz window at the end as shown in Figure 4-8. The solid angle of the radiometer was designed such that the field of view does not cover any part of the inner wall surface of the port or the hot refractory wall. Therefore, the radiometer measures the thermal radiation solely coming from the hot flue gas and the particles entrained in the gas.

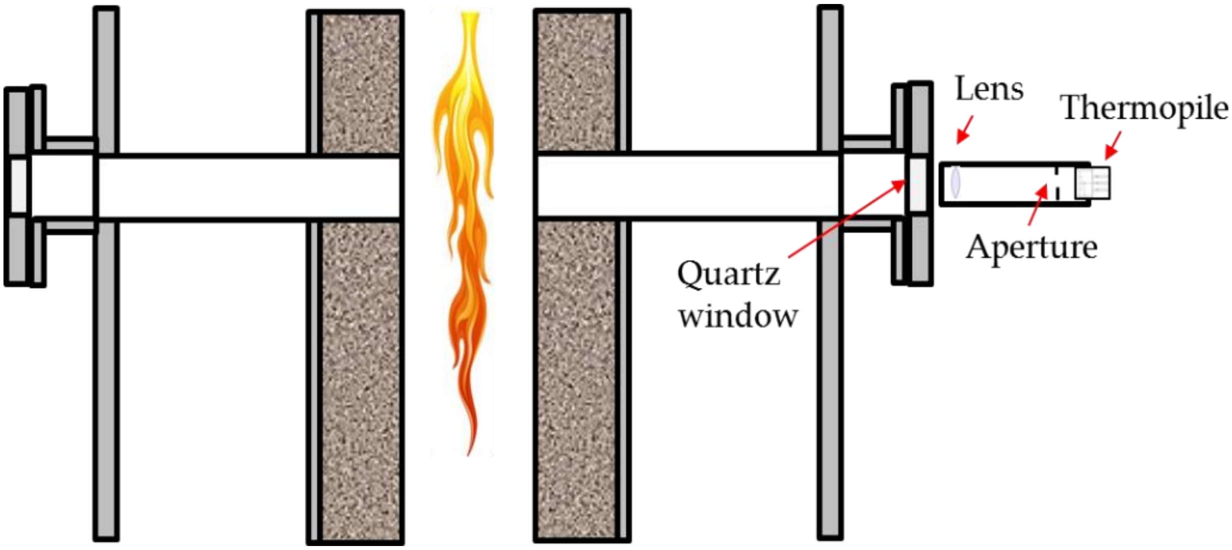



**Figure 4-8**
**Sketch of the In-house Radiometer and the Setup**

Before radiation measurements, the radiometer was calibrated against a blackbody furnace. Two calibration curves were obtained, one with a quartz window placed between the radiometer and the blackbody furnace, and the other without a quartz window, as shown in Figure 4-9. The radiation received by the radiometer without the quartz window was higher than that with the quartz window, because the window blocks part of the thermal radiation. The calibration curve with the quartz window was used in the flame measurement.

For system automation, new automated flow control valves were installed for multiple gas inputs, pressure control and quench water feeding, and water-level control. As an improvement of the safety interlock system, a methane detection sensor was installed to detect any potential fuel back flow into the pressurized-coal feeding pipe. An oxygen detection sensor was installed inside the pressurized-coal vessel to detect oxygen back flow into the coal vessel and another oxygen sensor was installed to detect flue gas leaks into the PV in different sections.

A flame safeguard system was installed and tested. This system consists of a Fireye® flame scanner, which connects to a dedicated control panel that is separate from, and redundant to, the operator control and data acquisition system. This safety system ensures safe reactor shutdown in the event of an unexpected flame out, ability for a user initiated emergency stop, or when a critical process variable is outside of its operating range.

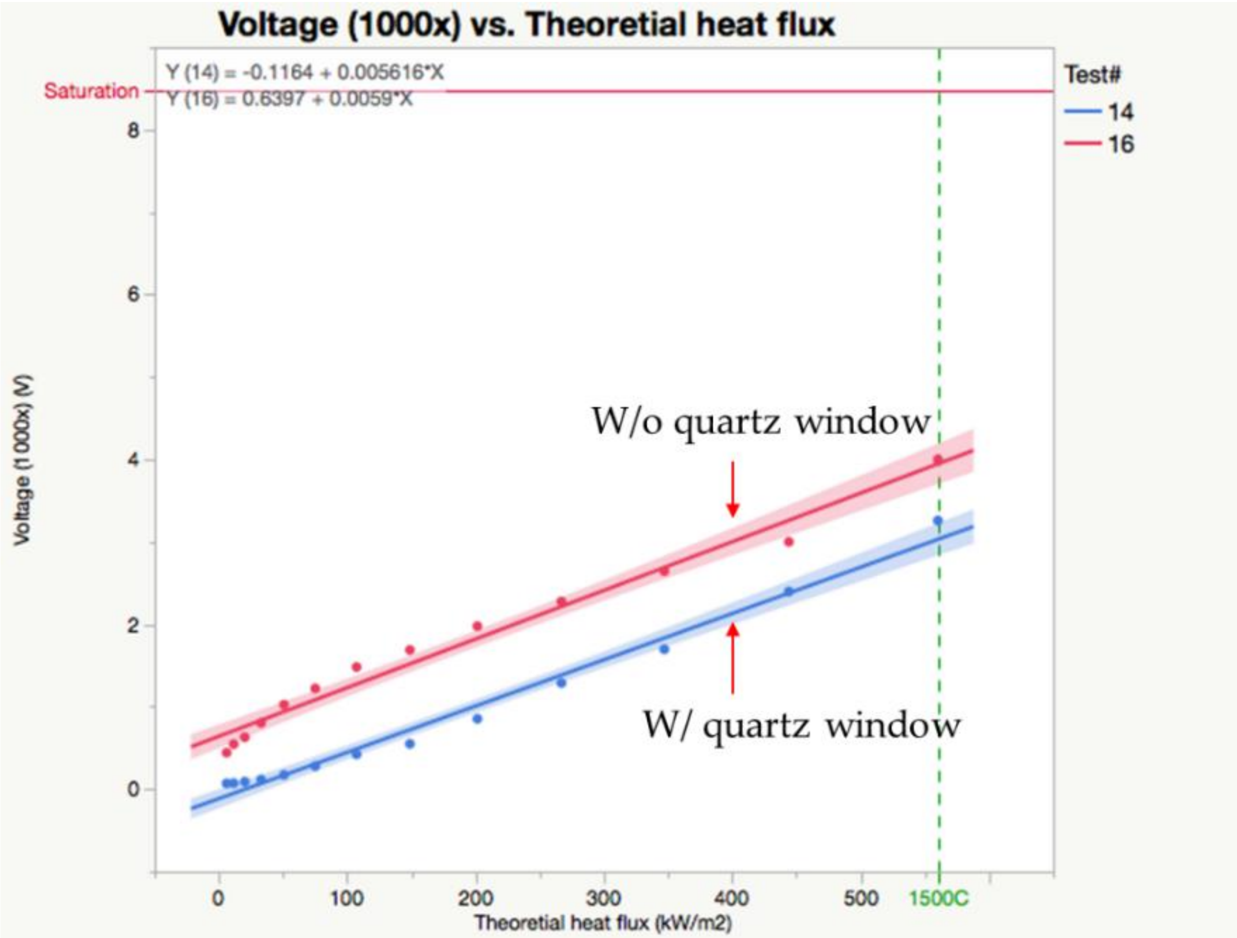



**Figure 4-9**
**Calibration Data for the In-house Radiometer**

Due to reliability issues of the original LabVIEW-based control system, an outside professional process engineering and consultant group, EPIC Systems, Inc., was contracted to review the existing facility and to make recommendations for needed upgrades to the flow controls, user interface, and safety interlock systems. Based on the recommendations from the consultant group, a hybrid automation system that combines an industry-standard Allen-Bradley Programmable Logic Controller system and a laboratory-standard LabVIEW system was implemented into the facility. The Allen-Bradley system is used for flow controls, human-machine interface, and safety interlock systems. The LabVIEW system is used for high-resolution experimental data acquisition. Before the system automation upgrade, the pilot facility was mainly operated manually (six people were required for operation); after the upgrade, the facility is fully automated and only two people are required for standard operation.

A Flexicon powder deliver system was installed to deliver coal from the ground floor to the coal vessel on the 3rd floor, to automate coal charging.

### *Process Safety Review*

WUSTL held several process safety review meetings for the pressurized facility with respect to potential safety hazards, and to determine any changes that might be needed prior to operating the facility at high pressure and high thermal input. WUSTL initially consulted with an expert from Commonwealth Scientific and Industrial Research Organisation in Australia, who was responsible for a pressurized gasification unit. This facility shares several similarities with WUSTL's pressurized combustor. Valuable operation experiences and safety procedures were shared with WUSTL.

Following this, WUSTL contracted the services of WHA-International, who specializes in oxygen systems safety. A consultant from WHA spent two days at WUSTL to review the test facility oxygen system for potential fire hazards and to provide input on materials selection for application in the full-scale SPOC boiler. Recommendations were provided to the team in a summary report.

Finally, WUSTL held a process safety review meeting that included experts from EPRI, Sandia, the lead engineers from EPIC Systems, Inc., and numerous personnel from WUSTL. The team reviewed facility procedures and the newly-implemented control system, including automated shutdown sequence and safety interlock and permissive.

The committee recommended that some changes be made to the control system, and that the modifications should be implemented and checked out before proceeding to pressures greater than 5 bara (72.5 psia). The modifications included additional automation of the flame-ignition sequence and additional safety interlocks.

These changes, as recommended by the safety review committee, were implemented and checked out. As this was a prerequisite for conducting combustion experiments under high pressure, the control sequences and interlocks for all gas input flows, coal vessel and reactor pressures, coal delivery, and quench water level were all tested separately for over 48 hours. The results of this test were satisfactory.

## Testing Plan

### *Original Testing Plan*

Two test campaigns were originally planned for this project, one simulating the first stage (Stage 1) of the SPOC process, the other one simulating the last stage (Stage 4). The purpose of these campaigns was to examine the stability and overall combustion performance of the designed full- and partial-load operating conditions for the these two most critical stages in the SPOC process. Another purpose was identifying the minimal load of the two stages, which is defined as the lowest thermal load before combustion becomes unstable.

In each test campaign, four thermal loads were scheduled: designed full load (100 kWth), 75% load, half load, and minimal load (as low as stable). The designed flow conditions for each test are listed in Table 4-2.

**Table 4-2**
**Original Proposed Test Matrix**

| **Stage 1 Designed Conditions** | Test S1-100 | Test S1-75 | Test S1-50 | Test S1-ML |
|---|---|---|---|---|
| **15 bara (217 psia)** | Full-load | Partial-load | Partial-load | Partial-load |
| Thermal Input, kWth | 100 | 75 | 50 | Minimal[a] |
| Stoichiometric Ratio | 2.0 | 2.0 | 2.0 | 2.0 |
| Overall $O_2$ Concentration, vol % | 50 | 50 | 50 | 50 |
| Oxidizer Temperature, °C (°F) | 15 (59) | 15 (59) | 15 (59) | 15 (59) |
| Coal Feeding Rate, kg/hr (lb/hr) | 12.7 (28.1) | 9.6 (21.1) | 6.4 (14.1) | - |
| Methane Flow Rate, SLPM (scfm)[b] | 15 (0.53) | 11.3 (0.4) | 7.5 (0.26) | - |
| Coal Carrier $CO_2$ Flow, SLPM (scfm) | 15 (0.53) | 11.3 (0.4) | 7.5 (0.26) | - |
| Inner $O_2$ Flow Rate, SLPM (scfm) | 242 (0.85) | 181.5 (6.41) | 121 (4.27) | - |
| Outer $O_2$ Flow Rate, SLPM (scfm) | 290 (10.2) | 217.5 (7.68) | 145 (5.12) | - |
| Outer $CO_2$ Flow Rate, SLPM (scfm) | 538 (19.0) | 403.5 (14.2) | 269 (9.50) | - |
| **Stage 4 Designed Conditions** | Test S4-100 | Test S4-75 | Test S4-50 | Test S4-ML |
| **15 bara** | Full-load | Partial-load | Partial-load | Partial-load |
| Thermal Input, kWth | 100 | 75 | 50 | Minimal[a] |
| Stoichiometric Ratio | 1.05 | 1.05 | 1.05 | 1.05 |
| Overall $O_2$ Concentration, vol % | 15 | 15 | 15 | 15 |
| Oxidizer Temperature, °C, (°F) | 300 (572) | 300 (572) | 300 (572) | 300 (572) |
| Coal Feeding Rate, kg/hr (lb/hr) | 12.7 (28.1) | 9.6 (21.1) | 6.4 (14.1) | - |
| Methane Flow Rate, SLPM (scfm)[b] | 15 (0.53) | 11.3 (0.4) | 7.5 (0.26) | - |
| Coal Carrier $CO_2$ Flow, SLPM (scfm) | 15 (0.53) | 11.3 (0.4) | 7.5 (0.26) | - |
| Inner $O_2$ Flow Rate, SLPM (scfm) | 242 (0.85) | 181.5 (6.41) | 121 (4.27) | - |
| Outer $O_2$ Flow Rate, SLPM (scfm) | 84 (2.97) | 63 (2.22) | 42 (1.48) | - |
| Outer $CO_2$ Flow Rate, SLPM (scfm) | 1861 (65.7) | 1396 (49.3) | 931 (32.9) | - |

[a] Minimal load to be identified by gradually dropping the load until the combustion process becomes unstable.

[b] Methane flow is for flame stabilization and corresponds to 10% of the total thermal input. The flow rate is subject to change based on testing. If less or no methane is required for stable combustion, the coal feeding rate increases correspondingly.

When the system is operated in turn-down (partial-load) mode, all the oxidizer flows decrease proportionally with fuel flow, such that the stoichiometric ratio (SR) and overall oxygen concentration remain the same as in full-load mode.

Examination of basic combustion characteristics at each operating condition was done by visually observing the flame through the optical access of the facility and measuring the carbon monoxide (CO) and soot concentrations in the flue gas. The visual observation involved two types of cameras: high-definition webcams, and a high-speed, high-resolution camera with a maximum frame rate of 200,000 frames/second.

The high-definition webcams were located inside the pressurized chamber, looking at the flame from 4 different angles. They provide a complete picture of the quartz reactor and cover most parts of the flame. The high-speed camera focuses on local regions of the flame and provides detailed information including the flow eddies and particle trajectories in the combustion region.

The measurement of CO and soot concentrations in the flue gas was carried out by on-line gas sampling. High CO and soot concentrations in the flue gas indicate unstable operation and incomplete combustion. Ash particles, which are sampled together with flue gas, were analyzed off-line to identify any incomplete char combustion or soot. Loss-on-ignition testing was used to analyze the ash particles. The devices used in the above measurements are listed in Table 4-3. Together, these measurements indicate the overall combustion performance at each operating condition.

**Table 4-3**
**Measurement Strategy for Performance Tests**

| Measurement | Device |
|---|---|
| Visual Observation of Flame | High-speed camera and high-definition webcam |
| Flue Gas CO and Soot Concentration | Flue gas sampler, Horiba multi-gas analyzer, and optical particle sizer) |
| Ash Carbon Concentration | Flue gas sampler, cyclone, and TGA |

Additional tests were performed to investigate the heat release and combustion development. The purpose of these tests was to generate a database for model validation. Measurements were taken based on the stable full-load operating conditions identified from the initial tests. The measurement techniques employed are listed in Table 4-4. The centerline gas compositions and particle size distributions were planned at three locations by moving a pressurized gas and particle sampler located at the bottom of the combustor.

**Table 4-4**
**Measurement Strategy for Model Validation**

| Measurement | Device |
|---|---|
| Wall Heat Fluxes (both convective and radiative at port locations) | Medtherm Schmidt-Boelter heat flux sensor |
| Flue Gas Composition | Flue gas sampler and HORIBA multi-gas analyzer |
| Centerline Profiles of Gas Composition (i.e., $CO_2$, $O_2$, CO, and $H_2O$) | Pressurized gas and particle sampler and HORIBA multi-gas analyzer |
| Centerline Particle Size Distributions | Pressurized gas and particle sampler and DEKATI ELPI |
| Centerline Temperatures | Thermocouple |

### *Boiler Design Workshop and Revised Testing Plan*

At a team workshop held on the March 13 and 14, 2019 at Doosan Babcock's Renfrew offices in the United Kingdom, WUSTL proposed modifying the operating conditions for the SPOC process, such that a modular design can be achieved for all stages. Accordingly, the test plan for the project was modified. A summary of the updated test conditions is provided in Table 4-5. Because in the new design all stages in the process are operated at the same conditions, the second campaign to mimic the last stage of the process was removed.

The new test campaign was designed as follows:

- The thermal input will be varied substantially to assess the turndown capability of the lab-scale burner.

- Domains of stable operation will be identified based on visual observation and flue gas composition measurements.
- Measurement of CO and soot will be made to allow for identification of unstable or incomplete combustion.
- After stable modes of operation over a wide range of turndown are identified, a thorough test campaign will be conducted for the most promising burner/combustion chamber configurations.
- Wall heat flux (both convective and radiative) and combustion products will be measured.
- Centerline axial profiles of composition, particle size distribution, and temperature will be obtained.

Measurements and conditions were chosen to develop a database for model validation. The expected outcomes of the testing are heat flux profile validation of CFD modeling application at scale, combustion efficiency at low excess oxygen levels, and demonstration of successful turndown operation.

**Table 4-5**
**Revised Test Matrix**

| **Designed conditions** | Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|---|
| **15 bara (271 psia)** | Full-load | Partial-load | Partial-load | Partial-load |
| Thermal Input, kWth | 100 | 75 | 50 | Minimal |
| Stoichiometric Ratio | 1.12 | 1.12 | 1.12 | 1.12 |
| Overall $O_2$ Concentration, vol % | 30 | 30 | 30 | 30 |
| Oxidizer Temperature, °C, (°F) | 15 (59) | 15 (59) | 15 (59) | 15 (59) |
| Coal Feeding Rate, kg/hr (lb/hr) | 14.2 (31.3) | 10.6 (23.4) | 7.1 (15.6) | - |
| Coal Carrier $CO_2$ Flow, SLPM (scfm) | 15 (0.53) | 11.3 (0.4) | 7.5 (0.26) | - |
| Methane Flow Rate, SLPM (scfm) | 0 (0) | 0 (0) | 0 (0) | - |
| Inner $O_2$ Flow Rate, SLPM (scfm) | 119 (4.20) | 89.2 (3.15) | 59.5 (2.10) | - |
| Inner $CO_2$ Flow Rate, SLPM (scfm) | 277 (9.78) | 207.7 (7.33) | 138.5 (4.89) | - |
| Outer $O_2$ Flow Rate, SLPM (scfm) | 231 (8.16) | 173.3 (6.12) | 115.5 (4.08) | - |
| Outer $CO_2$ Flow Rate, SLPM (scfm) | 539 (19.0) | 403.5 (14.2) | 269 (9.50) | - |

## Testing Results

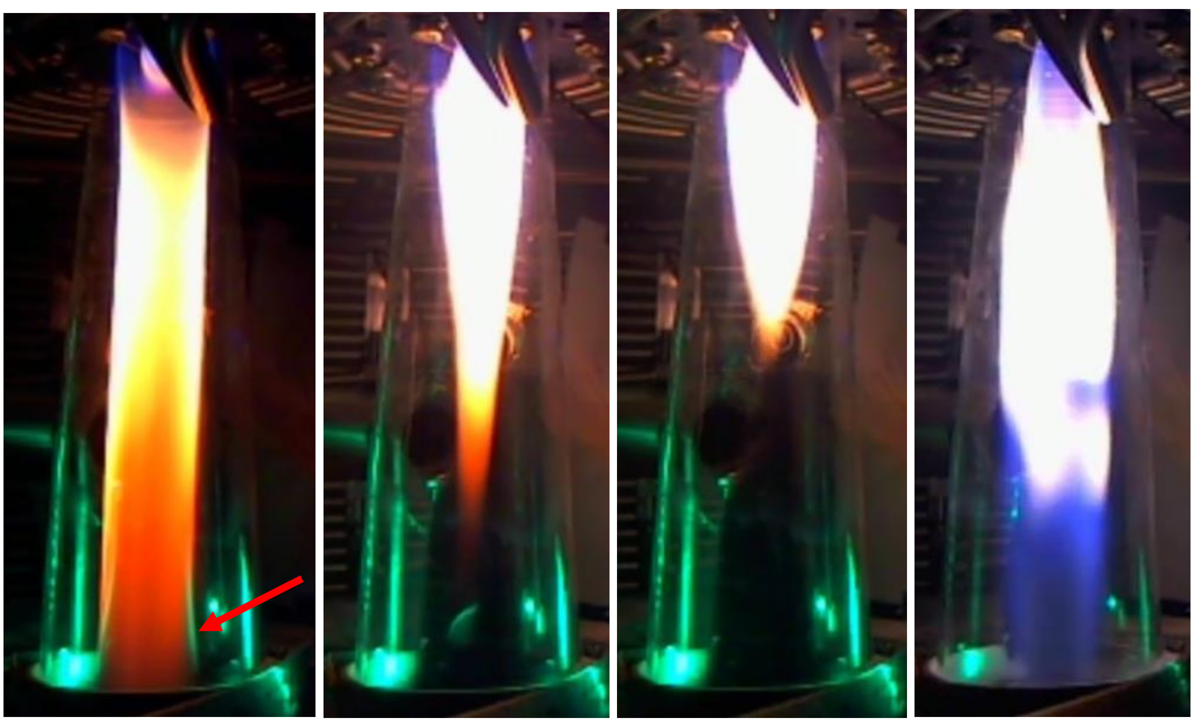
To ensure safe operation, the pilot facility demonstration was executed step by step: starting from atmospheric pressure with low thermal input; then at low pressures (3–5 bara [43.5–72.5 psia]) with moderate thermal input; finally, at high pressures (10–15 bar [145–217 psia]) with high thermal input. Experience was gradually gained by the WUSTL operation team during this process.

Note that all testing activities at atmospheric and low pressures and part of the activities at higher pressures were conducted before the test plan was revised during the team workshop. Therefore, all conditions at atmospheric and the lower pressures, and part of the conditions at high pressure, were designed to simulate Stage 1 or Stage 4 based on the original test plan. Even though the test plan was revised, these testing activities are still valuable as they demonstrated the flexibility of the new burner design and provided data with a wide range of conditions for model validation.

### *Testing at Atmospheric Pressure*

Ignition tests were first carried out at atmospheric pressure. Various stoichiometric conditions and flow conditions were examined for the ignition tests. Results indicated that, after the retrofit, the ignition characteristics of the system remain almost the same as before. Efforts were made to identify an optimal ignition condition. Under this condition, the system can be easily ignited within a relatively short time. The ignition is repeatable and reliable and the flame after ignition is clean (i.e., non-smoking). A standard operating procedure for ignition was established after these tests.

Then combustion tests using methane were conducted to determine the operating range of the new burner, and to test the laser and imaging equipment. Some results of the combustion testing are shown in Figure 4-10 with (a) methane-air combustion at ignition conditions; (b) the resulting flame after starting of central oxygen flow; (c) the resulting flame after further increase in central oxygen flow; and (d) the resulting flame after increasing thermal input to 7 kWth.



**(a) (b) (c) (d)**

**Figure 4-10**
**Photographs of Methane Combustion at Atmospheric Pressure in the SPOC Test Facility**

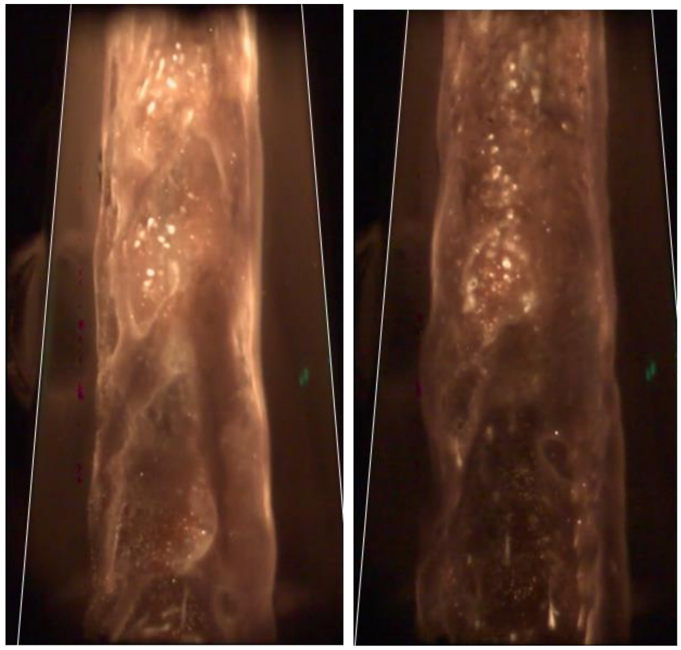
During methane/air combustion at low thermal input conditions, as shown in Figure 4-10a, the flow is laminar, and there is a large yellow/orange luminous zone indicating the formation of fine carbonaceous particles, or soot. Cold (non-luminous) particles (indicated by the red arrow), near the edges of the orange zone, are also made visible by the green laser sheet.

The presence of such particles indicates that the flame is smoking, meaning that black soot particles are being emitted from the flame without being fully oxidized. To prevent fouling downstream and to increase combustion efficiency, the emission of soot must be prevented. This issue is of interest as increasing pressure is known to enhance soot particle formation. The elimination of smoking is accomplished by using more oxygen, which is injected into the central port of the burner. The resulting flame is shown in Figure 4-10(b). The injection of oxygen improves soot burnout, as indicated by the absence of scattered green light in the post-flame region. Note that the remaining visible green light observed in Figure 4-10(b) is due to scattering from the quartz section, and not from fine particles. Further increase in the oxygen flow rate results in a shorter flame with no soot emissions, shown in Figure 4-10(c). At this condition, the SR was like what would be expected in Stage 1 of the SPOC process. The thermal input was then increased to the final condition, resulting in a more blue and turbulent flame, as shown in Figure 4-10(d). These preliminary tests demonstrated the benefits of utilizing the new burner to control soot formation.

Further testing was then carried out with coal and methane together. The testing included oxygen-enhanced combustion with 5 kWth methane and 2 kWth coal input and oxygen-enhanced combustion with 2 kWth methane and 5 kWth coal input. In the two oxy-combustion tests, the overall oxygen concentration was 50%. A high-speed camera was used to record the flame shapes in all the combustion tests.

Figure 4-11 shows the photographs of the two oxygen-enhanced coal-methane flames taken by the high-speed camera. Figure 4-11(a) is for the flame with 5 kWth methane and 2 kWth coal, and Figure 4-11(b) is for the flame with 2 kWth methane and 5 kWth coal. The white lines in the figure represent the walls of the quartz tube.

Note that although the flames in the photos look dark, the actual luminosities of the flames are very high, due to a high oxygen concentration. The high-speed camera serves as a powerful tool to improve the ability to diagnose the flame characteristics. In the high-speed videos, detailed information can be readily observed, including the flow field, particle motions, and particle burnout processes (i.e., particle ignition, volatile release and combustion, and char combustion).



(a) (b)

**Figure 4-11**
**Photographs of Coal-Methane Combustion at Atmospheric Pressure in the SPOC Test Facility Using High-Speed Camera**

### *Testing at Intermediate Pressures*

The test facility was operated for approximately 100 hours at pressures lower than 4 bara (58 psia). The purpose of these tests was to evaluate and improve system reliability and performance over a wide range of operating conditions at lower pressures. During these tests, the total thermal input was varied from 7–80 kWth, and both pulverized PRB coal and methane were burned. Tests were conducted with variable SR (1.2 to 3) to mimic inlet conditions that correspond to various boiler stages of the SPOC process (based on original testing plan). Results showed that below a certain burner exit gas velocity, flame oscillations occur. These oscillations are believed to be due to an unsteady pressure imbalance between the reactor and coal feed vessels. They only occur at very low flow rates and can be eliminated by operating the system at the designed operating conditions for the facility.

It was also confirmed that the flame size can be maintained by increasing thermal input proportionally with operating pressure. Steady operating conditions were found at all pressures, and the coal feed system was proven to be reliable. The burner performance met expectations, providing stable combustion and the desired flame shape. No flame impingement or ash deposition was observed on the quartz wall. With the help of the central oxygen flow, zero CO concentration in the exhaust gas was achieved even when the SR is as low as 1.1. In addition, steady coal combustion was achieved without the assistance of a gas pilot. A summary of the test conditions and results is provided in Table 4-6.

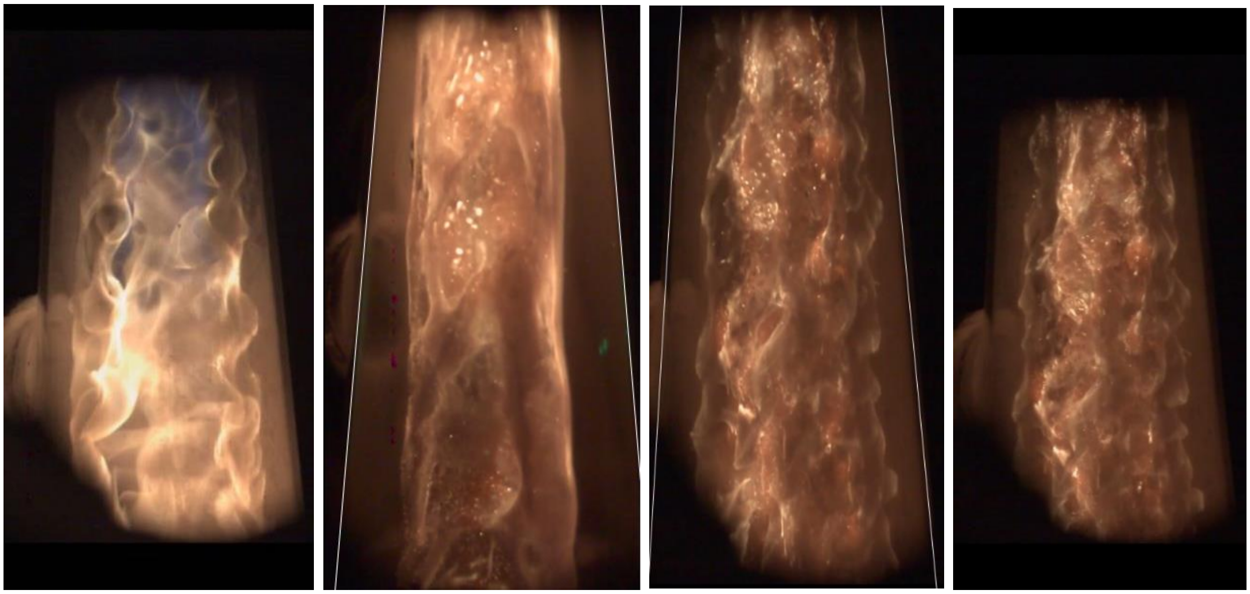
**Table 4-6**
**Intermediate Pressure Test Conditions and Summary Findings**

| Objectives | Conditions | Results |
|---|---|---|
| • Test burner performance with pulverized coal at elevated pressure and thermal input<br>• Observe the effects of pressure on flame size/shape<br>• Determine combustion efficiency under conditions of reduced oxygen concentration | • Fuel: PC (and methane where required for stable flame)<br>• Surrounding oxidizer: $O_2$ and $N_2$<br>• Central oxidizer: $O_2$<br>• Thermal input: 3–80 kWth<br>• Fraction of coal thermal input in the total thermal input: 0–100%<br>• SR: 1.1–2.5<br>• Central oxidizer SR 0–0.7<br>• Pressure: 1–4 bara (14.5–58 psia) | • The flame size can be maintained by increasing thermal input proportionally with operating pressure.<br>• Steady operating conditions were found at all pressures.<br>• At all conditions, the flame stays at the center of the reactor, and no flame impingement or ash deposition on quartz wall were observed.<br>• Stable 20 kWth coal flames at 3 bara (43.5 psia) without methane pilot were obtained, which shows the robustness of SPOC burners. The central oxygen flow helps stabilize the flame in a co-flow burner configuration.<br>• 80 kWth coal flame was tested for more than 30 minutes. No flame impingement or ash deposition on quartz wall was observed.<br>• With the central oxygen flow, zero CO concentration in the exhaust gas was achieved when the SR is as low as 1.1. |

High-speed video was taken during the above conditions, with snapshots shown in Figure 4-12 and Figure 4-13. These videos revealed the effects of flow rate on the turbulent eddy flame structure and the combustion rates of individual groups of coal particles.

Figure 4-12(a), (c), and (d) show flame shapes at 3 bara (43.5 psia) with 20 kWth methane, 20 kWth methane plus 2 kWth coal, and 2 kWth methane plus 20 kWth coal. The oxidizer flows are the same in these three conditions. As can be seen, as coal thermal input increases and methane thermal input decreases (total thermal input remains constant), the flame shape remains the same, but more and more particles can be observed inside the flame. Figure 4-12(b) shows a methane-coal flame at atmospheric pressure.

The velocities of the fuel and oxidizer streams in the condition in Figure 4-12(b) are the same as those in the condition in Figure 4-12(c) (i.e., the fuel and oxidizer streams increases proportionally with pressure). Comparing Figure 4-12(b) and Figure 4-12(c), it can be seen that with the same flow velocity, pressure has a strong impact on the flame structure. More eddies are observed at high pressure due to the stronger turbulence.

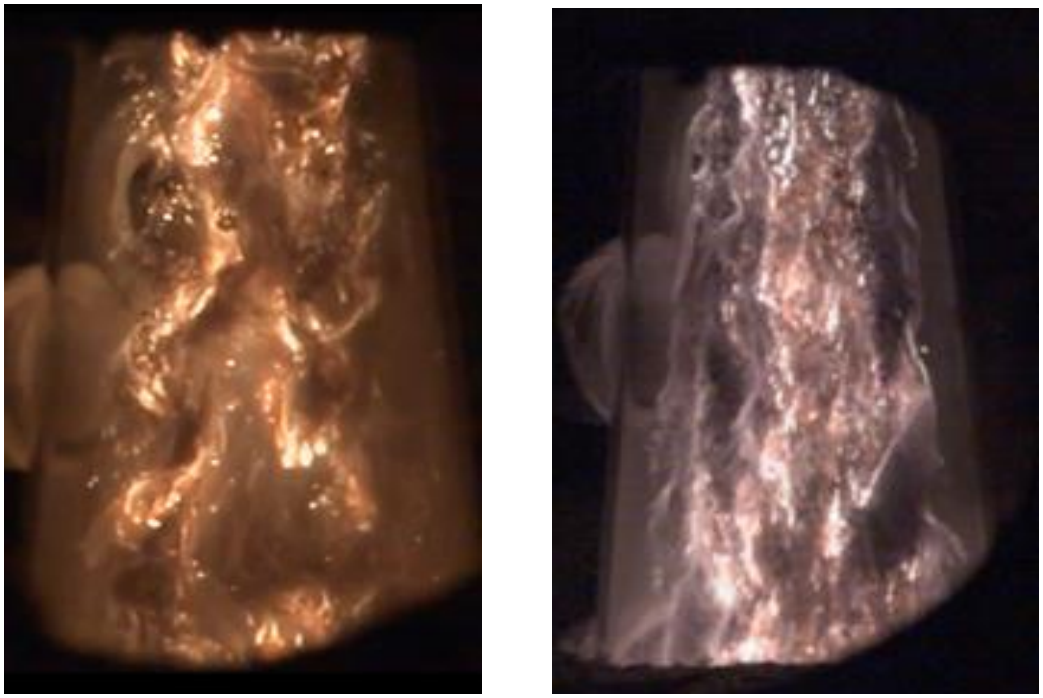


**(a)** **(b)** **(c)** **(d)**

**Figure 4-12**
**Photographs of Low-Pressure Coal-Methane Combustion in the SPOC Test Facility Using High-Speed Camera**

Figure 4-13(a) shows a pure coal flame at 20 kWth and 3 bara (43.5 psia). This test demonstrated that a pure coal flame can be achieved without gaseous fuel support with the new burner. Figure 4-13(b) shows an 80 kWth flame at 3 bara (43.5 psia).

From the ports below the quartz tube section, it was observed that the flame is longer with higher thermal input, but in the quartz tube section, the top part of the flame remains like that at lower thermal input.



(a) (b)

**Figure 4-13**
**Photographs of 100% Coal Combustion in the SPOC Test Facility Using High-Speed Camera: a) 20 kWth and b) 80 kWth**

### *Testing at High Pressures*

Ignition at different pressures with methane was tested. A new ignitor was utilized and proved to be very effective for HP ignition. To achieve smooth ignition, the methane and oxidizer flows were increased proportionally with pressure, such that the velocities of both streams could be kept constant. Ignition becomes unstable if the flow rates were too small.

With the same thermal input/pressure ratio and the same SR, ignition time remains almost the same. Repeatable ignition was achieved, and ignition time was within 10 seconds. The overall flame length after ignition was similar, but locally, the flame is ‘wrinkled’ at higher pressure, due to the stronger turbulence intensity (higher Reynolds number).

Coal combustion tests were conducted at 10 bara (145 psia) and 15 bara (217 psia). Initially, central oxidizer stream was not used, for simplification of operation. Both air combustion and oxy-combustion modes were tested at the same SR. Smooth transition was achieved from air combustion mode to oxy-combustion mode. Stable coal combustion was achieved at both pressures.

With the same thermal input/pressure ratio, the overall flame shape was very similar. Particles flow mainly in axial direction and no particle impaction was observed on the quartz wall. A summary of the test conditions and results is provided in Table 4-7.

**Table 4-7**
**Summary of Test Conditions and Results at High Pressure without Central Oxidizer Flow**

| Objectives | Conditions | Results |
|---|---|---|
| • Test burner ignition at high pressure | • Fuel: Methane<br>• Surrounding oxidizer: $O_2$ and $N_2$<br>• Thermal input: 10–30 $kW_{th}$<br>• S.R. 1.1–2<br>• Pressure: 5, 10, and 15 bara (72.5, 145, and 217 psia) | • Ignition time is within 10 seconds and is repeatable.<br>• With the same thermal input/pressure ratio, similar results for ignition time and flame shape can be achieved across a wide range of pressures.<br>• The gaseous flame becomes more turbulent at higher pressure. |
| • Test coal combustion at high pressure<br>• Observe the effect of pressure on coal flame | • Fuel: PRB and methane<br>• Surrounding oxidizer: $O_2$ and $N_2$ or ($O_2$ and $CO_2$)<br>• Thermal input: 20–50 $kW_{th}$<br>• SR: 1.1–2.0<br>• Pressure: 10 and 15 bara (145 and 217 psia) | • Stable coal combustion can be achieved at high pressures.<br>• With the same thermal input/pressure ratio, the overall flame shape is very similar, but turbulence intensity increases significantly at high pressures.<br>• Particles flows mainly in the axial direction, with no particle impaction on the quartz wall observed. |

A series of tests were then conducted at 15 bara (217 psia), with central oxidizer being used to control flame shape and soot formation. A summary of the test conditions and results is provided in Table 4-8.

First, gaseous combustion was tested with a wide range of operating conditions. The goal of this test was to identify an optimal operating condition for heating the refractory wall during cold startup. It was found that, even though a down-fired methane flame has a high-sooting tendency at elevated pressure, by choosing an optimal operating condition, soot emission can be eliminated.

A 40 kWth methane flame with oxidizer-fuel equivalence ratio of 2.2 and 30 vol % overall oxygen fractions in oxidizer streams was identified as the best operating condition for preheating. After preheating, transitions from air-fired mode to oxy-fired mode and from methane flame to coal flame were tested at 15 bara (217 psia). Smooth transitions were achieved.

Target operating conditions at full load (100 kWth, Figure 4-14 and Figure 4-15) and half load (50 kWth) were tested. It was found that a stable coal flame can be achieved without any methane flow. Also, no soot or CO emissions were detected at the exit of the reactor even when the oxygen fraction was as low as 3 vol %. Particle samples at the exit of the reactor were analyzed using Energy-dispersive X-ray spectroscopy and zero unburnt carbon content was detected. As the energy-dispersive X-ray spectroscopy has 4% error in carbon content measurement, and the carbon and ash contents in the raw coal are 62.8 wt % and 8.4 wt %, respectively, zero detected unburnt carbon indicates over 99.5% carbon conversion rate.

**Table 4-8**
**Summary of Test Conditions and Results at High Pressure without Central Oxidizer Flow**

| Objectives | Conditions | Results |
|---|---|---|
| • Identify optimal operating conditions for heating up | • Fuel: Methane<br>• Thermal input: 40 kWth<br>• Oxidizer-fuel equivalence ratio: 1.5–3<br>• Oxygen concentration in oxidizer: 21–40 vol %<br>• Pressure: 15 bara (217 psia) | • Without proper flame design, a down-fired methane flame has a very high-sooting tendency at elevated pressure.<br>• After a proper flame design, a gaseous flame without soot emission can be achieved. |
| • Demonstrate air-fired mode to oxy-fired mode shifting and gas-to-coal shifting under pressurized conditions | • Fuel: PRB and methane<br>• Thermal input: 50 kWth<br>• Oxidizer-fuel equivalence ratio: 1.12–2<br>• Oxygen concentration in oxidizer: 30–40 vol %<br>• Pressure: 15 bara (217 psia) | • Smooth transitions were achieved from air-fired mode to oxy-mode with 40 kWth gaseous flame, and from gaseous flame to coal flame while maintaining total thermal input of 50 kWth, 15 bara (217 psia).<br>• At the same thermal input, coal flame has less sooting tendency at elevated pressure than gaseous flame. |
| • Demonstrate oxy-coal combustion at half- and full-load conditions | • Fuel: PRB<br>• Thermal input: 50–100 $kW_{th}$<br>• Oxidizer-fuel equivalence ratio: 1.12–2<br>• Oxygen concentration in oxidizer: 30–40 vol %<br>• Pressure: 15 bara (271 psia) | • Stable coal combustion can be achieved without gaseous flame support.<br>• No soot and CO emissions are detected at the exit of the reactor even when oxygen concentration at the exit is as low as 3%.<br>• No unburnt carbon is observed in particle samples at the exit of the reactor. |

Flue gas was cooled using a direct-contact water spray. This led to low NOx and SOx emissions in the flue gas due to absorption in the cooling water. NOx emissions were also limited due to the absence of $N_2$ and the thermal NOx formation mechanism. At the end of the test campaign, the total thermal input was increased to 125 kWth (100 kWth coal and 25 kWth methane) without problems.

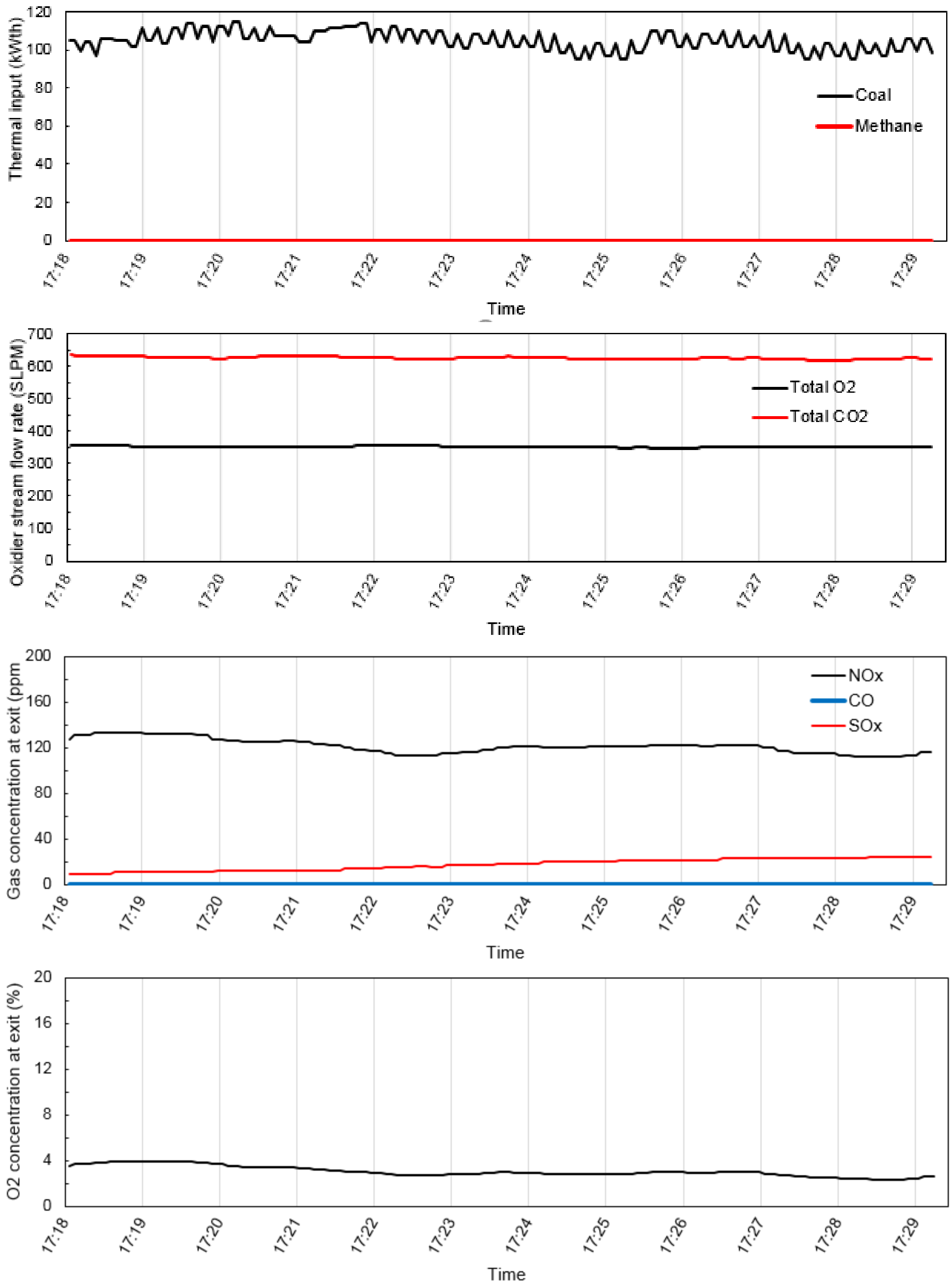



**Figure 4-14**
**SPOC Test Facility Operating Data at Design Operating Conditions: 15 bara (271 psia), 100 kWth**

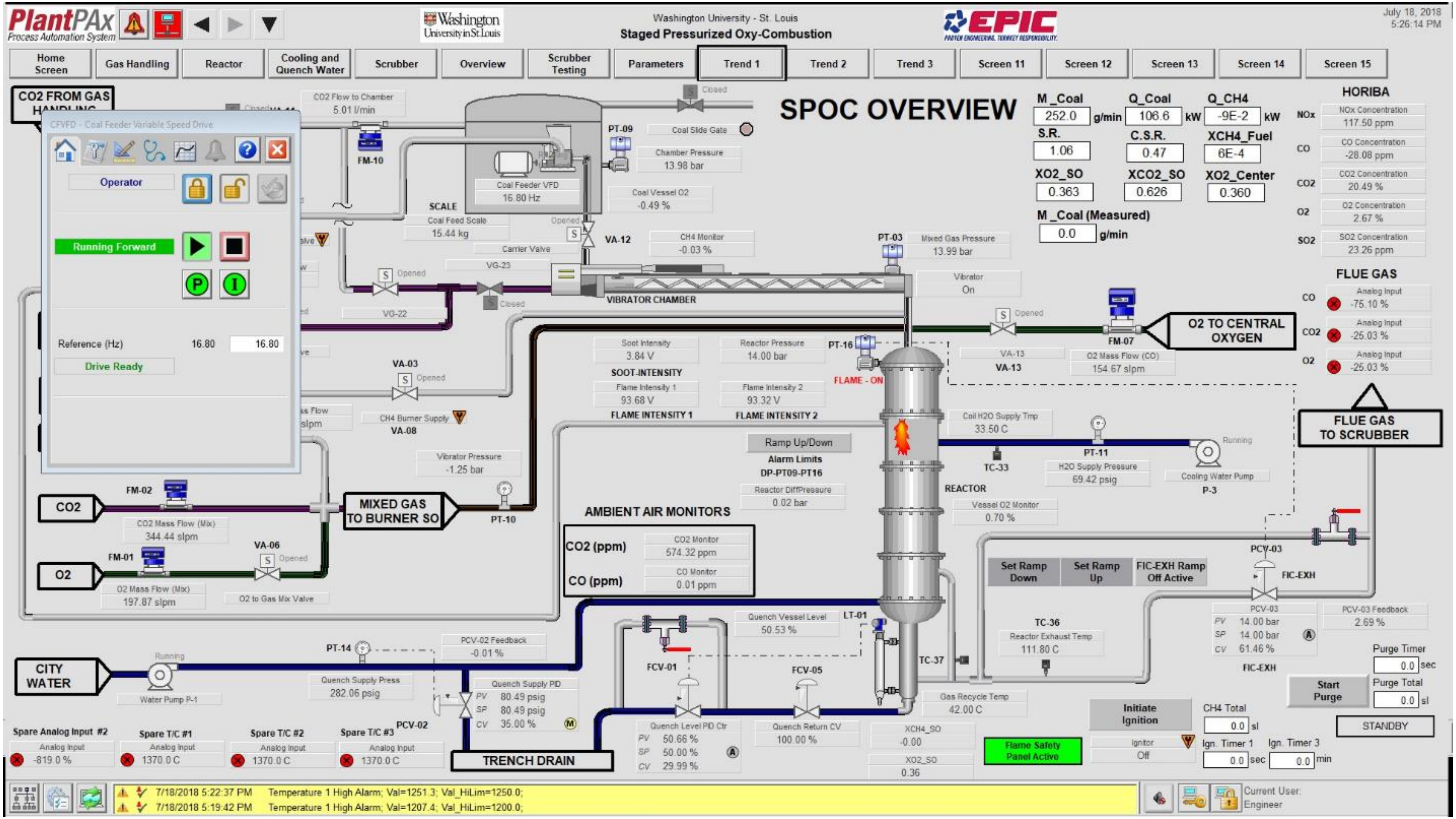



**Figure 4-15**
**SPOC Test Facility Operator Screen Shot at Target Conditions: 15 bara (271 psia), 100 kWth**

A series of measurements were taken at both half- and full-load conditions to further characterize the combustion performance in the combustor.

First, narrow angle radiation measurements were taken through a port 350 mm (13.8 in) away from the burner exit (as shown in Figure 4-16). During measurements, the distance between the radiometer and the quartz window was the same as that in the calibration setup. Also, during measurement, a stream of warm $CO_2$ was injected into the ports to purge out the hot flue gas and to avoid water condensation on the quartz windows. Note that this warm $CO_2$ can absorb part of the thermal radiation emitted from the flame along the path length, making the radiation measurement underestimated. At the chosen measurement location, the radiometer read an average value of 2 V, which indicates ~400 kW/m$^2$ (0.126 MMBtu/hr-ft$^2$) heat flux, based on the calibration curve. CFD simulation results showed ~600 kW/m$^2$ (0.190 MMBtu/hr-ft$^2$) at the same location. The difference between the two results is likely caused by multiple reasons, including the $CO_2$ purging inside the port, the uncertainties of the model, and the uncertainties of the radiometer.

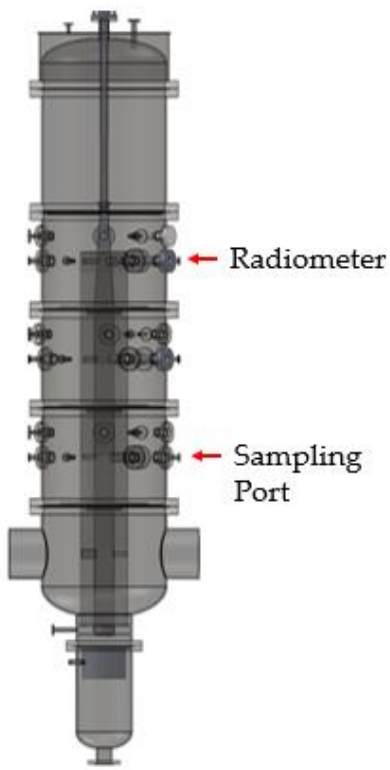



**Figure 4-16**
**Radiation Measurement Port and Particle Sampling Port for Size Distribution Measurement**

Size distributions of fine particles were also measured using the two-stage dilution in-house built pressurized sample probe. The location of the particle sampling port is shown in Figure 4-16. During this measurement, the sampling probe was positioned at the centerline of the reactor. Figure 4-17 shows the fine particle size distribution at full-load and half-load conditions. Calculations show that the sampling location corresponds to a residence time for the particles of 3 seconds at full-load and 6 seconds at half-load. It was shown that, as the residence time increases, the number density of the smaller particles decreases and that of the larger particles increases. This shift from smaller particles to larger particles is due to particle coagulation and mineral matter vapors condensing on the existing particles.

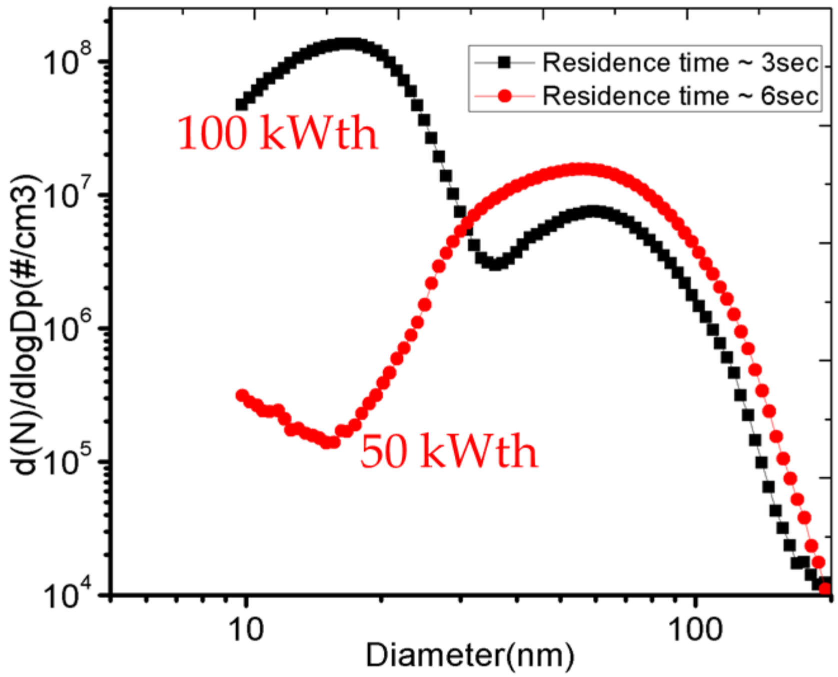



**Figure 4-17**
**Size Distribution of Ultra-Fine Particles Measured by Scanning Mobility Particle Sizer Spectrometer**

In an atmospheric-pressure oxy-combustion power plant, the oxygen concentration in the flue gas is normally kept above a minimum value, typically 3 vol % to ensure complete coal combustion.[19] However, studies have shown that coal conversion rates under pressurized conditions are higher, because char gasification rates increase significantly with pressure. Also, the gas volume in a boiler decreases proportionally with pressure, reducing velocity and increasing residence time. This further increases the coal conversion at the exit of the boiler. Accordingly, the oxygen concentration in the flue gas can likely be smaller in a pressurized oxy-combustion boiler. If so, the amount of oxygen required from the ASU can be reduced, and on the back end, less oxygen must be removed from the flue gas before sequestration, leading to increased plant efficiency and reduced COE. In this project, WUSTL examined the minimum excess oxygen required for complete coal combustion in the pilot-scale pressurized oxy-combustor.

During measurement, the operating pressure was at 15 bara (271 psia), and the thermal input was relatively steady with the average being at ~120 kWth. The fluctuation in thermal input is within

[19] NETL (2008). Pulverized coal oxycombustion power plants: Bituminous coal to electricity, Vol. 1. Washington D.C., DOE/NETL-2007/1291.

± 10 kWth, as shown in Figure 4-18. Stable coal combustion was achieved without any gaseous fuel support. The oxidizer was composed of ~30 vol % $O_2$ and ~70 vol % $CO_2$ as shown in Figure 4-19. The flue gas concentration was continuously measured by a Horiba PG-300 portable gas analyzer, as shown in Figure 4-20.

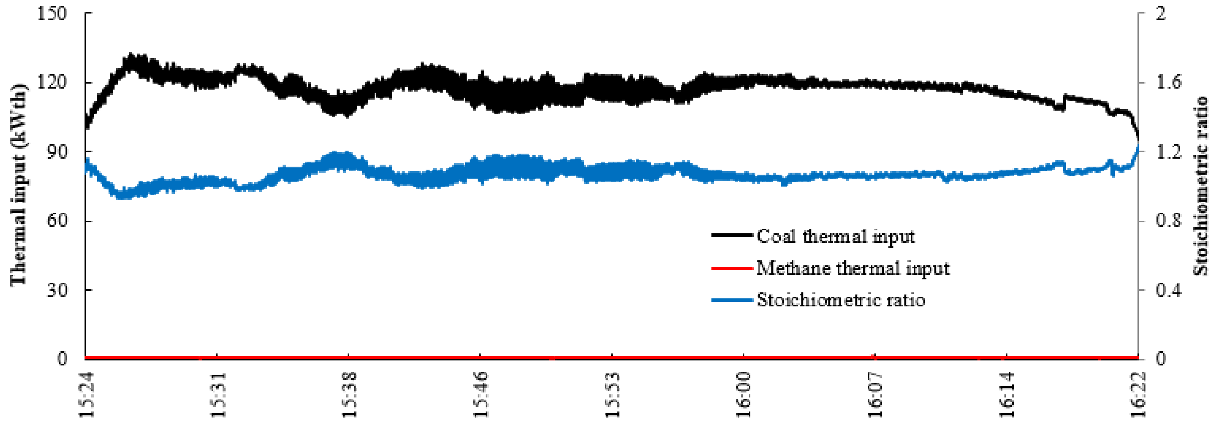



**Figure 4-18**
**Thermal Input and SR During Measurement for the 120 kWth, 15 bar (271 psia) Case**

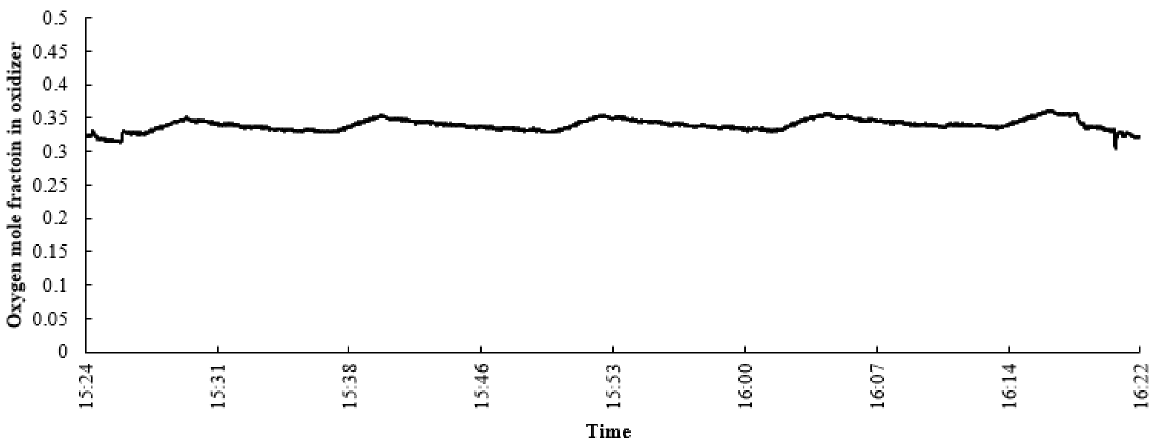



**Figure 4-19**
**Oxygen Mole Fraction in Oxidizer During Measurement for the 120 kWth, 15 bar (271 psia) Case**

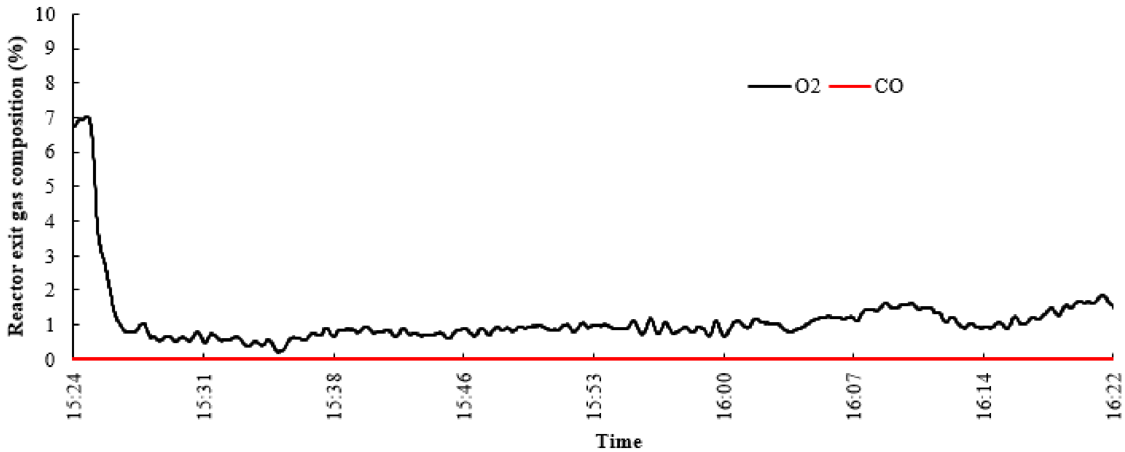



**Figure 4-20**
**Oxygen and CO Concentration at the Outlet of the Combustor for the 120 kWth, 15 bar (271 psia) Case**

Fixed operating conditions were maintained for about an hour, during which the oxygen concentration at the outlet of the combustor was maintained at about 1 vol % most of the time. No CO was observed in the flue gas during this time, which indirectly indicates complete coal combustion.

Multiple samples of fly ash particles were taken at the exit of the reactor using a one-stage dilution, translatable pressurized sampling probe as shown in Figure 4-7. The ash samples appeared to be white/gray, indicating very low carbon content. The ash samples were then analyzed using TGA. The procedures for TGA analysis are summarized in Table 4-9. These procedures have been widely used for measuring unburnt carbon in coal fly ash.[20] For each TGA test, a 25±5 mg (55±11 mlbs) sample of fly ash was loaded into the TGA and nitrogen was introduced into the apparatus at a flow rate of 20 mL/min (0.3 gal/hr) to purge the lines of oxygen and stabilize the apparatus.

**Table 4-9**
**Procedures for TGA for Measuring Unburnt Carbon in Ash Samples**

| Time | Temperature | Environment |
|---|---|---|
| 0–9 min | Increases from 20°C (68°F) to 200°C (392°F) at a rate of 20°C/min (36°F/min) | $N_2$ |
| 9–39 min | Hold at 200°C (392°F) | $N_2$ |
| 39–66.5 min | Increases from 200°C (392°F) to 750°C (1382°F) at a rate of 20°C/min (36°F/min) | $N_2$ |
| 66.5–126.5 min | Hold at 750°C (1382°F) | $N_2$ |
| 126.5–186.5 min | Hold at 750°C (1382°F) | Air |

[20] Fan M, Brown RC. Comparison of the Loss-on-Ignition and Thermogravimetric Analysis Techniques in Measuring Unburned Carbon in Coal Fly Ash. Energy & Fuels. 2001;15(6):1414-7.

The TGA weight loss curve for the fly ash sampled at 120 kWth with 1 vol % oxygen in the flue gas indicated that the unburnt carbon content in the fly ash sample is about 2.6 wt %. Since the carbon and ash contents in the raw coal are 62.8 wt % and 8.4 wt %, respectively, 2.6 wt % unburnt carbon content in the fly ash indicates that the carbon conversion ratio is over 99.6%, which can be considered complete combustion. Another combustion tests at 85 kWth and 75 kWth, 15 bara (271 psia), with 1 vol % oxygen concentration in the flue gas were also conducted, during which the TGA test for the fly ash sampled at the exit of the combustor also indicated about 99.6% carbon conversion.

Test conditions carried out at 15 bara (271.5 psia) are summarized in Table 4-10 for both 3% and 1% oxygen in the flue gas. Note that carbon burnout was determined by Energy-dispersive X-ray spectroscopy for tests with 3% oxygen concentration in the flue gas, and by TGA for tests with 1% oxygen concentration in the flue gas. The testing results are promising as the particle residence time in this pilot-scale combustor is much smaller than that in a full-scale combustion boiler. Therefore, the threshold oxygen concentration needed in the flue gas required for complete coal combustion in the full-scale case is likely to be even lower than 1 vol %. This could greatly benefit the economics of a pressurized oxy-combustion plant.

**Table 4-10**
**Test Conditions for Determining Carbon Burnout**

| | | | |
|---|---|---|---|
| **15 bara (271.5 psia)<br>3% $O_2$ in the Flue Gas** | | | |
| Thermal Input, kWth | 100 | 50 | |
| Overall Oxygen Concentration, vol % | 31 | 31 | |
| Carbon Burnout at Reactor Outlet, % | >99.5% | >99.5% | |
| **15 bara (271.5 psia)<br>1% $O_2$ in the Flue Gas** | | | |
| Thermal Input, kWth | 120 | 85 | 75 |
| Overall Oxygen Concentration, vol % | 31 | 31 | 31 |
| Carbon Burnout at Reactor Outlet, % | 99.6% | 99.6% | 99.6% |

As discussed, two factors contribute to the enhanced coal burnout under pressurized oxy-combustion conditions. One is that the particle residence time in pressurized combustion is longer. The average particle residence time in a typical atmospheric pressure combustion boiler is around 5 seconds, but in a full-scale pressurized combustor, this residence time can be over 20 seconds. The other factor is the enhanced char gasification rates under pressure. To understand the importance of this mechanism, the theoretical reaction rates (both oxidation reactions and gasification reactions) were calculated for a 50-μm particle under atmospheric pressure and pressurized (15 bara [271 psia]) oxy-combustion conditions, as shown in Figure 4-21. The gas environment is assumed to contain 3% $O_2$, 6 % $H_2O$, and 91 % $CO_2$ by volume. As shown in the figure, at atmospheric pressure, the char conversion is dominated by oxidation reactions. But as pressure increases, the contribution of gasification reactions to total char reaction rate becomes significant, especially when particle temperature is higher than 1327°C (2420°F). As the gasification reactions do not require oxygen, the importance of oxygen concentration in the flue gas for complete char combustion is much less under pressure. Therefore, the minimal flue gas oxygen concentration required for complete combustion can be reduced as low as 1 vol %.

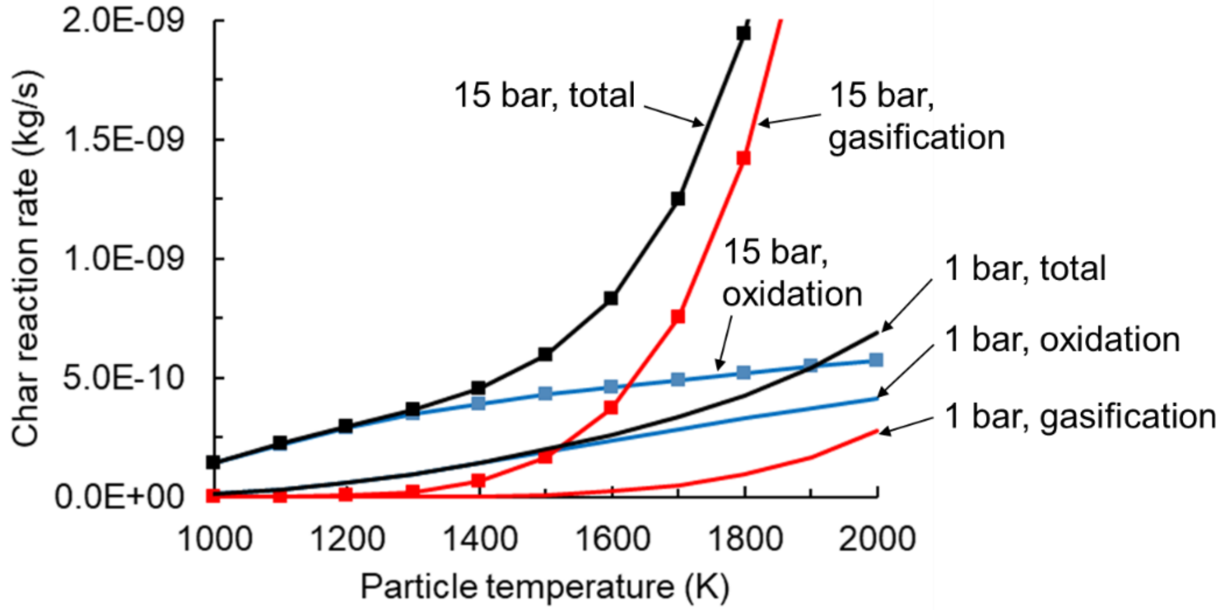



**Figure 4-21**
**Calculated Oxidation and Gasification Reaction Rates for a Char Particle at Different Temperatures and Pressures**

Using the translatable pressurized sampling probe, ash samples were taken at three different locations for model validating: 1) the highest location the sampling probe can reach (5 ft from the burner); 2) the outlet of the combustor (8.7 ft from the burner); 3) the middle of the first two locations (6.9 ft from the burner). The operating condition was at 85 kWth at 15 bara (271 psia) with 1 vol % $O_2$ concentration in the flue gas. Ash samples were analyzed in TGA and the results are summarized in Table 4-11. As expected, the carbon content in the fly ash decreases as sampling location moves away from the burner (i.e., the residence time increases).

**Table 4-11**
**Summary of Test Conditions at 15 bara (217.5 psia)**

| Measurement Location | Distance from Burner, m (ft) | Carbon Burnout from TGA Analysis |
|---|---|---|
| Location 1 | 1.53 (5.0) | 98.6% |
| Location 2 | 2.09 (6.9) | 99.5% |
| Location 3 (outlet) | 2.64 (8.7) | 99.6% |

A further effort was made to determine the minimal load of the 100 kWth pilot-scale combustor. The minimal load was tested by slowly dropping thermal input until a flame could not be sustained. This test was started with a 50 kWth pure coal flame with 1% oxygen concentration in the flue gas. The load was gradually dropped while maintaining the oxygen concentration in the flue gas (i.e., proportionally reducing both coal and oxidizer input). The flame remained stable at 25% load. Interestingly, at 25% load, it was observed that the flame started transit from turbulent to laminar due the lower flow rate. This laminarization might be the cause of flame instability as fast mixing is key to coal particle ignition.

As the Reynolds number in a utility scale SPOC boiler is ~200 times larger than that in the pilot-scale combustor, the flame in the utility scale SPOC boiler will always remain turbulent during part-load operation. Therefore, the minimal load in a utility-scale SPOC boiler can potentially be even lower than 25%. To get a sense of how flame stability is affected by the laminarization, the flow rate of the oxidizer was increased to ensure the flame is turbulent, then slowly reduced the coal input. The oxygen concentration of the oxidizer is also held constant during this test at around 32%.

The system automatically shut down when the thermal input was 8 kWth (8% of full load). After analyzing the shutdown, it was determined that the shutdown was triggered by the flame safety panel, as the flame became too small for the Fireye® flame scanner to detect, which triggered an automatic shutdown. This indicated that we can potentially even reach less than 8% load without losing flame. Note that this test result doesn't directly indicate that the minimal load of a utility-scale SPOC boiler can reach as low as 8%, because the stochiometric ratio in the test condition is much higher than it should be. But it's promising that the minimal load of a utility-scale SPOC boiler can be at least lower than 25%.

# 5
# BASELINE DESIGN AND INTEGRATION

Based on results from the OEM review of the SPOC concept and the 100 kWth pilot testing, the 550 MWe baseline SPOC design was formulated. This entailed the following activities:

- **Defining the overall process flow diagram –** The system was configured as a four-stage arrangement with hot FGR and integrated heat recovery to the steam turbine system.
- **Boiler design of SPOC stages –** The SPOC system was modeled using boiler performance software, which required a validation step due to the pressurized operation. The heating surface was configured to deliver the required thermohydraulic performance.
- **Steam turbine modeling –** This was carried out using commercially available EBSILON® software. Initially the model was created to have the correct system flowsheet and was then calibrated to match the performance of NETL baseline case S12A. This model was then configured to represent the SPOC process by adjusting the gross power to suit the required net output of 550 MWe, while accounting for the additional auxiliary power requirements of the ASU and the CPU.
- **Flue gas heat recovery –** The heat release opportunities the flue gas exiting the SPOC stages was modeled using Aspen Plus™, including the first stage compression and product compression aftercooling.
- **ASU heat recovery –** The intercooling of the main air compressor (MAC) and aftercooling the booster air compressor (BAC) in the ASU yields additional opportunities for heat recovery.

## Overall Process Configuration

At the initiation of the project, the SPOC system front-loaded oxygen and incrementally added fuel (and some additional oxygen) to each stage to ultimately consume the oxygen before exiting the final stage. This required each combustor to operate at different combustion domains with the early stages having high levels of excess oxygen, as can be seen in Figure 5-1.

Additionally, it was considered that individual SPOC stages could be configured to have dedicated heating surfaces in each stage, allowing for differential control of the superheater and reheat thermal uptake. The concept being that one stage could have exclusively superheater banks and another stage may have reheater banks, thereby making thermal delivery to each duty requirement controllable by adding more or less fuel to these specific stages. It became clear following consultation with the DBL, as boiler OEM, that having discreet stage performance requirements would be thermo-hydraulically complex and expensive to realize both from a design and manufacturing perspective.

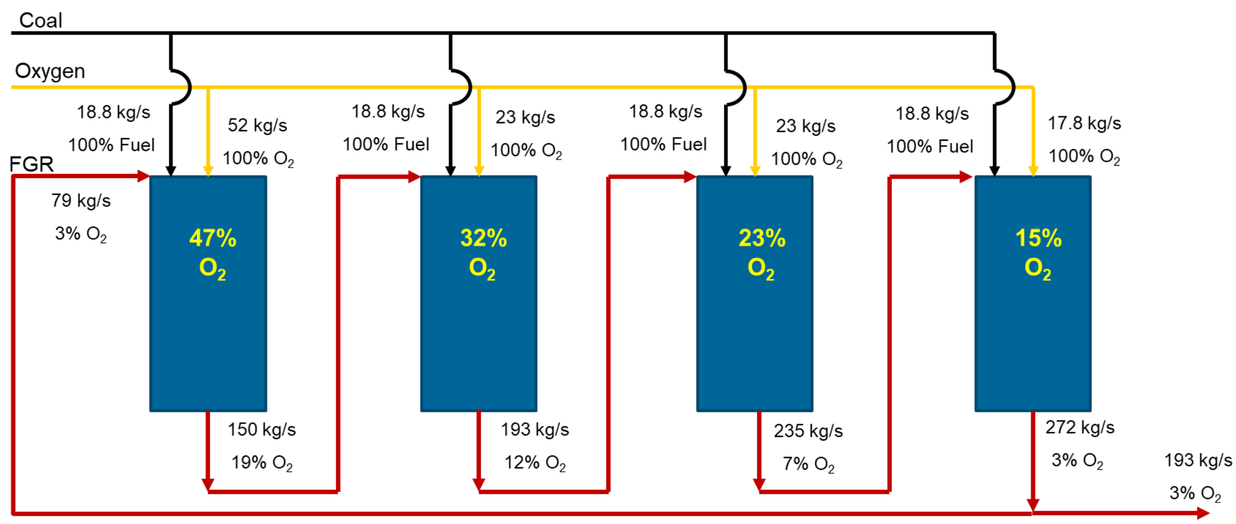



**Figure 5-1**
**SPOC Arrangement at Project Initiation**

Because of manufacturing considerations, a standardized module was considered as this keeps the costs lower as surfaces are identical across each stage. To facilitate this, the flue gas flow entering the convective banks (gas weight) needed to be similar across all stages. The original SPOC concept had cumulative gas increased as the process proceeded through each subsequent stage as more fuel and oxygen would be added at each step. Through a brainstorming exercise, one possible arrangement for a 4-stage SPOC system was to have the final 2 stages in parallel, as shown in Figure 5-2.

Although this had closer variance between stages than the original concept, it would have required two different boiler arrangements with variable flue gas cross-sectional area between stages to ensure appropriate flue gas velocities were maintained in each section.

Additionally, the balance of heat transfer between the furnace section, consisting of evaporative surface and dominated by radiative heat transfer, and the back-end convective surface that contains superheating and reheating surfaces, would differ for each stage. Stage 2 would have more heat transfer to the superheating and reheating banks due to the higher gas flowrate and thus causing balance between individual SPOC stages on the steam side to be challenging.

Subsequently, the decision to standardize the modules ensures not only a lower-cost option from a manufacturing perspective, it also simplifies the operation and control of the unit as thermodynamic balance can be achieved across all four stages when they are operated at identical thermal input.

The optimized arrangement is therefore configured to be in-series on the gas side with hot FGR recycled from the outlet of Stage 4 used to ensure that Stage 1 is identical to the subsequent stages. The steam/water circuit is split equally across all stages with each stage being serviced by an independent water separator and circulation pump (i.e., feedwater from the steam turbine is distributed to the four circuits) and generated main steam is then combined at an outlet manifold to balance pressure across stages. Each SPOC stage is therefore an independent boiler circuit but is linked on the gas side, as shown in Figure 5-3.

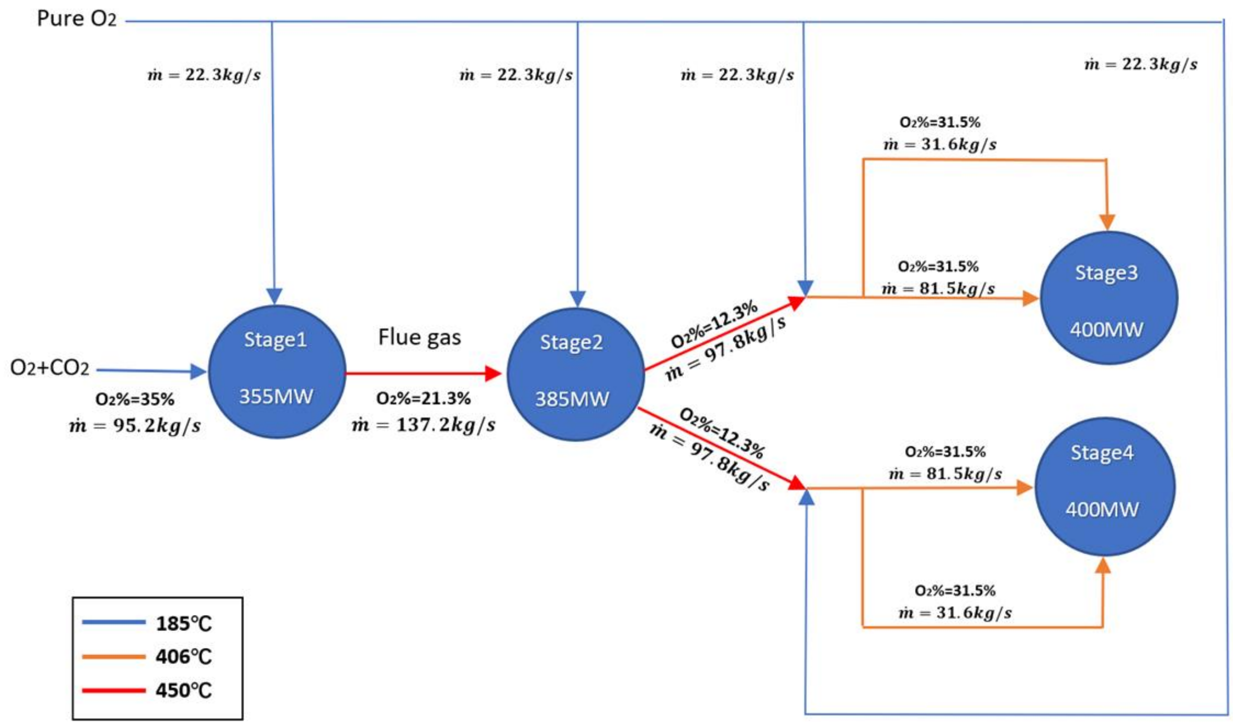



**Figure 5-2**
**SPOC Alternative Arrangement with Parallel Stages**

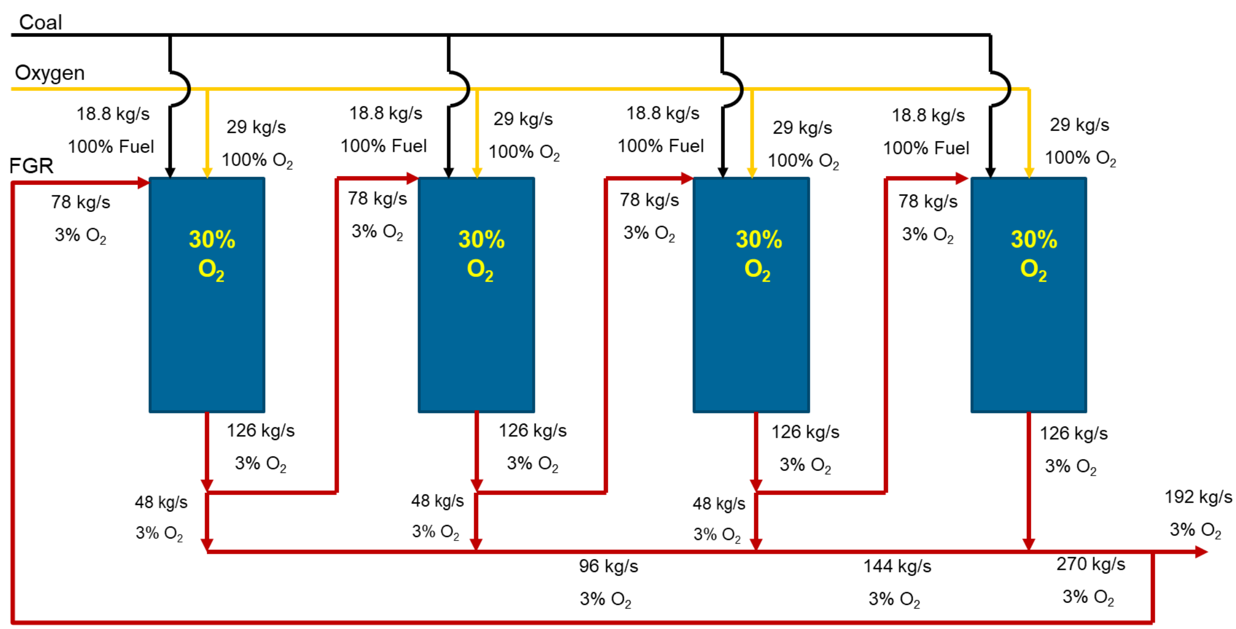



**Figure 5-3**
**Revised SPOC Arrangement**

The aim of the design was to achieve standardization and balance across the stages while maintaining performance and flexibility where possible. Hot FGR is a challenging prospect however, given that the flue gas will contain a substantial fly-ash component, making the mechanical design of the blower necessary to withstand erosion. A lower-risk option is to recycle flue gas after the particulate and DCC module. This however will complicate the performance characteristics of the first stage relative to the others unless a gas-gas reheater is employed.

### *2-Pass Arrangement*

Following agreement to standardize the SPOC stages, the concept arrangement comprised of a furnace module with a downward-fired, open-pass combustion zone followed by a 2nd pass upward-flow convective module containing cross-flow heating surface was further developed. To maintain equivalent gas flowrates in each stage, a portion of the flue gas leaving each stage needed to be purged from the main stream to remove the flue gas generated from coal combustion with oxygen. As each stage incurs a pressure drop, largely from passing the flue gases through the burner section and the convective banks, the pressure of the receiving plenum will be lower than the transfer gas ducts between stages. Subsequently, contra-rotating damper arrangements will be utilized to ensure the correct flue gas quantity is released at each interstage duct. The ducting for these purge steams would be sized to carry the entire flue gas flowrate of a stage at full load to enable downstream stage bypassing that is needed for high turndown system flexibility.

The design determined that two PVs (2-off) are needed for a single SPOC stage with four SPOC stages (4-off) required for the 550 MWe net SPOC power plant.

## Boiler Design

### *Basis of Model*

Based on results from the OEM review of the SPOC concept, CFD modeling and the 100 kWth pilot testing, the 550 MWe boiler performance model was configured using a peak radiant heat flux of 450 kW/m$^2$ (0.142 MMBtu/hr-ft$^2$) as confirmed from direct heat flux measurements carried out during combustion testing.

To ensure evaporator tube cooling in all-service conditions without exceeding allowable material stress levels, consideration was given to achieve suitable tube-side water/steam mass fluxes that would ensure sufficient cooling was achievable throughout the entire furnace-circuit envelope. The mass flux can be adjusted with selection of evaporator tube diameter, wall thickness and membrane fin width, and the number of tubes. Additionally, the tubes can be internally ribbed or plain bore depending on the desired cooling characteristics needed throughout the radiant sections of the system.

### *Furnace Module*

The furnace module was designed based on combustion progression and subsequent heat release characteristics that were validated against the combustion testing carried out at the 100 kWth SPOC pilot unit. The flue gas residence time in this arrangement is substantial, allowing for effective carbon burnout with minimal excess oxygen levels. Even in the relatively short residence time of the SPOC pilot unit, successful burnout was achieved at 1 vol % oxygen concentration in the resultant flue gas. The overall height was determined based on ensuring sufficient gas cooling was possible to make certain that the particulate material is at a lower temperature than the ash initial deformation temperature for the Montana Rosebud PRB fuel.

This is a key requirement to avoid ash accumulation on surfaces when geometrical gas flow changes are applied, such as that needed to transfer the flue gas to the upward-flowing convective module.

The SPOC process uses a downward-fired arrangement for each stage with a single burner located at the center of the furnace module roof. As with every section of this design, for fabrication efficiency, the maximum diameter of the PV is limited by road transportation limits, in this case 4.5 m (15 ft) as shown in Figure 5-4.

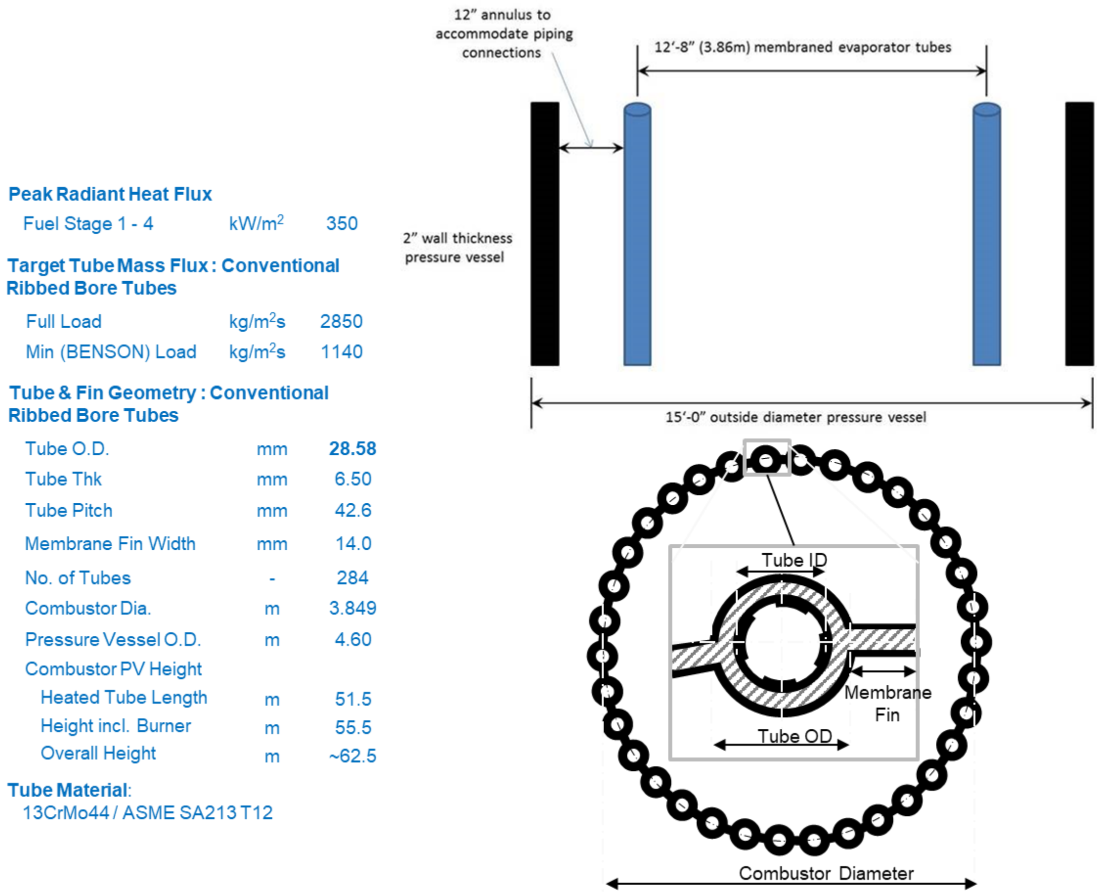



**Figure 5-4**
**SPOC Radiative 'Downward-Fired' Stage for Full-scale 550 MWe SPOC Performance**

This arrangement included some allowance for internal pipework connections and insulation within the PV. The original concept for the combustion module was based on an ideal arrangement for the introduction of the comburant and fuel mixture, where the flow would expand in a near linear fashion as the reaction proceeds and heat release causes the gases to expand. The SPOC burner uses a weak (non-turbulent) mixing strategy that relies on a near laminar pipe flow characteristic as the gases proceed downwards through the combustion module. This allows for a more controlled heat release profile to be achieved when using limited FGR quantities. The anticipated heat release and thermal profile for this arrangement are shown in Figure 5-5.

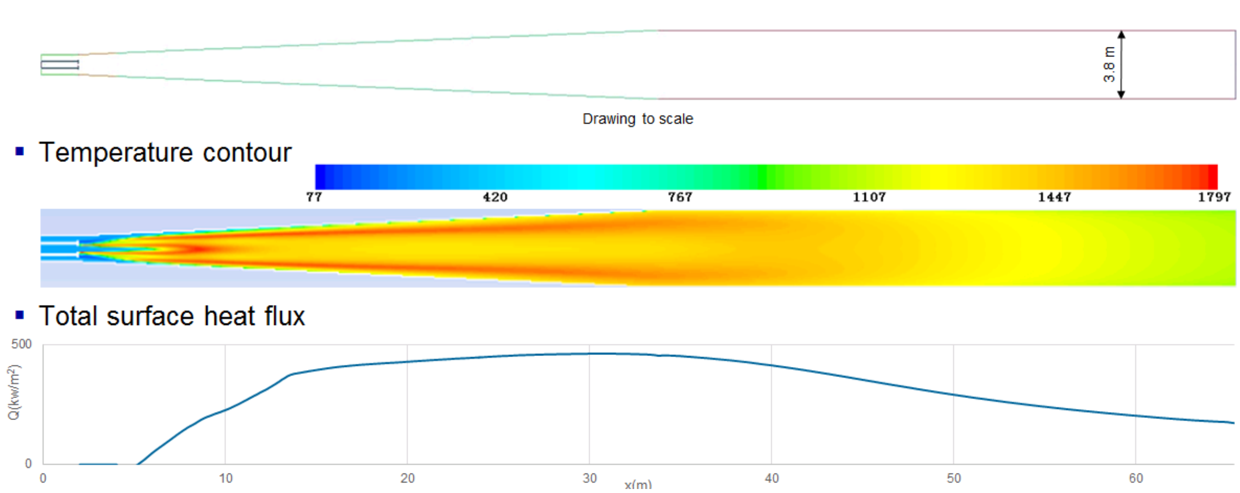



**Figure 5-5**
**Combustor Vessel Geometry Prior to Optimization**

This configuration delivers the required performance needed from the combustion module. However, it was recognized that delivering a membrane wall-cooled furnace envelope would be complex both in terms of manufacturing and in parallel-flow thermal stability. As the ring of furnace tubes begins the transition to the conical section, the membrane width would need to be reduced before some of the tubes would need to be stepped back to facilitate the smaller overall furnace diameter. As the tubes then proceed further upwards, more tubes would be stepped back as the furnace enclosure diameter reduces further. As the conical section represents almost half of the furnace height, the removed tubes would effectively have a greatly reduced heated length and the tubes that remained in direct contact with the furnace would undergo intensification of heating near the top of the unit (i.e., less tubes sharing similar heat release levels).

Although the heat flux is predicted to be far lower near the top of the furnace (where the cooling steam is already hot), the unheated tube circuits would be far cooler. During subcritical pressure operation, it would be possible for these tubes to be delivering two-phase flow, while the fully heated tubes could be delivering superheated steam to the separators. This thermohydraulic imbalance would risk undercooling of some tube elements and thermal shocking of collecting headers and the separator vessels when operating. Although some of this risk could be mitigated by substituting underheated tubes with fully heated ones at different points in the formation of the cone, differential thermal expansion would likely cause mechanical stress on the membrane elements. Manufacturing complexity would also make this a very expensive arrangement to build.

Subsequently, DBL requested that WUSTL investigate options for reducing or eliminating the conical section at the top half of the combustor vessel with the aim to maximize the height of the cylindrical section of the combustor membrane. This allows for a simplified design of the combustor pressure parts, especially with respect to the mechanical design challenges relating to differential expansion, flow imbalance, and mechanical support. To ensure that the alternative arrangement offered no detriment to the combustion performance, WUSTL optimized the design of the combustor by significantly reducing the length of the conical section while ensuring that target design combustion performance requirements remained in place. The results of this analysis are shown in Figure 5-6.

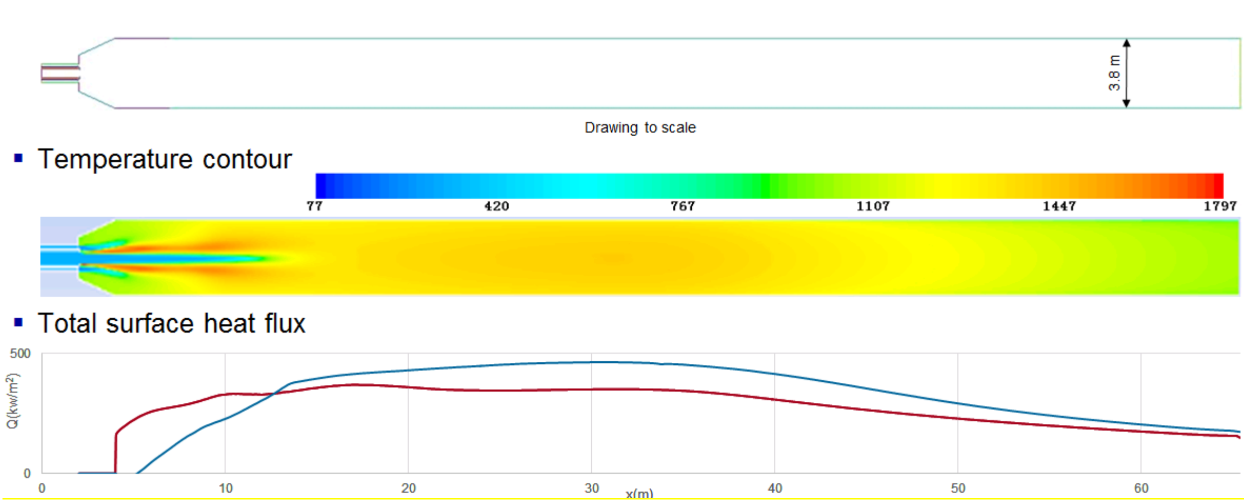



**Figure 5-6**
**Combustor Vessel Geometry Post Optimization**

To allow the heat release to be optimized for the long slender profile of the SPOC combustion module, the incoming fuel particle size distribution was adjusted to facilitate a flatter heat release profile. For clarity, the revised heat flux is plotted (red) against the original heat flux (blue) in Figure 5-5. The full membrane wall can now proceed through the entire length of the furnace module (ensuring even heating of each element is achieved) and the entire arrangement can be top supported from the PV, allowing straightforward management of the differential expansion of the heating surface and the vessel. A small 45° conical section is formed near the burner opening that may be constructed with refractory lining to ensure thermal radiation is reflected and stable combustion is maintained, as there is only a single burner in each SPOC combustion module. The CFD model shows that this adjusted geometry does not significantly alter the way the gases expand into the furnace volume and so the SPOC combustion proceeds successfully as before due to gas cushioning at the top of the furnace.

### *Boiler Module*

As agreed during the configuration development, only a single boiler module design is needed for the SPOC system as the flue gas flowrate entering the stage is identical, regardless of which stage. The only difference between stages is the resultant operating pressure that decays from stage to stage due to pressure losses incurred in the burner and convection banks. It was estimated that the overall stage pressure drop is 167 mbar (2.4 psi). Therefore, including inter-stage pressure drop from dampers and ducting, the outlet of SPOC system is expected to operate within 1 bar (14.5 psi) of the feed pressure of Stage 1 (16 bara [242 psia]).

The boiler module consists of a cylindrical PV that has a vertically supported boiler circuit suspended within which is bounded by membrane wall circuits. This allows sub-headers to distribute and collect steam to and from heating circuit elements within the PV, thereby minimizing vessel penetrations and limiting costs.

## Oxy-Combustion Flue Gas Properties

Extensive analysis was carried out on the convective heat transfer results from the DBL in-house OEM modeling tool “SteamGen” that was updated to include pressurized oxy-combustion conditions against predictions using commercially available process modeling software tools such as Thermoflex™, Aspen Plus™, and Fluent CFD™ models. The first step of this analysis was to compare the calculated properties for the pressurized oxy-combustion flue gas for a range of compositions reflecting higher and lower excess oxygen cases as shown in Table 5-1.

**Table 5-1**
**Composition of Oxy-Combustion Flue Gas**

| | High Oxygen | | Low Oxygen | |
|---|---|---|---|---|
| **Species** | **vol %** | **wt %** | **vol %** | **wt %** |
| $CO_2$ | 33.9 | 45.67 | 55.9 | 74.03 |
| $SO_2$ | 0.0537 | 0.11 | 0.0885 | 0.17 |
| $O_2$ | 38.2 | 37.42 | 1.7 | 1.64 |
| $N_2$ | 4.65 | 4.01 | 4.01 | 3.40 |
| Ar | 0.0 | 0.0 | 0.0 | 0.0 |
| $H_2O$ | 23.2 | 12.79 | 38.3 | 20.76 |

These flue gas cases were evaluated to reflect the key influencing properties for convective heat transfer for flow at a right angle to tube bundles:[21]

$$U_o = 0.33 \mathrm{Re}^{0.7} \mathrm{Pr}^{0.3} \frac{k}{D}$$

where:

$U_o$ is the outside heat transfer coefficient (W/m$^2$-K)

Re is the Reynolds number (dimensionless)

Pr is the Prandtl number (dimensionless)

k is the bulk fluid thermal conductivity (W/m-K)

D is the characteristic diameter of the tube (outside diameter, m)

This relationship can be rearranged to show the influence of each property on the outside heat transfer coefficient:

$$U_o = 0.33 \frac{GD}{\mu}^{0.7} \frac{C_P \mu}{k}^{0.3} \frac{k}{D}$$

where:

G is the bulk fluid mass flux (kg-s/m$^2$)

μ is the bulk fluid viscosity (kg/ms)

Cp is the fluid heat capacity (J/kg-K)

[21] Chemical Engineering – Volume 1 4th ed pg 351 Coulson and Richardson 1990

Hence the final exponents for each fluid property can be assessed such that the overall influence of each property can be assessed on the heat transfer coefficient to develop an overall relative error. Values fort the equation are shown in Table 5-2.

**Table 5-2**
**Influence of Fluid Properties on Convective Heat Transfer**

| Property | GD/μ | Cp-μ/k | k/D | Overall |
|---|---|---|---|---|
| Heat Capacity | | 0.3 | | 0.3 |
| Thermal Conductivity | | -0.3 | 1 | 0.7 |
| Viscosity | -0.7 | 0.3 | | -0.4 |

In addition to these key properties for heat transfer, the enthalpy and specific volume were also assessed to qualify temperature and velocity calculations, summarized in Table 5-3.

**Table 5-3**
**Comparative Assessment of High Excess Oxygen Flue Gas Properties**

| Property | Temperature, °C (°F) | Doosan Steam-Gen | Thermo-flow Thermo-flex | Aspen Plus | ANSYS Fluent | Dev $2\sigma$ | 95% Confidence Limits | | Relative Range |
|---|---|---|---|---|---|---|---|---|---|
| Enthalpy, kJ/kg (Btu/lb) | 1150–700 (2102–1292) | 613.8 (263.9) | 612 (263.1) | 612 (263.1) | 611.3 (262.8) | 2.138 (0.92) | 616 (265) | 612 (263) | 0.7% |
| | 700–400 (1292–752) | 379.1 (163.0) | 377.7 (162.4) | 376 (161.7) | 376.8 (162.0) | 2.658 (1.14) | 382 (164) | 376 (162) | 1.4% |
| Specific Volume, $m^3$/kg ($ft^3$/lb) | 1150 (2102) | 0.226 (3.62) | 0.226 (3.62) | 0.227 (3.64) | 0.226 (3.62) | 0.001 (0.02) | 0.227 (3.64) | 0.225 (3.60) | 0.9% |
| | 700 (1292) | 0.155 (2.48) | 0.155 (2.48) | 0.155 (2.48) | 0.155 (2.48) | 0.000 (0.00) | 0.155 (2.48) | 0.155 (2.48) | 0.0% |
| | 400 (752) | 0.107 (1.71) | 0.107 (1.71) | 0.107 (1.71) | 0.107 (1.71) | 0.000 (0.00) | 0.107 (1.71) | 0.107 (1.71) | 0.0% |
| Specific Heat, kJ/kg-K (Btu/lb°-F) | 1150 (2102) | 1.405 (0.336) | 1.41 (0.337) | 1.406 (0.336) | 1.404 (0.335) | 0.005 (0.001) | 1.410 (0.337) | 1.400 (0.334) | 0.7% |
| | 700 (1292) | 1.312 (0.313) | 1.30 (0.310) | 1.304 (0.311) | 1.307 (0.312) | 0.010 (0.002) | 1.322 (0.316) | 1.302 (0.311) | 1.5% |
| | 400 (752) | 1.218 (0.291) | 1.21 (0.289) | 1.204 (0.288) | 1.199 (0.286) | 0.016 (0.004) | 1.234 (0.295) | 1.202 (0.287) | 2.7% |
| Conductivity, W/m-K (Btu/hr-ft-°F) | 1150 (2102) | 0.1108 (0.064) | - | 0.092 (0.053) | 0.099 (0.057) | 0.019 (0.011) | 0.130 (0.075) | 0.092 (0.053) | 34.6% |
| | 700 (1292) | 0.077 (0.044) | - | 0.072 (0.041) | 0.072 (0.041) | 0.006 (0.003) | 0.083 (0.048) | 0.071 (0.041) | 15.6% |
| | 400 (752) | 0.0524 (0.030) | - | 0.051 (0.029) | 0.051 (0.029) | 0.002 (0.001) | 0.054 (0.031) | 0.051 (0.029) | 6.7% |
| Viscosity, μPa-s (lbf-s/$ft^2$ $*10^6$) | 1150 (2102) | 56.1 (1.172) | - | 55.24 (1.154) | 55.0 (1.149) | 1.157 (0.024) | 57.26 (1.20) | 54.94 (1.15) | 4.1% |
| | 700 (1292) | 42.83 (0.895) | - | 41.37 (0.864) | 42.49 (0.887) | 1.528 (0.032) | 44.36 (0.93) | 41.30 (0.86) | 7.1% |
| | 400 (752) | 32.38 (0.676) | - | 31.88 (0.666) | 32.46 (0.678) | 0.629 (0.013) | 33.01 (0.69) | 31.75 (0.66) | 3.9% |

As can be seen from this summary, only the thermal conductivity and viscosity showed disagreement at higher temperatures. The same assessment was conducted for the low excess oxygen flue gas, detailed in Table 5-4, showing similar results for low oxygen flue gas.

**Table 5-4**
**Comparative Assessment of Low Excess Oxygen Flue Gas Properties**

| Property | Temperature, °C (°F) | Doosan Steam-Gen | Thermo-flow Thermo-flex | Aspen Plus | ANSYS Fluent | Dev 2σ | 95% Confidence Limits | | Relative Range |
|---|---|---|---|---|---|---|---|---|---|
| Enthalpy, kJ/kg (Btu/lb) | 1150–700 (2102–1292) | 682.7 (293.5) | 680.2 (292.4) | 679 (219.9) | 679 (291.9) | 3.489 (1.50) | 686 (295) | 679 (292) | 1.0% |
| | 700–400 (1292–752) | 416.6 (179.1) | 415 (178.4) | 414 (178.0) | 413.2 (177.6) | 2.930 (1.26) | 420 (180) | 414 (178) | 1.4% |
| Specific Volume, $m^3$/kg ($ft^3$/lb) | 1150 (2102) | 0.223 (3.57) | 0.223 (3.57) | 0.223 (3.57) | 0.223 (3.57) | 0.000 (0.00) | 0.223 (3.572) | 0.223 (3.572) | 0.0% |
| | 700 (1292) | 0.152 (2.43) | 0.152 (2.43) | 0.157 (2.51) | 0.152 (2.43) | 0.005 (0.08) | 0.157 (2.515) | 0.147 (2.355) | 6.6% |
| | 400 (752) | 0.105 (1.68) | 0.105 (1.68) | 0.105 (1.68) | 0.105 (1.68) | 0.000 (0.00) | 0.105 (1.682) | 0.105 (1.682) | 0.0% |
| Specific Heat, kJ/kg-K (Btu/lb°-F) | 1150 (2102) | 1.571 (0.375) | 1.57 (0.375) | 1.573 (0.376) | 1.569 (0.375) | 0.003 (0.001) | 1.574 (0.376) | 1.568 (0.374) | 0.4% |
| | 700 (1292) | 1.449 (0.346) | 1.44 (0.344) | 1.438 (0.343) | 1.440 (0.344) | 0.010 (0.002) | 1.459 (0.348) | 1.439 (0.344) | 1.4% |
| | 400 (752) | 1.335 (0.319) | 1.31 (0.313) | 1.316 (0.314) | 1.307 (0.312) | 0.025 (0.006) | 1.360 (0.325) | 1.310 (0.313) | 3.8% |
| Conductivity, W/m-K (Btu/hr-ft-°F) | 1150 (2102) | 0.1158 (0.067) | - | 0.0905 (0.052) | 0.108 (0.062) | 0.026 (0.015) | 0.141 (0.082) | 0.090 (0.052) | 44.3% |
| | 700 (1292) | 0.0768 (0.044) | - | 0.0725 (0.042) | 0.075 (0.043) | 0.004 (0.003) | 0.081 (0.047) | 0.072 (0.042) | 11.3% |
| | 400 (752) | 0.0501 (0.029) | - | 0.0497 (0.029) | 0.052 (0.031) | 0.002 (0.001) | 0.053 (0.030) | 0.048 (0.028) | 9.8% |
| Viscosity, μPa-s (lbf-s/$ft^2$ *$10^6$) | 1150 (2102) | 52.67 (1.100) | - | 50.22 (1.049) | 52.46 (1.096) | 2.716 (0.057) | 55.39 (1.16) | 49.95 (1.04) | 10.3% |
| | 700 (1292) | 39.53 (0.826) | - | 38.34 (0.801) | 40.02 (0.836) | 1.728 (0.036) | 41.26 (0.86) | 37.80 (0.79) | 8.7% |
| | 400 (752) | 29.12 (0.608) | - | 27.84 (0.581) | 30.13 (0.629) | 2.295 (0.048) | 31.42 (0.66) | 26.82 (0.56) | 15.8% |

The variability between models for each fluid property can be combined by quadrature (i.e., summing the square of the errors and finding the square root of the result):

$$\frac{\partial_{uo}}{u_O} = \sqrt{0.7\left(\frac{\partial_k}{k}\right)^2 + 0.4\left(\frac{\partial_\mu}{\mu}\right)^2 + 0.3\left(\frac{\partial_{Cp}}{C_P}\right)^2}$$

The uncertainties in the convective heat transfer coefficient are shown in Table 5-5.

**Table 5-5**
**Convective Heat Transfer Coefficient Uncertainty**

| $\partial h_o$ | Units | High $O_2$ | Low $O_2$ |
|---|---|---|---|
| 1150°C (2102°F) | $W/m^2K$ ($Btu/hr\text{-}ft^2\text{-}°F$) | 0.298 (0.052) | 0.378 (0.067) |
| 700°C (1292°F) | $W/m^2K$ ($Btu/hr\text{-}ft^2\text{-}°F$) | 0.167 (0.029) | 0.139 (0.024) |
| 400°C (752°F) | $W/m^2K$ ($Btu/hr\text{-}ft^2\text{-}°F$) | 0.140 (0.025) | 0.192 (0.034) |

As the anticipated heat transfer coefficient is expected to be in the 50 $W/m^2K$ range (8.8 $Btu/hr\text{-}ft^2\text{-}°F$), these uncertainties are within 1%. As part of the overall bank absorption assessment, relative error on the enthalpy combines with the heat transfer coefficient to yield an overall uncertainty on final gas-temperature predictions. With a surface metal temperature of 350°C (662°F), the predicted final gas temperatures based on the highest and lowest combination of heat transfer coefficient and enthalpy assessment are shown in Table 5-6.

**Table 5-6**
**Convective Heat Transfer Outlet Temperature Prediction Relative Error Boundaries**

| Flue Gas Composition | Inlet Gas Temperature, °C (°F) | Highest Outlet Temperature, °C (°F) | Lowest Outlet Temperature, °C (°F) | Relative Error, °C (°F) |
|---|---|---|---|---|
| High $O_2$ | 1150 (2102) | 869.9 (1597.8) | 861.7 (1583.1) | 7.2 (13.0) |
| | 700 (1292) | 568.9 (1056.0) | 564.4 (1047.9) | 4.5 (8.1) |
| Low $O_2$ | 1150 (2102) | 870.2 (1598.4) | 860.3 (1580.5) | 9.9 (17.8) |
| | 700 (1292) | 568.8 (1055.8) | 564.4 (1047.9) | 4.3 (7.7) |

The relative error represents between 2–4% of the overall temperature drop of the bank heat transfer assessment due to property uncertainty. Note that radiative heat transfer has not been characterized in this assessment however measurements taken at the 100 kWth pilot unit correlated with the CFD predictions carried out by WUSTL.

## Performance Modeling

To further assess the DBL SteamGen pressurized oxy-combustion heat transfer predictions, a test case was developed using an appropriately sized reheater bank and flue gas flowrate commensurate with the 550 MWe-scale design to compare elemental heat transfer coefficients. The expected thermal duty of these reheater banks was 235 MWth (split across four stages). The boundary conditions were defined from the combustion modeling and anticipated reheat steam conditions (from the base case turbine heat balance) to allow comparative modeling to be carried out. As the DBL SteamGen model is extensively validated against atmospheric-pressure heat transfer cases, this comparative test was also carried out using atmospheric-pressure oxy-combustion flue gas.

WUSTL constructed the reheat bank in a CFD model to evaluate the predicted outside tube heat transfer coefficients. The test bank used typical reheater bank geometry, as advised by DBL, as shown in Table 5-7.

**Table 5-7**
**Reheater Bank Simulation Geometry**

| Item | Value |
|---|---|
| Tube Outside Diameter, mm (in) | 44.5 (1.8) |
| Cross Pitch (across gas flow), mm (in) | 230 (9.1) |
| Back Pitch (in line with gas flow), mm (in) | 80 (3.1) |
| Number Wide/Deep | 4 / 12 |
| Upstream Cavity, mm (in) | 1113 (43.8) |
| Downstream Cavity, mm (in) | 2225 (87.6) |

This geometry was also created by DBL in a SteamGen model to allow direct comparison. Both models were given identical flue gas composition and process boundary conditions, as detailed in Table 5-8.

**Table 5-8**
**Reheater Bank Simulation Flue Gas Boundary Conditions**

| Item | Value |
|---|---|
| Temperature, °C (°F) | 1200 (2192) |
| Pressure, bara (psia) | 1.01 (14.7) |
| Inlet velocity, m/s (ft/s) | 7.9 (25.9) |
| Gas Composition, wt %: $CO_2$ | 45.67 |
| $O_2$ | 37.42 |
| $H_2O$ | 12.79 |
| $N_2$ | 4.01 |
| Ar | 0.00 |
| $SO_2$ | 0.11 |

The test bank was defined to have the expected steam side mass flux of the full-scale system to ensure that inside heat transfer coefficients (and the resultant metal temperature) were commensurate with the final model conditions. Two banks were constructed to represent the primary reheater bank (cooler gas temperatures, tighter cross pitch) and the final reheater that would generally be in the more radiative sections of a boiler system (and hence have a wider cross pitch to better harness radiative heat transfer). The geometry that was modeled is shown in Figure 5-7.

The fluent CFD model was built to have an equivalent geometry with the metal temperature being defined at fixed temperature above that of the reheat steam temperature in these tubes. A representative output diagram is shown in Figure 5-8.

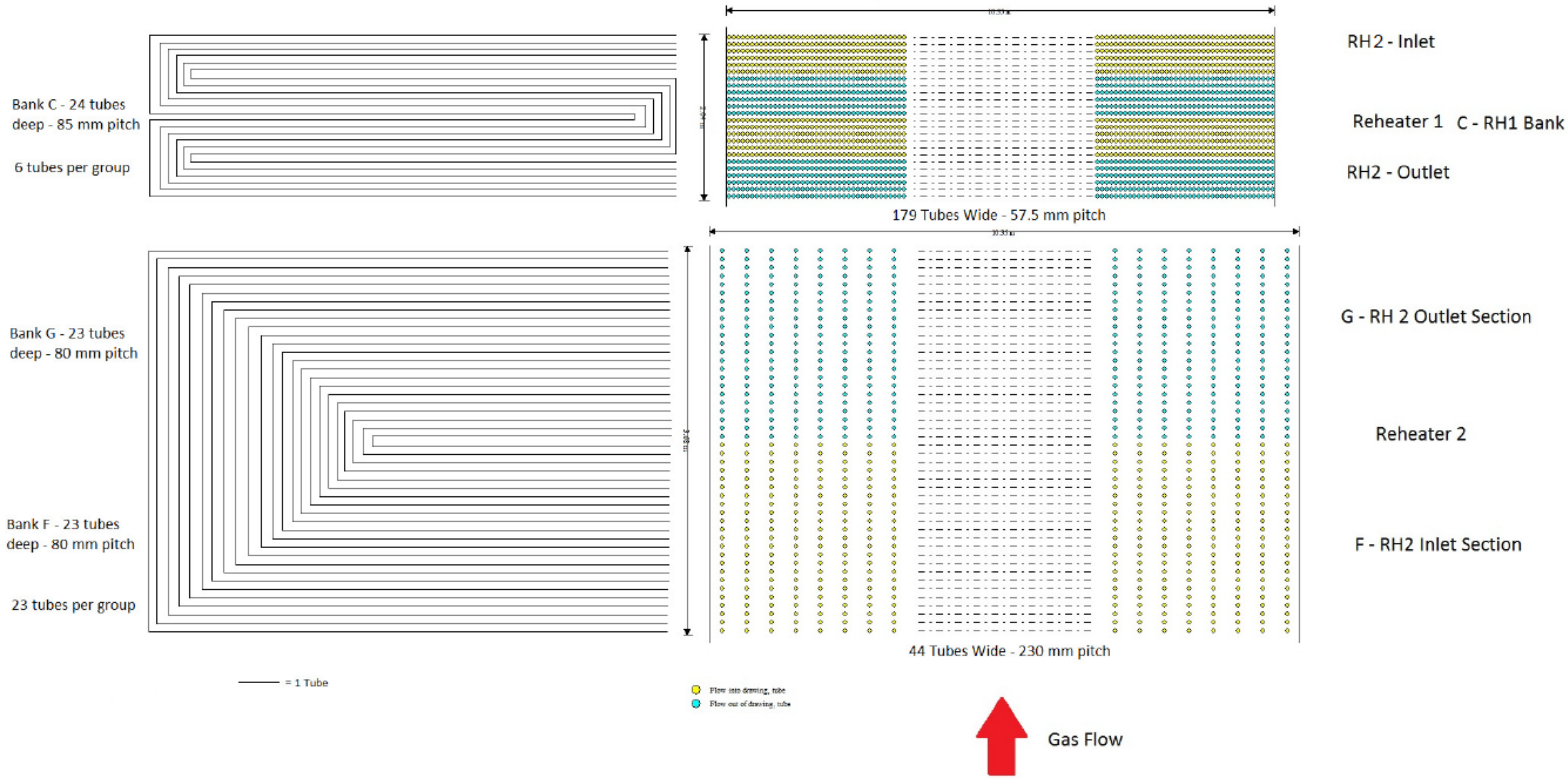



**Figure 5-7**
**Test Reheater Bank Arrangement**

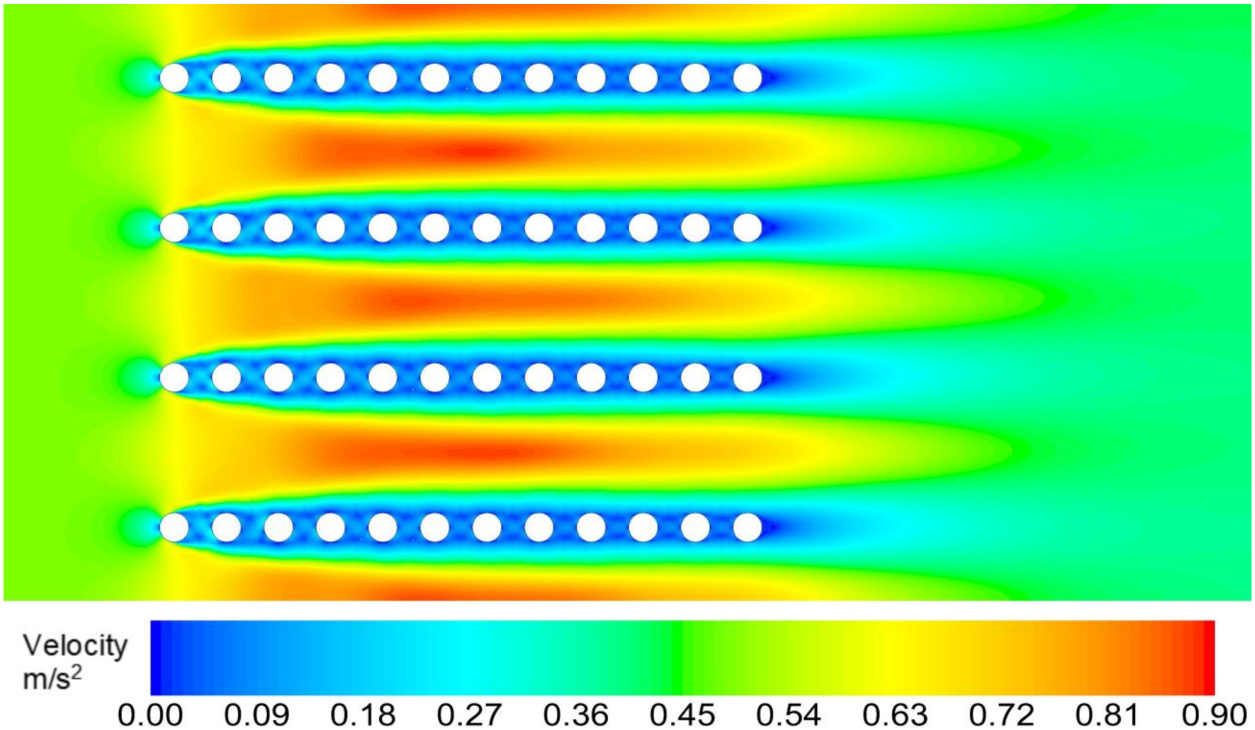



**Figure 5-8**
**Fluent CFD Reheater Model Showing Velocity Contours**

Comparisons suggested that the DBL OEM boiler thermal design tool predictions were more conservative than the WUSTL CFD predictions and so have therefore been used as the basis for the boiler thermal design, ensuring that the resultant cost estimate will be as representative as possible. The final 4-stage SPOC arrangement is shown in Figure 5-9 and this was used to develop the boiler design.

Using appropriate steam-side mass fluxes for each bank, DBL defined a boiler geometry that would deliver both the thermal performance (heat absorption) and acceptable tube metal temperatures at every location. The conceptual SPOC convective heat transfer modules are comprised of an upward-flow gas path with appropriately configured heating surfaces, in cross-flow arrangement, of superheat, reheat (single reheat), and economizer (plain tube) pressure parts, as shown in Figure 5-10.

The water-steam circuit is parallel across the four fuel stages. Reheat steam temperature control is by means of spray attemperation and/or FGR. Within each PV, a gas-tight membrane wall steam-cooled enclosure is proposed to provide annular space to separate hot flue gas from PV and space for interconnecting pipework and headers.

Using the DBL OEM boiler thermal design tool, for a single SPOC convective stage and based on the optimized arrangement, results in a requirement for the convective boiler module to be approximately 50 meters (164 ft) long with an outside diameter of 4.5 meter (15 ft) limited by the requirement for road transportation. The convective PV concept considers a plenum at the base to aid ash drop-out. A provision is considered to introduce inert gas into the dead space between the PV and membrane enclosure (cage wall) to maintain the integrity of the PV.

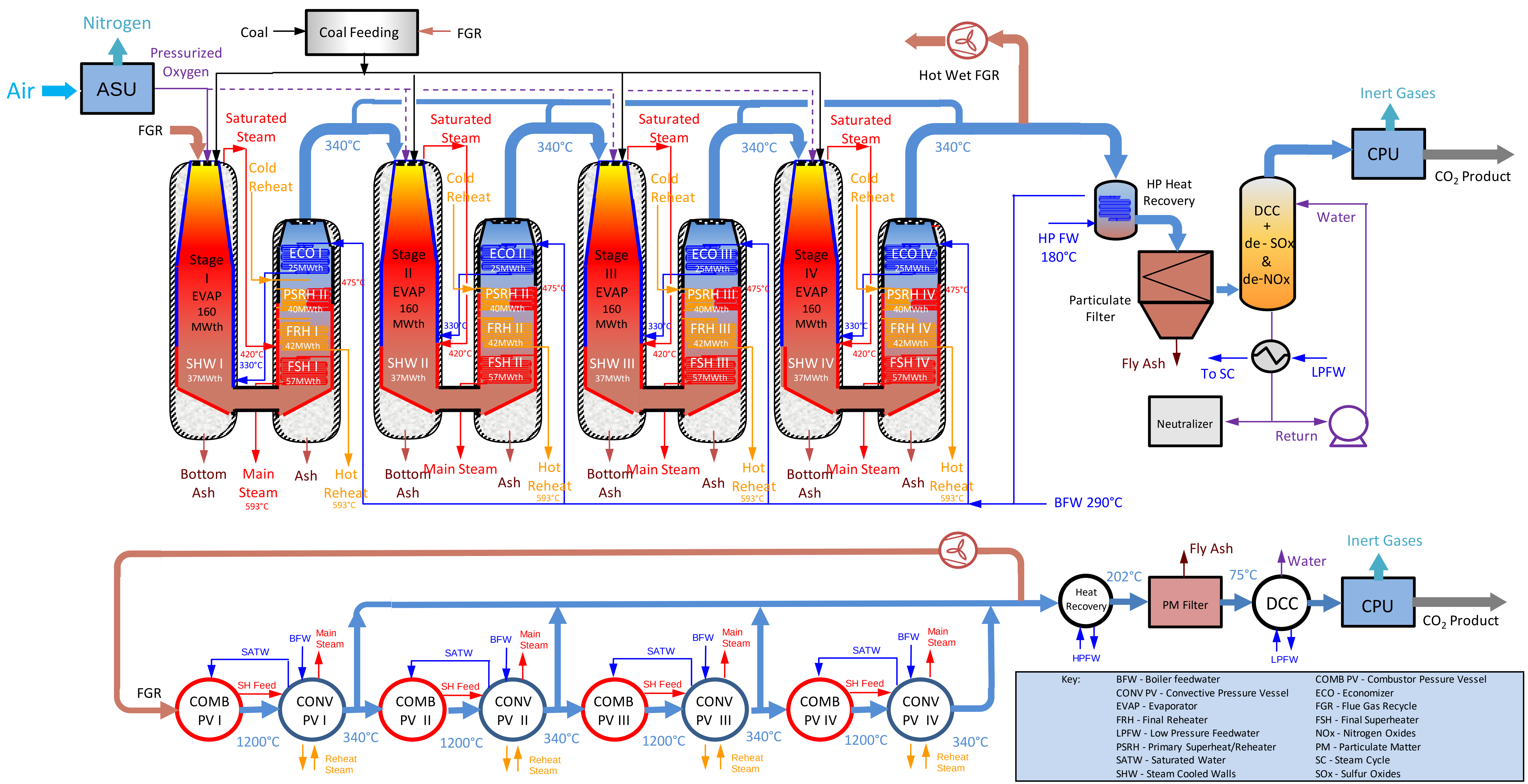
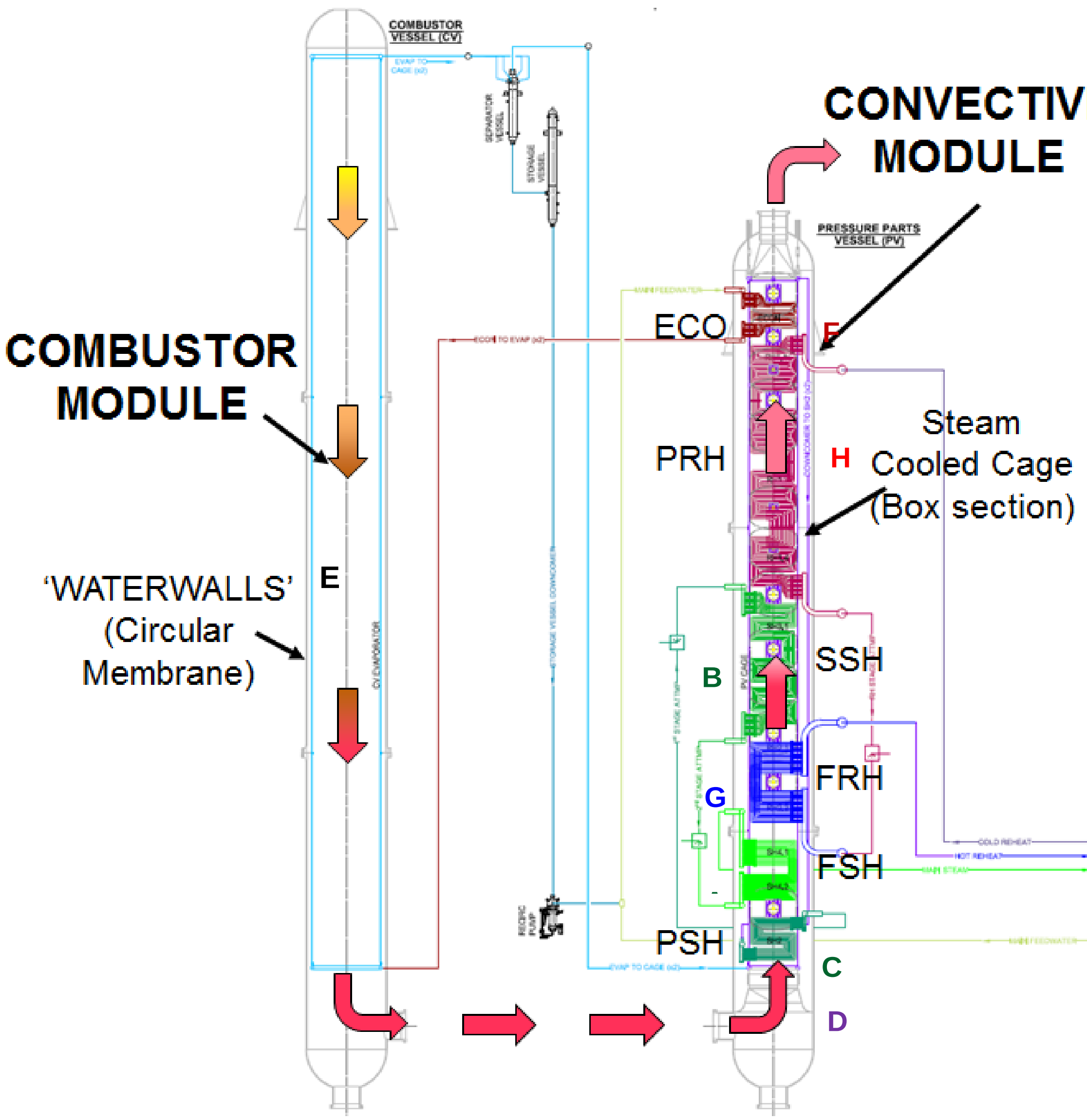



**Figure 5-9**
**4-Stage, 2-Pass SPOC Arrangement**




**Item:**

| | | | | | |
|---|---|---|---|---|---|
| **A** | **4th Stage Superheater** | **D** | **Convective PV Enclosure** | **G** | **Reheater 2** |
| **B** | **3rd Stage Superheater** | **E** | **Combustor PV Evaporator** | **H** | **Reheater 1** |

**Figure 5-10**
**Schematic SPOC Combustor PV and Convective PV Per Fuel Stage**

The PV has cavities included for installation of online ash cleaning such as explosive shock generators and has been split into three sections for ease of transport and assembly at site. The entire heating surface is top supported and thermal expansion will be significant. Thermal expansion is an area that would likely require further, detailed engineering to better develop the concept.

Details of the boiler bank surfaces for the convective PV stage are given in Table 5-9.

**Table 5-9**
**Convective PV Boiler Bank Details**

| Item Ref.: | SPOC Boiler Heating Surface Description (per Fuel Stage) | Tube OD mm (in) | Nominal Tube Thk mm (in) | Tube Cross Pitch mm (in) | Tentative Material Selection |
|---|---|---|---|---|---|
| | | | | | |
| **Convective PV** | | | | | |
| **A** | **4th Stage Superheater (SH4)** | | | | |
| | SH4.1 Outlet Leg | 42.4 (1 ⅔) | 7.1 (0.28) | 345.0 (13 ½) | HR3C 310NbN |
| | SH4.2 Inlet Leg | 42.4 (1 ⅔) | 6.3 (¼) | 345.0 (13 ½) | HR3C 310NbN |
| **B** | **3rd Stage Superheater (SH3)** | | | | |
| | SH3.2 Outlet Bank | 42.4 (1 ⅔) | 6.3 (¼) | 230.0 (9) | HR3C 310NbN |
| | SH3.1 Inlet Bank | 42.4 (1 ⅔) | 6.3 (¼) | 230.0 (9) | SA213 T12 |
| **C** | **2nd Stage Superheater (SH2)** | | | | |
| | SH2 Bank | 42.4 (1 ⅔) | 6.3 (¼) | 460.0 (18) | SA213 T91 |
| **D** | **Convective PV Enclosure (SH1)** | | | | |
| | Upper Enclosure Membrane Tubes | 51.0 (2) | 8.0 (0.31) | 115.0 (4 ½) | SA213 T12 |
| | Lower Enclosure Membrane Tubes | 38.0 (1 ½) | 6.3 (¼) | 57.5 (2 ¼) | SA213 T12 |
| | | | | | |
| **Combustor PV** | | | | | |
| **E** | **Membrane Wall Evaporator** | | | | |
| | Evaporator (Rifled Tubes**)** | 28.6 (1 ⅛) | 6.5 (0.26) | 42.6 (1 ⅔) | SA213 T12 |
| | | | | | |
| **Convective PV** | | | | | |
| **F** | **Economizer** | | | | |
| | Economizer Bank (Plain Tube) | 44.5 (1 ¾) | 5.0 (0.2) | 57.5 (2 ¼) | SA210C |
| | | | | | |
| **Convective PV** | | | | | |
| **G** | **Reheater Section (RH2)** | | | | |
| | RH2.1 Outlet leg | 44.5 (1 ¾) | 3.6 (0.14) | 230.0 (9) | HR3C 310NbN |
| | RH2.2 Inlet leg | 44.5 (1 ¾) | 3.6 (0.14) | 230.0 (9) | HR3C 310NbN |
| **H** | **Reheater Section (RH1)** | | | | |
| | RH1.4 Outlet | 51.0 (2) | 4.0 (0.16) | 86.25 (3 ⅜) | SA213 T22 |
| | RH1.3 | 51.0 (2) | 4.0 (0.16) | 86.25 (3 ⅜) | SA213 T12 |
| | RH1.2 | 51.0 (2) | 4.0 (0.16) | 65.7 (2 ⅝) | SA213 T12 |
| | RH1.1 Inlet | 51.0 (2) | 4.0 (0.16) | 65.7 (2 ⅝) | SA210C |

Interconnecting pipework is routed both internal and external to the PV, optimizing the use of the available space limitations within the vessel dead space. For both the combustor and convective vessels, performance has been based on model predictions that require validation. There are still several challenges that need to be overcome through detailed engineering design and testing at significant pilot scale.

A 3-D visualization of the optimized arrangement concept for a single SPOC stage of a 550 MWe net output system with interconnecting pipework is shown in Figure 5-11.

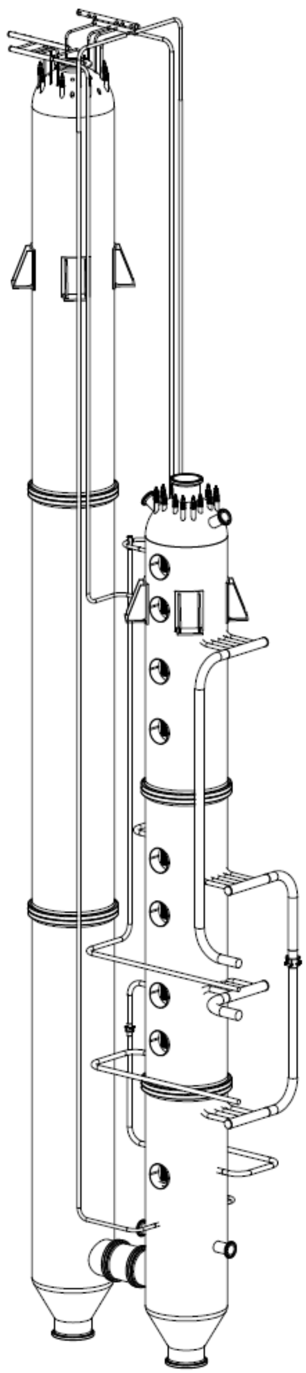


**Figure 5-11**
**Schematic SPOC Combustor PV and Convective PV Per Fuel Stage**

## Steam Turbine Modeling

### *Basis of Model*

The steam turbine model was defined using the NETL baseline Case S12A design, which specifies:

- Boiler interfaces (turbine inlet conditions at the stop valve, expected cold reheat conditions leaving the high-pressure cylinder, reheat pressure drop, and hot reheat turbine inlet temperature)
- Overall turbine arrangement (number of feedwater heaters, turbine extraction points, bled-steam pressure loss, deaerator location, feedwater heater approach temperatures at full load, pressure drops, cooling water conditions, and effective condenser pressure).
- Turbine expansion isentropic efficiency (for each stage, based on extraction conditions)
- Boiler feedwater pump turbine location, efficiency, and power requirements

### *Case S12A Results*

A steam cycle model based on NETL baseline Case S12A using the EBSILON steam cycle performance modeling software was developed and tuned to match the full-load performance. As the baseline S12A turbine heat balance diagram accounts for the total turbine shaft seal steam losses as flows leaving the steam seal regulator, the seal flow origin locations are not shown. As a result, the model did not explicitly consider the seal leakage flow except for the thermal contribution of the leakage flow to the relevant extraction streams for feedwater heaters 7 and 2. Despite this simplification, the initial model predicted the steam flowrate to within 0.4% of the published steam data. The model results are shown in Figure 5-12.

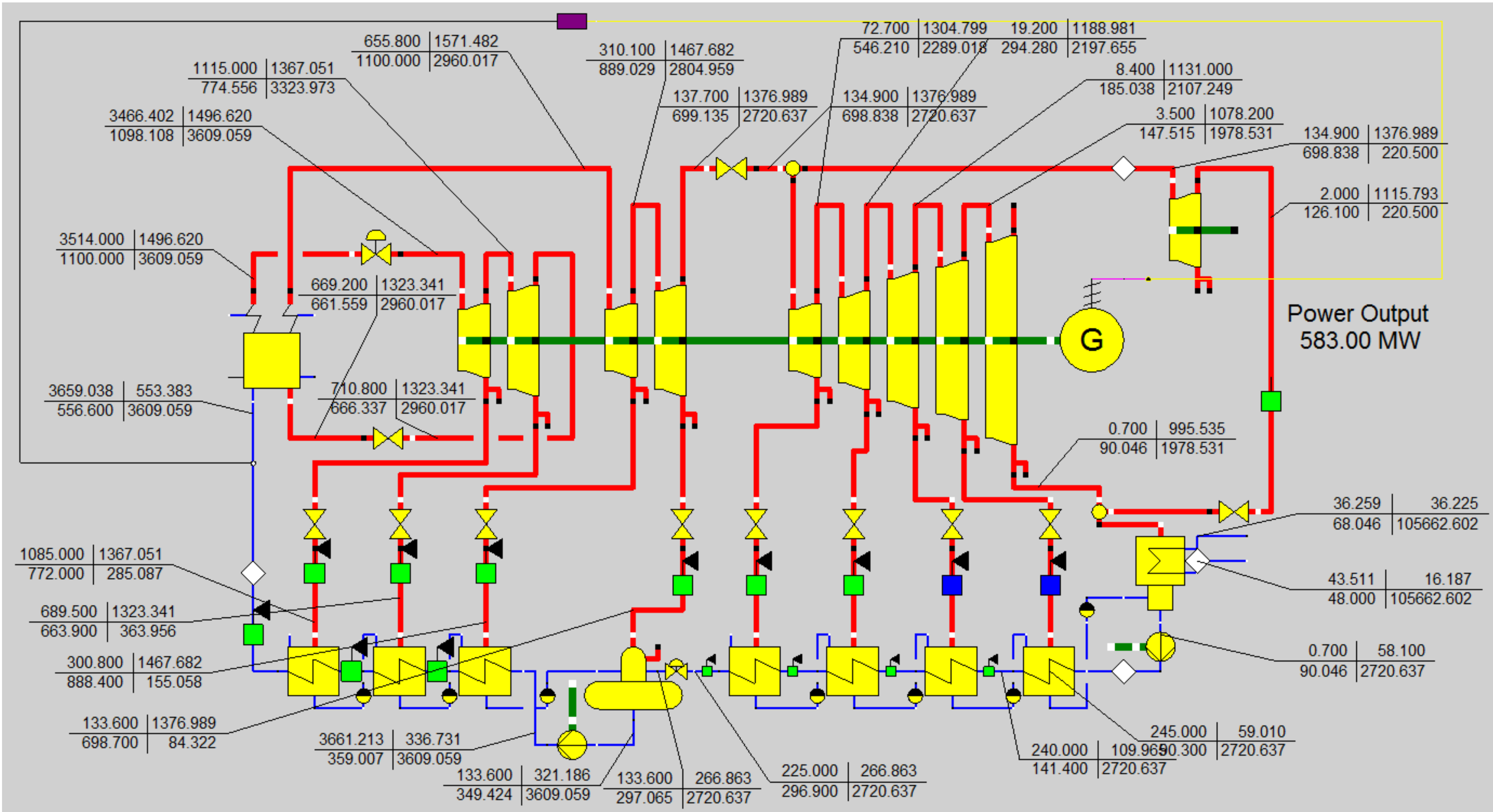



**Figure 5-12**
**NETL S12A Baseline Model Using EBSILON**

A direct comparison of the published S12A baseline steam data and the EBSILON model results are shown in Table 5-10.

**Table 5-10**
**NETL Baseline Case S12A Model Results**

| Parameter | | Units | Base Case S12A | EBSILON Model | Notes |
|---|---|---|---|---|---|
| Main Steam | Pressure | barg (psia) | 242.2 (3514) | 242.2 (3514) | Defined |
| | Temperature | °C (°F) | 593.3 (1100) | 593.3 (1100) | Defined |
| | Mass flowrate | kg/s (klb/hr) | 456.7 (3624) | 454.8 (3609) | No sprays |
| Feedwater | Pressure | barg (psia) | 288.7 (4186) | 288.6 (4185) | HP heater dP |
| | Temperature | °C (°F) | 291.4 (556.6) | 291.5 (556.7) | Calculated |
| | Mass flowrate | kg/s (klb/hr) | 456.7 (3624) | 454.8 (3609) | Calculated |
| Hot Reheat Steam | Pressure | barg (psia) | 45.2 (655.8) | 45.2 (655.8) | Defined |
| | Temperature | °C (°F) | 593.3 (1100) | 593.3 (1100) | Defined |
| | Mass flowrate | kg/s (klb/hr) | 378.5 (3004) | 373.0 (2960) | No sprays |
| Cold Reheat Steam | Pressure | barg (psia) | 49.0 (710.8) | 49.0 (710.8) | Defined |
| | Temperature | °C (°F) | 354.0 (669.2) | 350.5 (663.0) | Calculated |
| | Mass flowrate | kg/s (klb/hr) | 378.5 (3004) | 373.0 (2960) | Calculated |
| Boiler Feed Pump Turbine Steam Flow | | kg/s (klb/hr) | 27.8 (220.5) | 27.8 (220.5) | Power match |
| LP Feedwater Flowrate | | kg/s (klb/hr) | 345.5 (2742) | 342.8 (2720) | Calculated |
| Main Steam Duty | | MWth | 1002.4 | 998.2 | Calculated |
| Reheat Steam Duty | | MWth | 216.9 | 217.1 | Calculated |
| Total Heat to Steam | | MWth | 1219.3 | 1215.3 | Calculated |
| Gross Power Output | | MWe | 583 | 583 | Defined |
| Net Power Output | | MWe | 550 | 550 | Defined |

### *Resizing for SPOC Requirements*

This model was then used as a basis for the larger steam turbine that is needed to deliver the gross power for oxy-combustion. The model was scaled up to the initial estimated SPOC gross power requirement of 729 MWe. As the model was configured to calculate the steam flow needed to meet a gross power requirement, this increased the main steam flow proportionally to 567.1 kg/s (4500 klb/hr). The EBSILON model is shown in Figure 5-13.

Because of the pressurized operating condition of the SPOC process, substantial heat recovery opportunities are available from the product flue gas prior to $CO_2$ purification and compression. The bulk of the heat available is due to the latent heat content of the moisture generated in the combustion.

## Flue Gas Heat Recovery

A heat recovery assessment was carried out on the SPOC flue gases leaving the last combustion stage as they are passed thought the particulate removal system and ultimately entering the DCC section. Because of the elevated pressure of the SPOC system, this heat recovery can be achieved at higher temperatures than would be available from atmospheric flue gas systems, making the heat more useful in feedwater applications.

### *Non-condensing Stage*

The flue gas heat recovery was carried out in two main sections – the first section is a high-temperature heat exchanger that cools the flue gas using HP feedwater. The second section is a lower-temperature heat recovery that indirectly extracts the heat from the DCC circulating fluid using LP feedwater.

Because of the high-temperature FGR, the flue gas exits the SPOC boiler island at an elevated temperature. This heat can be recovered into the HP feedwater heater circuit as the temperature is sufficient to raise the cooling water to the nominal economizer inlet temperature.

Two options are available for the location of this cooler:

1) Prior to particulate removal, using plane tube or a sparse fin pitch (like the economizer surface) making the flue gas cooler for particulate removal.
2) After particulate removal, allowing for easier application of finned tubing with a tighter fin pitch (and hence smaller surface requirement) as the ash loading is substantially reduced.

To avoid the need for high-temperature dust removal, the non-condensing heat recovery is carried out by a dedicated economizer-type bank that is like the final surfaces of the convective PV modules as this location remains a high-dust environment. Only a portion of the HP feedwater is heated in this way (14.2%), with the remainder being heated using the HP feedwater heating train as before. The degree of cooling applied at this bank is currently set above the moisture dew point. However, further assessment is recommended to identify if the acid dew point is reached prior to the particulate removal step, as if so the degree of cooling applied will need to be reduced (thereby reducing the higher-temperature contribution to the steam turbine island).

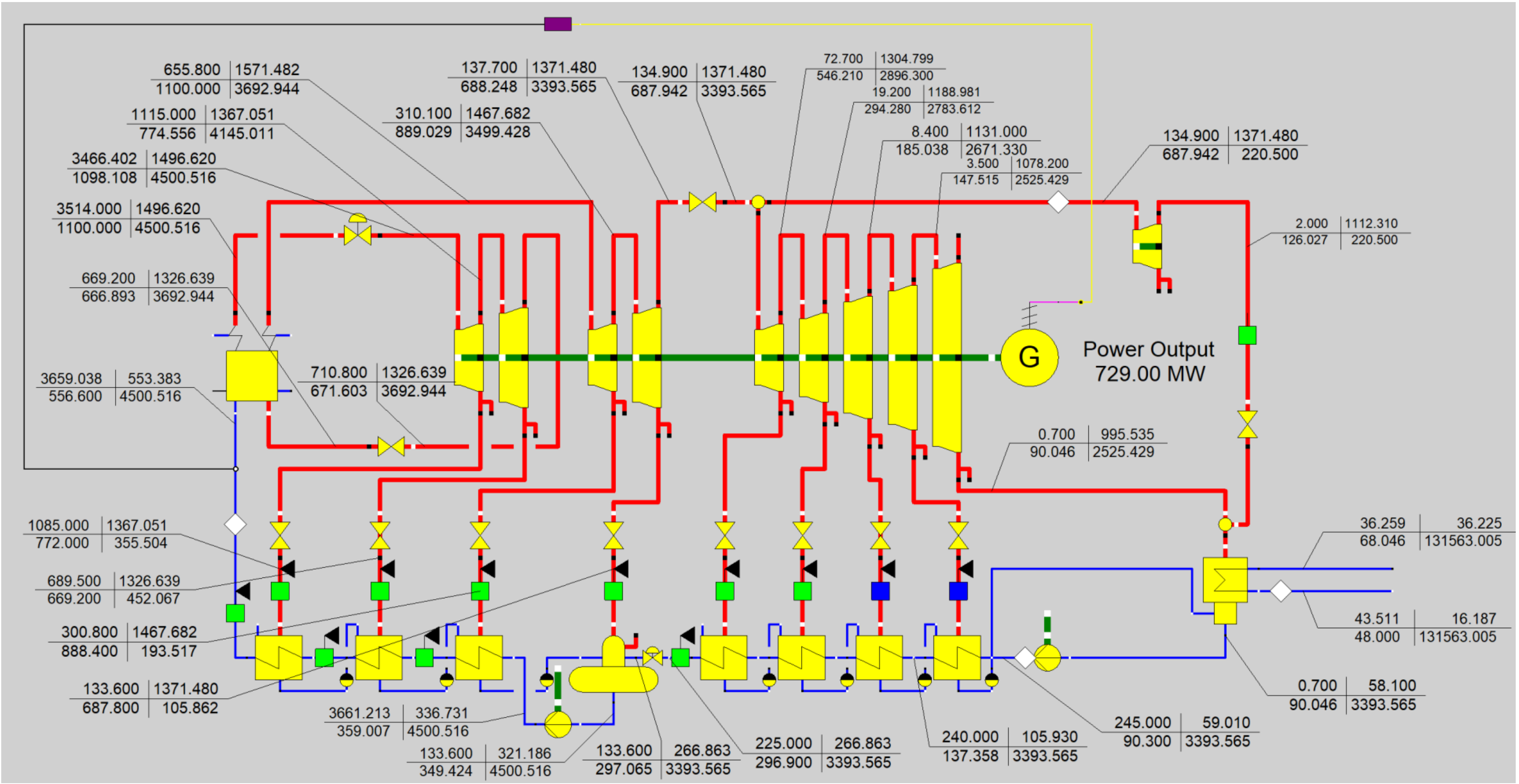



**Figure 5-13**
**SPOC Scaled Model without Heat Recovery**

The cooling and condensation process was modeled using Aspen Plus v10 software. The cooling curve for the flue gases and the heating curves for the different streams being heated are shown in Figure 5-14.

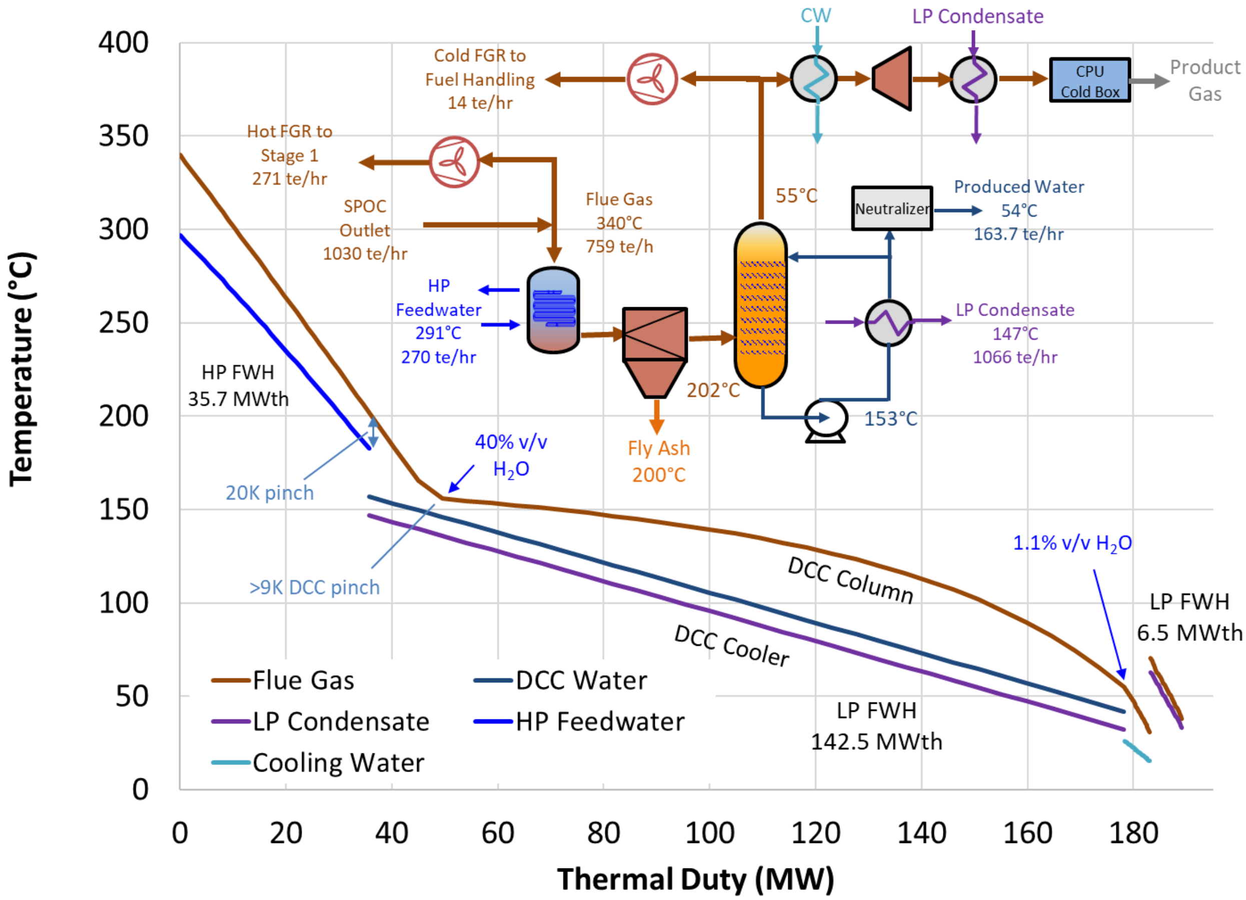



**Figure 5-14**
**SPOC Flue Gas Cooling Curve**

### *Direct-Contact Cooling*

Following the high-temperature heat recovery stage and dust removal, the flue gas is passed to a DCC module. The DCC heat recovery is a two-stage system with direct flue gas cooling using the circulating fluid (exposed to the flue gas and thus containing dissolved acid gases and trace solids) and then a DCC cooler heat exchanger that transfers heat from the circulating water to the clean LP feedwater stream.

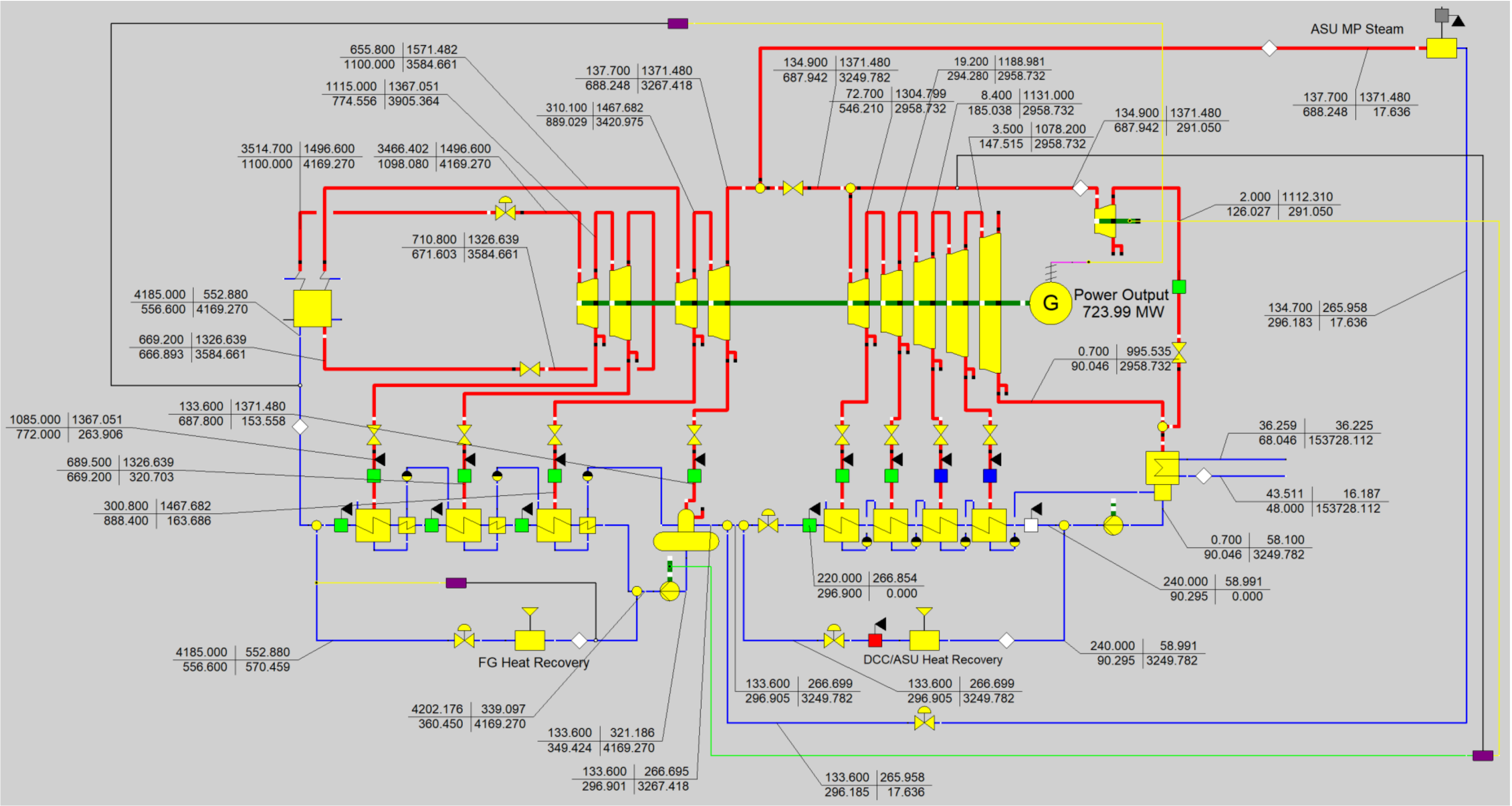



**Figure 5-15**
**SPOC Steam Turbine Model with Heat Recovery**

### *Compression and Purification Unit*

Although the flue gas heat recovery represents most of the low-grade heat available, additional heat recovery opportunities are also available from other sources in this process such as the ASU and the $CO_2$ compression system.

When the low-temperature thermal energy is recovered from the DCC, the MAC, the BAC, and the $CO_2$ compressor systems – the entire low-temperature feedwater heating requirements can be achieved. It follows that the low-temperature feedwater heater units would not be needed and would therefore not be installed in an SPOC steam turbine system, saving capital costs.

When the heat recovery was added to the 729 MWe gross power model, the main steam flow needed was reduced to 532.2 kg/s (4223 klb/hr), a 6% reduction in steam generation in comparison to having no heat recovery due to the improved effective turbine heat rate.

The reduced heat-to-steam requirement results in a smaller boiler being needed, proportionally reducing auxiliary load related to the fuel processing systems, as shown in Table 5-11.

**Table 5-11**
**Auxiliary Power in kWe of SPOC and NETL Baseline Cases**

| Parameter Case | S12A | S12B | S12F | SPOC |
|---|---|---|---|---|
| Coal Handling and Conveying | 510 | 630 | 570 | 512 |
| Pulverizers | 3850 | 5520 | 4770 | 4282 |
| Sorbent Handling and Reagent Preparation | 170 | 240 | 180 | 162 |
| Ash Handling | 860 | 1220 | 1070 | 960 |
| Fuel Delivery - Primary Air Fans or Lock-hopper | 2490 | 3550 | 2240 | 2227 |
| Comburant Delivery – Forced Draft Fans or $O_2$ Feed | 1460 | 2090 | 880 | 0 |
| Induced Draft Fans or Recycle | 6730 | 9620 | 7280 | 1047 |
| Main Air Compressor and ASU Auxiliaries | - | - | 94,710 | 124,607 |
| Economine | - | 22,900 | - | - |
| Baghouse | 120 | 170 | 150 | 150 |
| Spray-Dryer Flue Gas Desulfurization / DCC | 2240 | 3200 | 2910 | 150 |
| Selective Catalytic Reduction / Compression CPU | 10 | 49,020 | 64,740 | 21,774 |
| Miscellaneous BOP | 2000 | 2000 | 2000 | 2000 |
| Steam Turbine Auxiliaries | 400 | 400 | 400 | 400 |
| Condensate Pumps | 800 | 550 | 990 | 958 |
| Circulating Water Pumps | 2400 | 9140 | 3280 | 3141 |
| Ground Water Pumps | 250 | 690 | 320 | 320 |
| Cooling Tower Fans | 1560 | 5970 | 2110 | 2020 |
| Air-Cooled Condenser Fans | 4990 | 3680 | 6910 | 6617 |
| Transformer Losses | 1830 | 2350 | 2780 | 2662 |
| **Total Auxiliary Power** | **32,670** | **122,940** | **198,290** | **173,988** |
| **Gross Power Required** | **582,670** | **673,000** | **748,290** | **723,988** |

The overall gross power needed to deliver 550 MWe net was therefore reduced further to 724 MWe following the inclusion of the heat recovery, resulting in a main steam flow 7.3% lower than the initial case with no integration.

## Overall Plant Performance

The overall plant performance is summarized against the three NETL baseline cases for comparison in Table 5-12. As can be seen from the results, early-stage $CO_2$ compression is avoided with the SPOC process as the flue gas enters the CPU at an elevated pressure in comparison to Case S12F. However, the need to feed pressurized oxygen into the process consumes a significant portion of the power saved.

The main differentiator is the ability to recover far greater quantities of heat from the process for use in the steam turbine island. As a result, the SPOC process outperforms the NETL baseline Case S12F by 3.3% points on an HHV basis at the same 90% $CO_2$ capture rate.

This performance is only 4% points lower than the unabated Case S12A, using the same fuel and steam turbine technology level. Another point to note is that both oxy-combustion cases achieve a higher boiler efficiency than the conventional air-fired cases. The condenser duty in Case S12B is far lower than what would be expected for the gross power generated due to the large extraction steam flow taken for solvent regeneration. The reverse is true for the SPOC case, where heat recovery serves to keep more of the extraction steam in the turbine, increasing the thermal duty on the condenser unit.

A summary of the energy flows for the SPOC design case is presented in Figure 5-16. The oxy-combustion cases outperform the PCC case on $CO_2$ emission intensity due to overall efficiency (i.e., Case S12B needs to burn more fuel to deliver 550 MWe net), hence with 90% capture a greater quantity of $CO_2$ is emitted. The SPOC case has the lowest $CO_2$ intensity at under 95 g/kWh (0.21 lb/kWh), which is 3-4 times lower than a typical natural-gas combined cycle unit.

**Table 5-12**
**Overall Comparison of SPOC with NETL Baseline Cases**

| Parameter Case | S12A | S12B | S12F | SPOC |
|---|---|---|---|---|
| Total Gross Power, MWe | 582.7 | 673.0 | 748.3 | 724.0 |
| $CO_2$ Capture/Removal Auxiliaries, kWe | - | 22,900 | 94,710 | 124,607 |
| $CO_2$ Compression, kWe | - | 49.000 | 64,740 | 21,774 |
| BOP, kWe | 32,670 | 51,040 | 38,840 | 27,607 |
| Total Auxiliaries, MWe | 32.67 | 122,940 | 198.29 | 174.0 |
| Net Power, MWe | 550.0 | 550.1 | 550.0 | 550.0 |
| HHV Plant Efficiency, % | 38.7 | 27.0 | 31.2 | 34.5 |
| HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh) | 9307 (8822) | 13,330 (12,635) | 11,532 (10,931) | 10,427 (9883) |
| LHV Plant Efficiency, % | 40.1 | 28.1 | 32.39 | 35.83 |
| LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh) | 8908 (8444) | 12,834 (12,165) | 11,115 (10,536) | 10,047 (9523) |
| HHV Thermal Input, MWth | 1422.0 | 2036.7 | 1761.9 | 1593.0 |
| LHV Thermal Input, MWth | 1370.3 | 1962.6 | 1697.8 | 1535.0 |
| Boiler Efficiency, % HHV | 85.7 | 85.8 | 88.7 | 87.5 |
| Heat to Steam, MWth | 1219.3 | 1748.1 | 1564.1 | 1412 |
| HP Heat Recovery, MWth | - | - | 0 | 35.7 |
| LP Heat Recovery, MWth | - | - | 64.46 | 197.8 |
| Condenser Duty, GJ/hr (MMBtu/hr) | 2227 (2111) | 1636 (1551) | 3075 (2915) | 3250 (3080) |
| As-Received Coal Feed, kg/hr (klb/hr) | 256,992 (566.7) | 368,084 (811.5) | 318,415 (702.0) | 287,892 (634.7) |
| $CO_2$ Generated, kg/hr (klb/hr) | 472,497 (1041.7) | 675,276 (1488.7) | 583,371 (1286.1) | 527,564 (1163.1) |
| $CO_2$ Captured, kg/hr (klb/hr) | 0 (0) | 607,619 (1339.6) | 530,219 (1168.9) | 475,287 (1047.8) |
| $CO_2$ Emitted, kg/hr (klb/hr) | 472,497 (1041.7) | 67,657 (149.2) | 53,152 (117.2) | 52,177 (115.0) |
| $CO_2$ Emission Intensity, kg/MW-hr (lb/MW-hr) | 859 (1894) | 123 (271) | 96.6 (213) | 94.9 (209) |

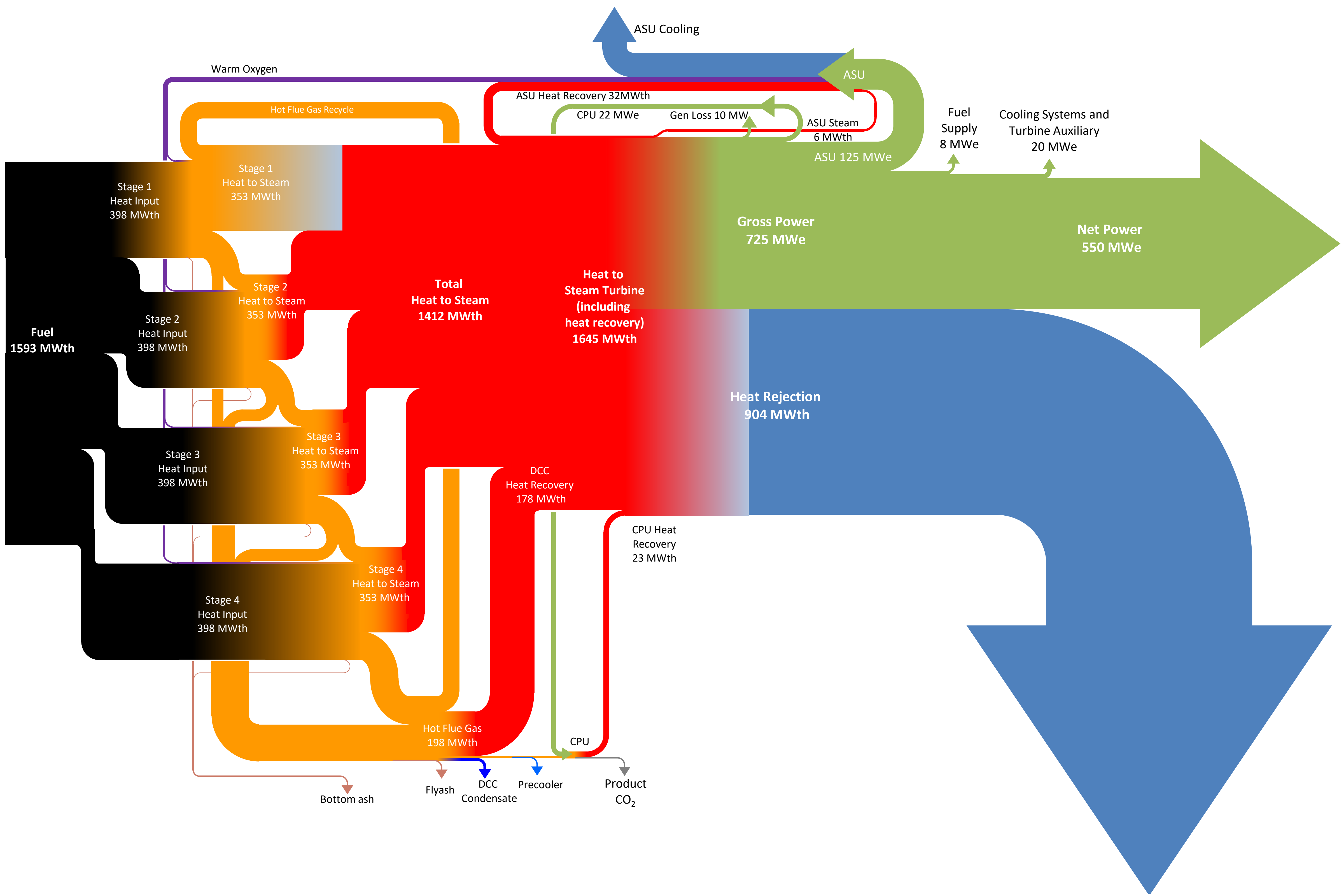



**Figure 5-16**
**SPOC Design Case Energy Sankey Diagram**

## Check Coal Case

The check coal, Illinois No. 6, was also modeled to investigate the performance impact on the SPOC system design (noting that no changes to the design-case equipment is included as this is a check case only). Using this bituminous coal in the SPOC system leads to one significant difference to that of the PRB case regarding the level of heat recovery possible from the flue gas. As Illinois No. 6 coal has 11.12 wt % moisture in comparison to the Montana PRB fuel at 25.77 wt % moisture, this yields a flue gas that is significantly drier than the design case. Table 5-13 shows the implication of this on the resulting flue gas generated from the SPOC system.

**Table 5-13**
**Comparison of Design Coal and Check Coal Flue Gas**

| Component | | | Design Case | Check Coal | Change |
|---|---|---|---|---|---|
| Gas Weight (entering heat recovery) | | kg/hr (klb/hr) | 754,798 (1664) | 659,349 (1454) | -12.6% |
| Carbon Dioxide | $CO_2$ | wt % (wet) | 73.19 | 76.93 | |
| Moisture | $H_2O$ | wt % (wet) | 21.79 | 16.45 | -5.3% |
| Nitrogen | $N_2$ | wt % (wet) | 0.56 | 0.71 | |
| Oxygen | $O_2$ | wt % (wet) | 1.02 | 0.99 | |
| Sulphur Dioxide | $SO_2$ | wt % (wet) | 0.58 | 1.64 | +1.06% |
| Argon | Ar | wt % (wet) | 2.85 | 3.15 | |
| Hydrogen Chloride | HCl | wt % (wet) | 0.00 | 0.10 | |
| Sulphur Trioxide | $SO_3$ | wt % (wet) | 0.00 | 0.01 | |
| Nitrogen Oxide | NO | wt % (wet) | 0.01 | 0.01 | |
| Nitrogen Dioxide | $NO_2$ | wt % (wet) | 0.00 | 0.00 | |

As the flue gas leaving the process is both lower in mass flow and lower in moisture content, the quantity of latent heat available from the condensing moisture in the DCC unit is substantially reduced, as can be seen in Table 5-14.

**Table 5-14**
**Overall Heat Recovery for Design Coal and Check Coal Cases**

| Component | | Design Case | Check Coal | Change |
|---|---|---|---|---|
| HP Heat Recovery | MWth | 35.7 | 29.8 | -16.6% |
| LP Heat Recovery | MWth | 197.8 | 153.3 | -22.5% |
| Gross Turbine Heat Rate | kJ/kWh (Btu/kWh) | 7014 (6648) | 7166 (6792) | +2.2% |

The net reduction in heat recovery possible with the check coal increases the turbine heat rate by over 2%. As this is a check case, and the design case has no LP feedwater heaters installed (all LP heating is achieved by heat recovery), the temperature entering the deaerator is lower than the targeted value of 147°C (297°F) by 22°C (41°F). This reduction in incoming heat will require an increased steam turbine extraction to the deaerator from the intermediate-pressure (IP) turbine exhaust – in this case by as much as 78%. Hence, if the fuel diet for the system included a significant range of moisture content in the fuel, design consideration would need to be considered for the sizing of the deaerator unit and the steam extraction line feeding it.

The overall performance of the Illinois No. 6 check coal case is shown in Table 5-15 along with the design coal case using Montana Rosebud PRB.

**Table 5-15**
**SPOC Design and Check Coal Performance**

| Parameter Case | Design | Check |
|---|---|---|
| Total Gross Power, MWe | 724.0 | 717.4 |
| $CO_2$ Capture/Removal Auxiliaries, kWe | 124,607 | 120,437 |
| $CO_2$ Compression, kWe | 21,774 | 19,995 |
| Balance of Plant, kWe | 27,607 | 26,944 |
| Total Auxiliaries, MWe | 174.0 | 167.4 |
| Net Power, MWe | 550.0 | 550.0 |
| HHV Plant Efficiency, % | 34.53 | 35.14 |
| HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh) | 10,427 (9883) | 10,244 (9710) |
| LHV Plant Efficiency, % | 35.83 | 36.44 |
| LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh) | 10,047 (9523) | 9880 (9364) |
| HHV Thermal Input, MWth | 1593.0 | 1565.0 |
| LHV Thermal Input, MWth | 1535.0 | 1509.5 |
| Boiler Efficiency, % HHV | 87.53 | 90.22 |
| Heat to Steam, MWth | 1412 | 1428 |
| HP Heat Recovery, MWth | 35.7 | 29.8 |
| LP Heat Recovery, MWth | 197.8 | 153.3 |
| Condenser Duty, GJ/hr (MMBtu/hr) | 3250 (3080) | 3156 (2991) |
| As-Received Coal Feed, kg/hr (klb/hr) | 287,892 (634.7) | 207,628 (457.7) |
| $CO_2$ Generated, kg/hr (klb/hr) | 527,564 (1163.1) | 484,254 (1067.6) |
| $CO_2$ Captured, kg/hr (klb/hr) | 475,287 (1047.8) | 436,029 (961.3) |
| $CO_2$ Emitted, kg/hr (klb/hr) | 52,177 (115.0) | 48,164 (106.2) |
| $CO_2$ Emission Intensity, kg/MW-hr (lb/MW-hr) | 94.9 (209.2) | 87.6 (193.1) |

Although the turbine heat rate increases, the boiler efficiency improves by a greater degree, thereby more than canceling out the overall impact and yielding an improved overall plant efficiency of 0.61% HHV.

This relatively small improvement in plant efficiency between sub-bituminous and bituminous coals shows the value of useful moisture latent heat recovery offered by the SPOC system when using lower-rank fuels.

As there is a lower $CO_2$ generation rate for the Illinois No. 6 fuel, this reduces the auxiliary power requirements on the CPU and the ASU, and hence the total heat input to the system is lower than the design case, yielding an improved $CO_2$ emission intensity. Process flow diagrams of the design and check coal cases are included in Appendix B, reported in both SI and English units for reference.

# 6
# FLEXIBILITY AND TURNDOWN

The flexibility of the SPOC system is driven by the ability to bypass individual combustion stages and hence can maintain stable combustion and heat transfer in the remaining modules. The main constraint to flexibility is the oxygen supply system and the CPU as both units contain compressors that operate efficiency within a tight operating window.

## SPOC Boiler Turndown

### *Strategy*

The SPOC process has been evaluated at part-load cases down to 12% net TMCR load. These cases are summarized in Table 6-1. The steam turbine is configured to operate in sliding-pressure mode from full load down to the boiler design Benson load; the Benson load being the lowest load at which the boiler is designed to maintain once-through operation. At loads below the Benson load constant pressure operation is maintained with the boilers operating in forced circulation mode. The design Benson load has been proposed as 40% BMCR (nominally 40% TMCR). Below this overall plant load, main steam is throttled at the turbine stop valve to ensure the boiler circuits do not operate at too low of a pressure to maintain stable furnace thermo-hydraulic performance.

**Table 6-1**
**SPOC Baseline Case Turndown Performance Summary**

| Parameter Load (% TMCR) | 100% | 75% | 50% | 25% | 12% |
|---|---|---|---|---|---|
| SPOC Modules in Service | 4 | 4 | 4 | 2 | 1 |
| Module Firing Load, % | 100 | 76.5 | 51.9 | 64.0 | 89.0 |
| Main Steam Pressure, bara (psia) | 242.4 (3515) | 180.4 (2616) | 118.5 (1718) | 113.7 (1649) | 112.9 (1638) |
| Cold Reheat Pressure, bara (psia) | 45.2 (655.8) | 33.9 (491.0) | 22.3 (323.7) | 13.6 (197.0) | 9.3 (135.4) |
| Thermal Input, MWth | 1593 | 1219 | 827.4 | 509.4 | 354.3 |
| Boiler Efficiency, % HHV | 87.53 | 87.61 | 87.38 | 87.56 | 87.21 |
| Heat-to-Steam, MWth | 1412 | 1080 | 731.4 | 455.5 | 313.1 |
| HP Heat Recovery, MWth | 35.7 | 27.47 | 18.83 | 11.38 | 7.96 |
| LP Heat Recovery, MWth | 197.8 | 159.0 | 106.5 | 53.69 | 38.46 |
| Gross Power, MWe | 724.0 | 552.1 | 382.3 | 225.4 | 152.9 |
| Auxiliary Load, MWe | 174.0 | 139.6 | 107.3 | 87.9 | 86.9 |
| Net Power, MWe | 550.0 | 412.5 | 275.0 | 137.5 | 66.0 |
| Net Plant Efficiency, % HHV | 34.53 | 33.85 | 33.24 | 26.99 | 18.63 |

For low load operation and to achieve significant plant turndown, the SPOC system can uniquely remove combustion stages, e.g. 4-off for 50%TMCR down to 2-off for 25%TMCR, by maintaining the combustor stage firing load in the stages remaining in operation.

If the system permitted full sliding-pressure operation, the prospect of operating at a high individual stage firing rate with ultra-low back pressure from the steam turbine operating at very low loads would be introduced. Very low pressure yields much larger density differences between water and steam at the point of boiling, normally requiring larger bore tubes to accommodate this flow without incurring excessive internal steam velocities. Throttling the steam turbine at reduced load also helps to maintain the system in a better state of readiness for rapid load ramping as the throttle valve can be opened immediately, while coordinating with bringing "hot standby" stages back into service.

The minimum individual stage firing rate is just over 50% of full firing rate with all 4 stages in service at the 50% net output case. WUSTL has demonstrated stable combustion down to as low as 8% fuel heat input in the 100 kWth pilot facility, suggesting boiler loads would only be limited by the steam turbine system ability to maintain synchronization on the grid. The main overall loss in efficiency at reduced-load operation centers around the ASU and CPU equipment. These compressor-based units can only turndown to 85% load before requiring recycle flow (thereby consuming more specific power). The CPU is a single-train arrangement, this will consume significantly more specific power at all loads below 85%. The extreme case here is that 12% net load consumes 22% fuel input to maintain these auxiliary power requirements.

## ASU Turndown

### *Baseline Case*

The ASU consists of two identical trains that supply 5250 TPD of pure gaseous oxygen each. Depending on the transport limitations, the number of trains and/or process solution can be modified. The scheme in Figure 6-1 shows the design flow considered for the two ASU trains, with 100% corresponding to the full flow requirement (10,500 TPD of pure gaseous oxygen).

As shown in Figure 6-1, PM is removed from the incoming air with an air filter and compressed in a MAC. Heat produced in the MAC is utilized for heating boiler feedwater (BFW). After pre-cooling and front-end purification, a part of the air is further compressed in a BAC, while the remaining air is directly sent to the main heat exchanger. Instrument air is extracted at the intermediate stage of the BAC. Heat produced at the BAC is utilized for pre-heating BFW and gaseous oxygen (GOx). The air is cooled and liquefied in the cold box to produce LOx and gaseous nitrogen (GAN). GAN is supplied to the driers and for coal drying. LOx is stored in a storage tank and pumped to required pressure using LOx pump. LOx is vaporized in the main heat exchanger to GOx, and then pre-heated using heat available from the BAC.

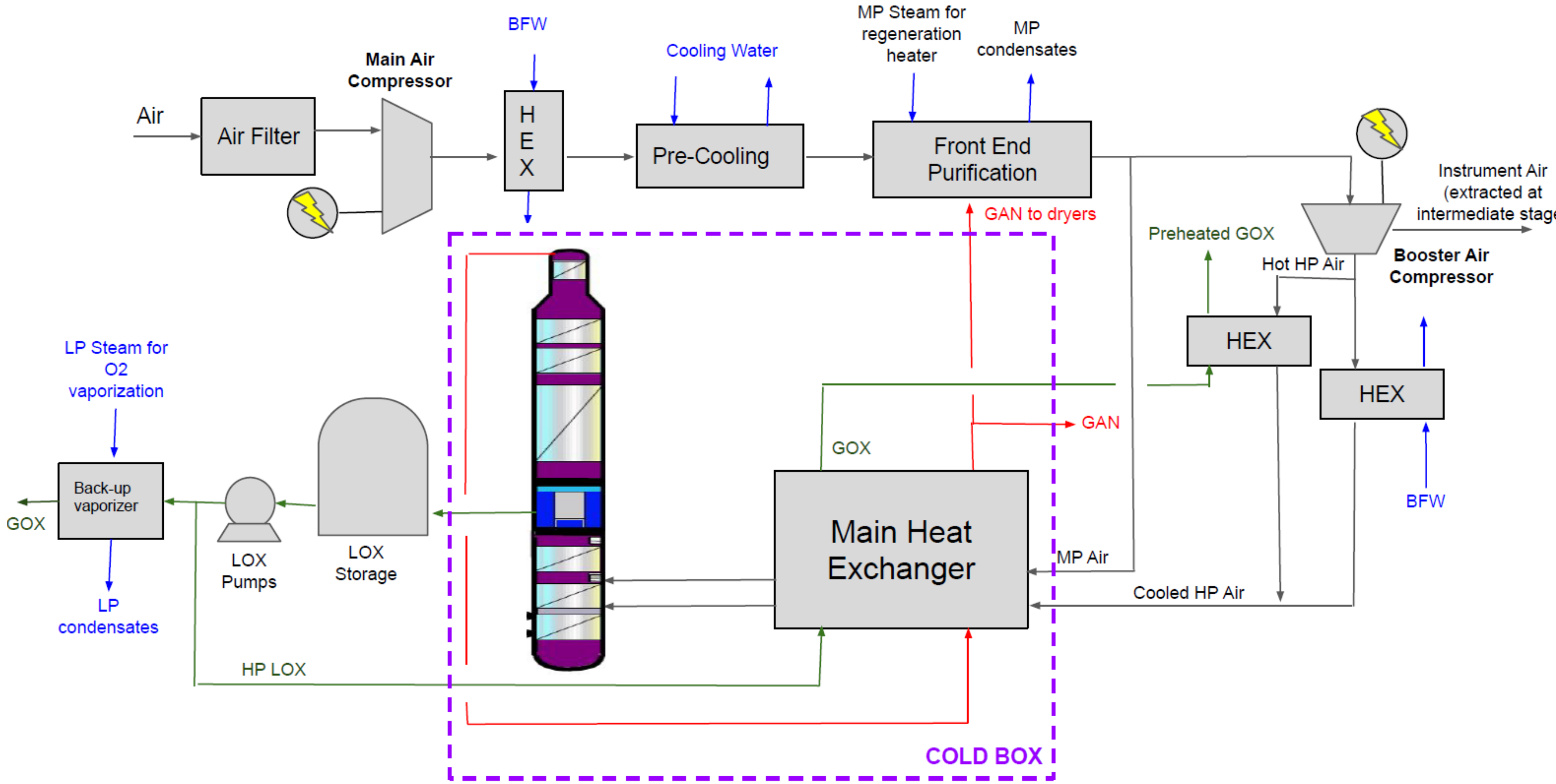



**Figure 6-1**
**ASU Configuration**

Because of the scale of the oxygen production needed, two ASU trains are required to generate the full 10,500 TPD duty. The oxygen is produced at a pressure commensurate with the feed to the SPOC combustor system. The two trains are largely independent except for the oxygen product manifold as shown in Figure 6-2.

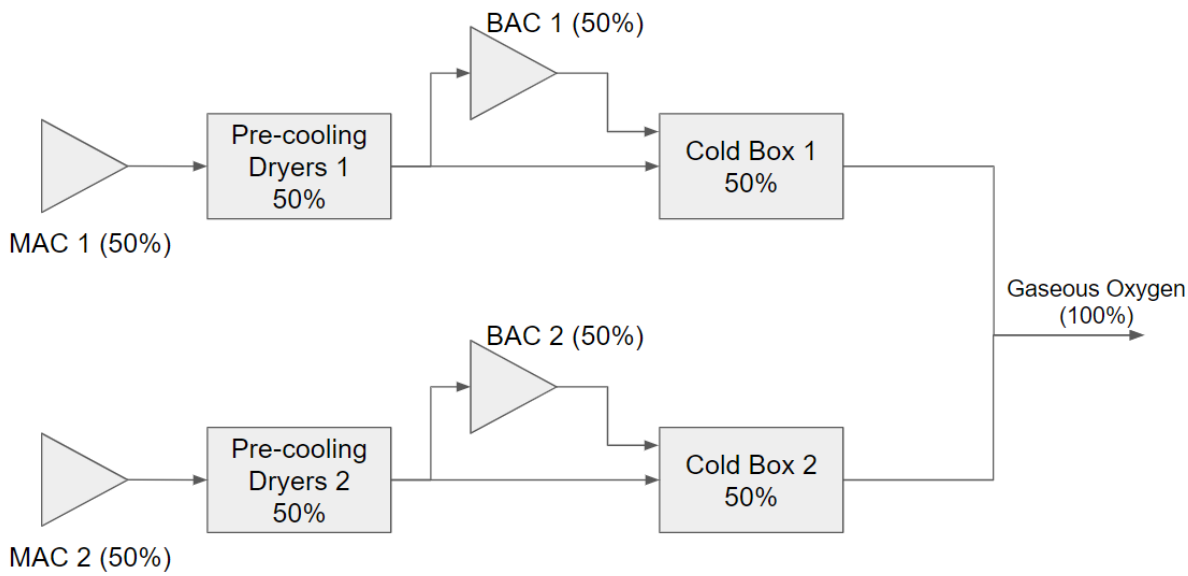



**Figure 6-2**
**Baseline Case 2-Train ASU Arrangement**

Depending on the transport limitations, the number of trains and/or process solution might be modified. The ASU, under steady conditions with the utilities available at battery limit, is expected to deliver products as indicated in Table 6-2.

**Table 6-2**
**Expected Production from the Baseline ASU**

| Production | Item | Design Conditions |
|---|---|---|
| GOx | Mass flow, TPD | 10,500 |
| | Pressure, bara ( psia) | ≥ 17 (246.6) |
| | Temperature, °C (°F) | ≥ 150 (302) |
| | $O_2$ content, vol % | ≥ 95.9 |
| LP GAN | Mass flow, TPD | 17,000 |
| | Pressure, bara (psia) | ≥ 0.950 (13.8) |
| | Temperature | ambient |
| | $N_2$ content, vol % | ≥ 99.5 |
| Instrument Air | Molar flow, $Nm^3/hr$ ($sft^3/hr$) | 4000 (152,160) |
| | Pressure, bara (psia) | ≥ 11 (159.5) |
| | Temperature | ambient |
| | Dew point, °C (°F) | < -40 (-40) |

As mentioned previously, the ASU produces 10,500 TPD of oxygen, expressed as pure $O_2$ at a pressure of 17 bara (246.6 psia) and temperature of 150°C (302°F). The composition of GOx produced is 95.9 vol % oxygen, 3.6 vol % argon, and 0.5 vol % nitrogen. Similarly, the ASU produces 17,000 TPD of nitrogen, expressed as gross flow at pressure of 0.95 bara (13.8 psia) and ambient temperature. This is used in the SPOC process as a drying gas for the incoming fuel during the pulverizing process and for any sealing or inerting applications as needed.

The composition of GAN is 99.75 vol % $N_2$, 0.09 vol % $O_2$, and 0.16 vol % argon. Additionally, 4000 $Nm^3$/hr (152,160 $sft^3$/hr) of instrument air is supplied at pressure of 11 bara (159.5) and has a dew point of -40°C (-40°F) for use in the SPOC system.

### LOx Production

Each train can produce up to 2% of LOx (~105 TPD per train or 210 TPD total). In this case, the GOx production will be reduced accordingly. The LOx production allows the refill the storage completely in around 17 days – allowing for rapid startup following a short outage.

### Expected Power and Utility Consumption

Each ASU train, under steady conditions and ambient site conditions, requires the following utilities at the battery limit:

- Electricity: 13.8 kV and 480 V and 60 Hz at terminals
- Cooling water at the respective user flanges
- Boiler feedwater at the respective user flanges
- Instrument air connection point to the header flange (for startup and stand-by)
- Nitrogen connection to $N_2$ header flange (for startup and stand-by for seal gas and inerting)
- Medium-pressure steam connection to header (10 bara [145 psia] saturated steam available)
- LP steam connection to header (6 bara [87 psia] saturated steam available)

Each ASU train, under steady conditions and ambient site conditions, is expected to consume the average utilities as shown in Table 6-3. IP steam is used by the regeneration heater of the adsorbers during the heating phase, and saturated steam at 10 bara (145 psia) is used. The steam condensate from regeneration heater is returned at 9 bara (130.5 psia). As the overall required production of 10,500 TPD is being supplied by two ASU trains, therefore the indicated full scale should be doubled to get the consumption for 10,500 TPD GOx supply.

**Table 6-3**
**Utility Consumption of Each Train for the Baseline ASU**

| Item | Unit | Value |
|---|---|---|
| Expected Electrical Power (at motor terminals) | MW | 62.2 |
| Expected IP Steam Consumption:<br>- Average<br>- Peak (during heating phase of regeneration) | kg/hr<br>(lb/hr)<br>kg/hr<br>(lb/hr) | 8000<br>(17,637)<br>22,300<br>(49,163) |
| Expected Condensate Return:<br>- Average<br>- Peak (during heating phase of regeneration) | kg/hr<br>(lb/hr)<br>kg/hr<br>(lb/hr) | 8000<br>(17,637)<br>22,300<br>(49,163) |
| Expected Cooling Water Supply | $m^3$/hr<br>($ft^3$/hr) | 1800<br>(63,566) |
| Expected Cooling Water Return | $m^3$/hr<br>($ft^3$/hr) | 1800<br>(63,566) |

The power and utilities consumption figure includes the following consumers:

- BAC
- Cooling water pump to send cooling water to the air/water tower
- Dryers regeneration heater
- Expansion turbines
- IP LOx pumps (combined with back up pumps)
- MAC

When the supply of 5250 TPD of GOx by vaporization of LOx is needed (via the back-up system), the expected associated LP steam consumption is 40,300 kg/hr (88,846 lb/hr). Saturated steam at 6 bara (87 psia) is considered for this duty, extracted from the steam turbine island. In this case, the GOx temperature will be 60°C (140°F), but 150°C (302°F) can be reached with an additional heat exchanger using IP steam. The condensate is sent back to the steam turbine island to the deaerator.

## BFW Preheating by ASU

During normal operation, each ASU, under steady conditions and ambient site conditions, is expected to transfer the heat quantities to BFW as shown in Table 6-4. The duty for BAC BFW pre-heater is the net heat available from the BAC for the steam cycle as GOx is heated internally in the ASU.

**Table 6-4**
**Expected Heat Transfer to BFW**

| Item | Units | Design Condition |
|---|---|---|
| BFW Inlet Temperature | °C (°F) | 33.2 (91.8) |
| Duty for MAC BFW Preheater | kWe | 29,700 |
| Maximum MAC BFW Outlet Temperature | °C (°F) | 147 (297) |
| Duty for BAC BFW Preheater | kWe | 2600 |
| Maximum BAC BFW Outlet Temperature | °C (°F) | 155 (311) |

### *Flexible Case Variant*

### Description

As shown in Figure 6-3, the flexible ASU consists of two cold boxes and pre-cooling/dryers sized for 50% of the overall flow requirement.

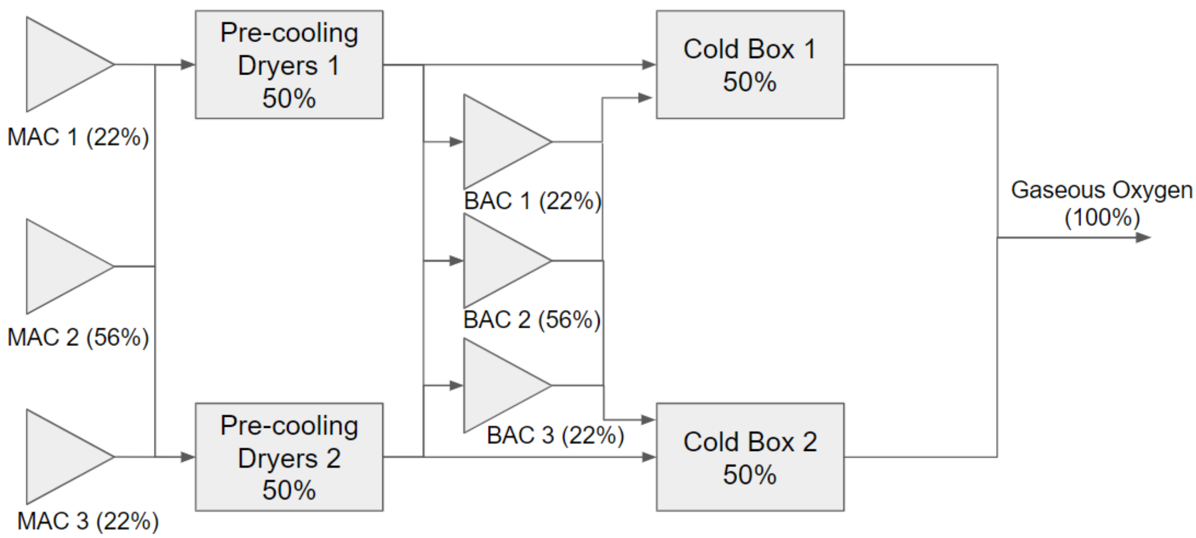



**Figure 6-3**
**Flexible ASU Arrangement**

Because of the required flexibility and possibility to operate efficiently without venting between 40% and 100% of the overall flow (except during the ramp-up and ramp-down transition phases that might require some venting because of the dynamics of the system), the first approach was to consider the following for the sizing of the MAC and BAC:

- One common machine sized for 56% of the overall flow
- Two common machines sized for 22% of the overall flow

This allows coverage of the full flow range between 40% and 100%, but some other machine configurations could be studied if required for future cases. For the 40% case, only the 56% machine is required in turndown mode. The turndown of each cold box is 40% (equivalent to

20% of the overall flow) and is operated in parallel during the overall turndown case. The ASU power consumption for the 25% and 12% load cases was estimated based on the multi-compressor configuration with a maximum turndown to 85% of full load as these loads were not considered in the baseline ASU design.

Again, depending on the transport limitations, the number of trains and/or process solution might be modified. To reach an expected 6%/min ramp-up and ramp-down, some liquid retention capacities is added in the cold box compared to the baseline case. The dynamics of the system should be studied during the ramp-up and the ramp-down phases (integration with the power plant, impact of the purity of the GOx to the power plant, startup and shutdown sequence of the MAC and BAC, etc.).

The ASU, under steady conditions with the utilities available at the battery limit, is expected to deliver the products as indicated in Table 6-5. The baseline case is also included as a reference.

**Table 6-5**
**Expected Production from the Flexible ASU**

| Production | Parameter | 100% Baseline Case | 100% Flexible Case | 40% Flexible Case |
|---|---|---|---|---|
| GOx | Mass flow, TPD | 10,500 | 10,500 | 4,200 |
| | Pressure, bara | ≥ 17 (246.5) | ≥ 17 (246.5) | ≥ 17 (246.5) |
| | Temperature, °C (°F) | ≥ 150 (302) | ≥ 150 (302) | ≥ 150 (302) |
| | $O_2$ content, %vol | ≥ 95.9 | ≥ 95.9 | ≥ 95.9 |
| LP GAN | Mass flow, TPD | 17,000 | 17,000 | 6800 |
| | Pressure, bara (psia) | ≥ 0.950 (13.8) | ≥ 0.950 (13.8) | ≥ 0.950 (13.8) |
| | Temperature, | ambient | ambient | ambient |
| | $N_2$ content, %vol | ≥ 99.5 | ≥ 99.5 | ≥ 99.5 |
| Instrument Air | Molar flow, $Nm^3/hr$ ($sft^3/hr$) | 4000 (152,160) | 4000 (152,160) | 1600 (60,,864) |
| | Pressure, bara (psia) | ≥ 11 (159.5) | ≥ 11 (159.5) | ≥ 11 (159.5) |
| | Temperature, | ambient | ambient | ambient |
| | Dew point, °C (°F) | < -40 (-40) | < -40 (-40) | < -40 (-40) |

As in the baseline case, the ASU produces 10,500 TPD of oxygen at full load, expressed as pure $O_2$ at a pressure of 17 bara (246.6 psia) and temperature of 150°C (302°F). The composition of GOx is 95.9 vol. % oxygen, 3.6 vol. % argon, and 0.5 vol. % nitrogen.

Similarly, the ASU produces 17,000 TPD of nitrogen at full load, expressed as gross flow at a pressure of 0.95 bara, (13.8 psia) and ambient temperature. The composition of GAN is 99.75 vol. % $N_2$, 0.09 vol. % $O_2$, and 0.16 vol. % argon. 4000 $Nm^3/hr$ (152,160 $sft^3/hr$) of instrument air is also supplied at a pressure of 11 bara (159.5 psia) and has a dew point of -40°C (-40°F).

The ranges for MAC and BAC covering 100%, 75%, 50%, and 40% loads are included in Table 6-6.

**Table 6-6**
**Percentage Load of Each MAC/BAC at Loads Ranging from 40 to 100%**

| ASU Load Case | 100% Load | 75% Load | 50% Load | 40% Load |
|---|---|---|---|---|
| MAC/BAC 1 (22%) | 100% | 0% | 0% | 0% |
| MAC/BAC 2 (56%) | 100% | 95% | 90% | 72% |
| MAC/BAC 3 (22%) | 100% | 100% | 0% | 0% |
| Total GOx, TPD | 10,500 | 7875 | 5250 | 4200 |
| Number of Cold Boxes in Operation | 2 | 2 | 2 | 2 |
| Expected Power Consumption, MWe | 63.3 | 47.05 | 30.8 | 24.3 |

### Expected LOx Production

As with the baseline case, for the flexible ASU arrangement at 100% load, each train can produce up to 2% of LOx (~105 TPD per train). In this case, the GOx production will be reduced accordingly. The LOx production provides the ability to refill the storage completely in around 17 days for the baseline case.

### Expected ASU Power and Utilities Consumption

Like the baseline ASU, the flexible ASU train under steady conditions and ambient site conditions will require the following utilities at the battery limit:

- Electricity: 13.8 kV and 480 V and 60 Hz at terminals
- Cooling water at the respective user flanges
- BFW at the respective user flanges
- Instrument air connection point to the header flange (for startup and stand-by)
- Nitrogen to $N_2$ header flange (for startup and stand-by for seal gas and inerting)
- IP steam connection to header (10 bara [145 psia] saturated steam available)
- LP steam connection to header (6 bara [87 psia] saturated steam available)

Each ASU train, under steady conditions and ambient site conditions, is expected to consume the utilities as indicated in Table 6-7. The baseline case is also included in the table for reference. As in the baseline case, IP steam is used by the regeneration heater of the adsorbers during the heating phase, and saturated steam at 10 bara (156 psia) is used for this purpose. The steam condensate from regeneration heater is returned at 9 bara (130.5 psia).

Note that the overall required production of 10,500 TPD is be supplied by two ASU trains, and therefore the indicated full-scale system should be doubled to get the consumption for 10,500 TPD GOx supply. Power for the combined 3 MACs and 3 BACs is shared proportionally between the two ASUs.

**Table 6-7**
**Expected Utility Consumption for Flexible ASU**

| Expected Utility | Units | 100% Baseline Case | 100% Flexible Case | 40% Flexible Case |
|---|---|---|---|---|
| Expected Electrical Power (at motor terminals) | MW | 62.2 | 63.3 | 24.3 |
| Expected IP Steam Consumption:<br>- Average<br>- Peak (during heating phase of regeneration) | kg/hr<br>(lb/hr)<br>kg/hr<br>(lb/hr) | 8000<br>(17,637)<br>22,300<br>(49,163) | 8000<br>(17,637)<br>22,300<br>(49,163) | 3200<br>(7055)<br>8900<br>(19,621) |
| Expected Condensate Return:<br>- Average<br>- Peak (during heating phase of regeneration) | kg/hr<br>(lb/hr)<br>kg/hr<br>(lb/hr) | 8000<br>(17,637)<br>22,300<br>(49,163) | 8000<br>(17,637)<br>22,300<br>(49,163) | 3200<br>(7055)<br>8900<br>(19,621) |
| Expected Cooling Water Supply | $m^3$/hr<br>($ft^3$/hr) | 1800<br>(63,566) | 1850<br>(65,332) | 1850<br>(65,332)* |
| Expected Cooling Water Return | $m^3$/hr<br>($ft^3$/hr) | 1800<br>(63,566) | 1850<br>(65,332) | 1850<br>(65,332)* |

* Cooling water flow not restricted during part-load operation.

The power and utilities consumption figure includes the following consumers:

- BAC
- Cooling water pump to send cooling water to the air/water tower
- Dryers regeneration heater
- Expansion turbines
- IP LOx pumps (combined with back-up pumps)
- MAC

When the supply of 5250 TPD of GOx by vaporization of LOx is needed (via the back-up system), the expected associated LP steam consumption is 40,300 kg/hr (88,846 lb/hr). Saturated steam at 6 bara (87 psia) is used for this duty. In this case, the GOx temperature will be 60°C (140°F), but 150°C (302°F) can be reached with an additional heat exchanger using IP steam. Condensate will be sent back to the steam turbine island at the deaerator.

Transient phases such as the transition between normal and back-up mode will need to be studied in a later stage of the project.

### BFW Preheating by ASU

During normal operation, each ASU, under steady conditions and ambient site conditions, is expected to transfer the heat quantities to the BFW as indicated in Table 6-8.

**Table 6-8**
**Expected Heat Transfer to BFW**

| Utility | Units | 100% Baseline Case | 100% Flexible Case | 40% Flexible Case |
|---|---|---|---|---|
| BFW Inlet Temperature | °C (°F) | 33.2 (91.8) | 33.2 (91.8) | 33.2 (91.8) |
| Duty for MAC BFW Preheater | kWth | 29,700 | 30,500 | 10,400 |
| Maximum MAC BFW Outlet Temperature | °C (°F) | 147 (296.6) | 150 (302) | 133 (271.4) |
| Duty for BAC BFW Preheater | kWth | 2600 | 2800 | 1300 |
| Maximum BAC BFW Outlet Temperature | °C (°F) | 155 (311) | 157 (14.6) | 166 (330.8) |

The duty for BAC BFW pre-heater is the net heat available from the BAC for the steam cycle as the GOx is heated internally in the ASU.

The flexible ASU reduces the auxiliary power consumption, particularly during low-load operation, as shown in Table 6-9.

**Table 6-9**
**SPOC Flexible ASU Turndown Case Performance Summary**

| Parameter Load | 100% | 75% | 50% | 25% | 12% |
|---|---|---|---|---|---|
| SPOC Modules in Service | 4 | 4 | 4 | 2 | 1 |
| Module Firing Load, % baseline | 100.1 | 76.3 | 51.4 | 56.7 | 67.3 |
| Main Steam Pressure, bara (psia) | 242.8 (3521) | 179.9 (2609) | 118.4 (1716) | 113.4 (1547) | 112.6 (1633) |
| Cold Reheat Pressure, bara (psia) | 49.2 (713.2) | 36.7 (531.5) | 24.0 (348.0) | 12.9 (187.0) | 7.6 (109.6) |
| Thermal Input, MWth | 1595 | 1219 | 819.1 | 446.0 | 268.1 |
| Boiler Efficiency, % HHV | 87.69 | 87.61 | 87.36 | 87.64 | 86.56 |
| Heat-to-Steam, MWth | 1415 | 1080 | 723.8 | 395.6 | 235.1 |
| HP Heat Recovery, MWth | 35.8 | 27.47 | 18.64 | 10.10 | 6.05 |
| LP Heat Recovery, MWth | 198.0 | 159.0 | 109.5 | 47.27 | 25.64 |
| Gross Power, MWe | 726.3 | 552.1 | 379.2 | 195.8 | 111.3 |
| Auxiliary Load, MWe | 176.3 | 139.6 | 104.2 | 58.3 | 45.3 |
| Net Power, MWe | 550.0 | 412.5 | 275.0 | 137.5 | 66.0 |
| Net Plant Efficiency, % HHV | 34.47 | 33.85 | 33.57 | 30.83 | 24.62 |

The ASU power consumption for the 25% and 12% load cases was estimated based on the multi-compressor configuration with a maximum turndown to 70% of full load for each compressor as these loads were not considered in the flexible ASU design.

The flexible case is less efficient at full load because of an additional 1 MWe of auxiliary power consumption from the compressors. However, as shown in Figure 6-4, the benefits of the flexible ASU are seen below 50% load where the smaller compressors can be used when oxygen demand is low, which saves significant power and hence improves efficiency.

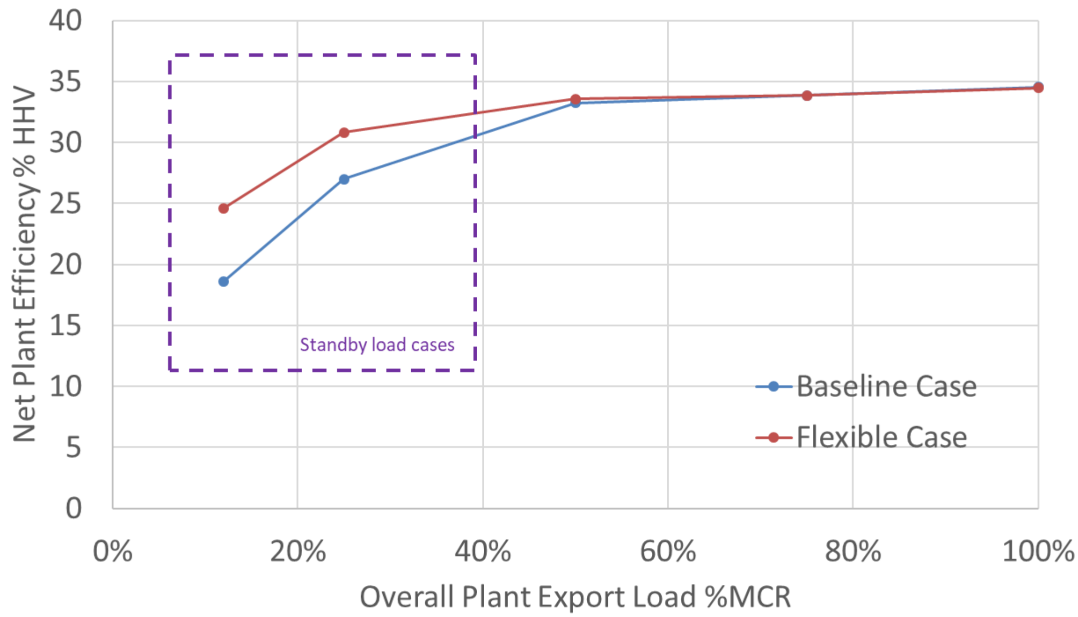



**Figure 6-4**
**Comparison of Baseline Case and Flexible Case Plant Efficiency**

All SPOC stages are operating down to 50% load, as shown in Figure 6-5, however alternative configurations could allow single stage to be bypassed at higher loads if required, i.e. 3 stages could operate in the load range 50-70%.

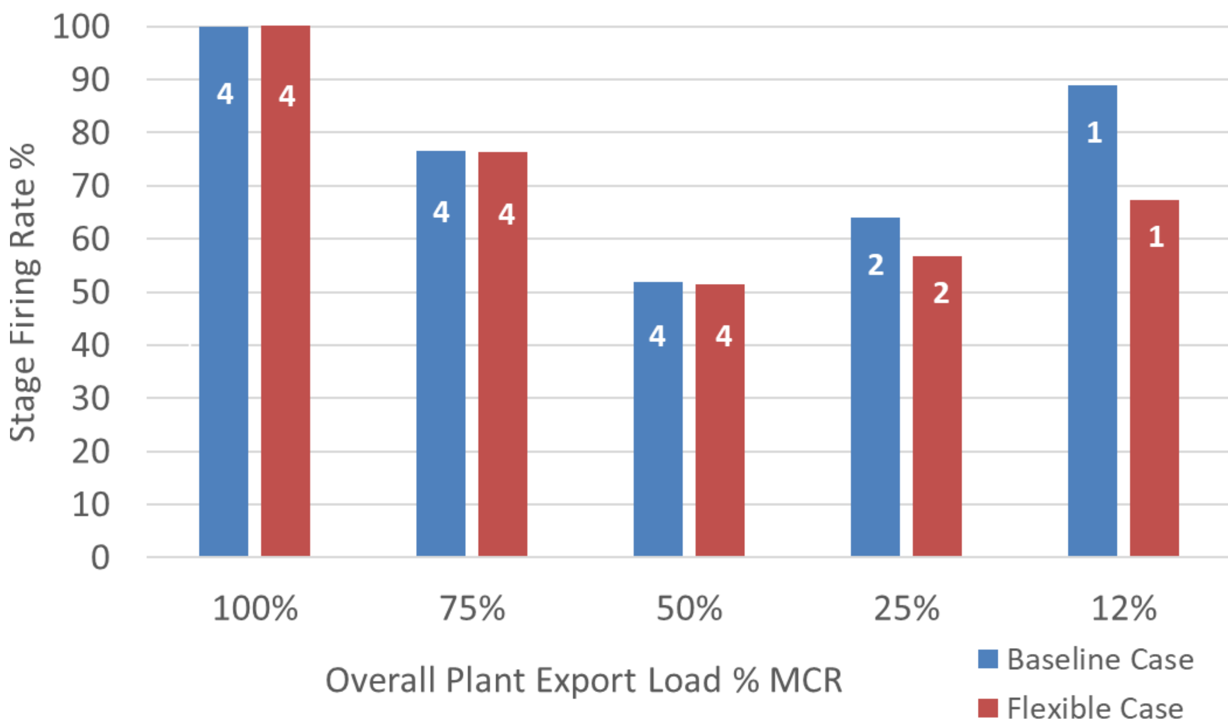



**Figure 6-5**
**Comparison of Baseline Case and Flexible Case Stage Firing Rates**

# 7
# ECONOMIC ANALYSIS

This chapter provides details on how the specific capital and operating costs were estimated for the SPOC case, highlighting key components that the team focused on developing unique cost estimates for, such as the pressurized oxy-combustor. These descriptions are then followed by the presentation of the capital and O&M costs, along with the first-year power cost, levelized cost of electricity (LCOE), and $CO_2$ captured and avoided cost for the SPOC case and relevant NETL baseline cases.

### *Site-Related Conditions*

The SPOC plant is located at a generic plant site in Montana, which was a Midwest site selected to be consistent with the NETL baseline cases. The site is typical of western power generation facilities and has access to water and rail transportation. The site is in Seismic Zone 1, at an elevation of 1036 meters (3399 ft) above sea level and is relatively level with no special requirements related to hazardous materials, archeological artifacts, or excessive rock. A raw water supply is available within 10 km (6.2 miles) of the site. The design is based on indoor construction.

### *Coal Characteristics*

The design fuel used for the SPOC case (Montana Rosebud PRB) is identical to that used in the corresponding NETL Baseline cases. The proximate, ultimate, and HHV data for the design fuel were included in Chapter 2. The cost of PRB sub-bituminous coal delivered to the Montana site is $1.21/GJ HHV.

### *Costing Methodology*

#### Capital Cost Estimating Basis

Capital costs are reported in January 2019 dollars (base-year dollars) to put them on a consistent and up-to-date basis. Construction costs at the reference site were based on non-union labor as is typically assumed in NETL techno-economic studies. For cost-estimating purposes, the SPOC plant in this study was generally assumed to be “mature”, meaning that no extra equipment or costs are included to account for unit malfunction or extra equipment outages. Costs associated with extra facilities needed for demonstration of first commercial plants are not normally reflected in the cost estimates.

As illustrated in Figure 7-1, this study will report capital cost at four levels: BEC, TPC, TOC, and Total As-spent Capital (TASC). BEC, TPC, and TOC are “overnight” costs and are expressed in “base-year” dollars. The base year is the first year of capital expenditure, which for this study is 2019. TASC is expressed in mixed-year, current-year dollars over the entire capital expenditure period, which is assumed to last five years for coal plants (2019 to 2023). BEC comprises the cost of delivered process equipment, on-site facilities, and infrastructure that support the plant (e.g., shops, offices, labs, road), and the direct and indirect labor required for its construction and/or installation. The cost of EPC services and contingencies are not included in the BEC. BEC is an overnight cost expressed in base-year dollars.

TPC comprises the BEC plus the cost of services provided by the EPC contractor and project and process contingencies. EPC services include: detailed design, contractor permitting (i.e., permits that individual contractors must obtain to perform their scopes of work, as opposed to project permitting, which is not included), and project/construction management costs. TPC is an overnight cost expressed in base-year dollars.

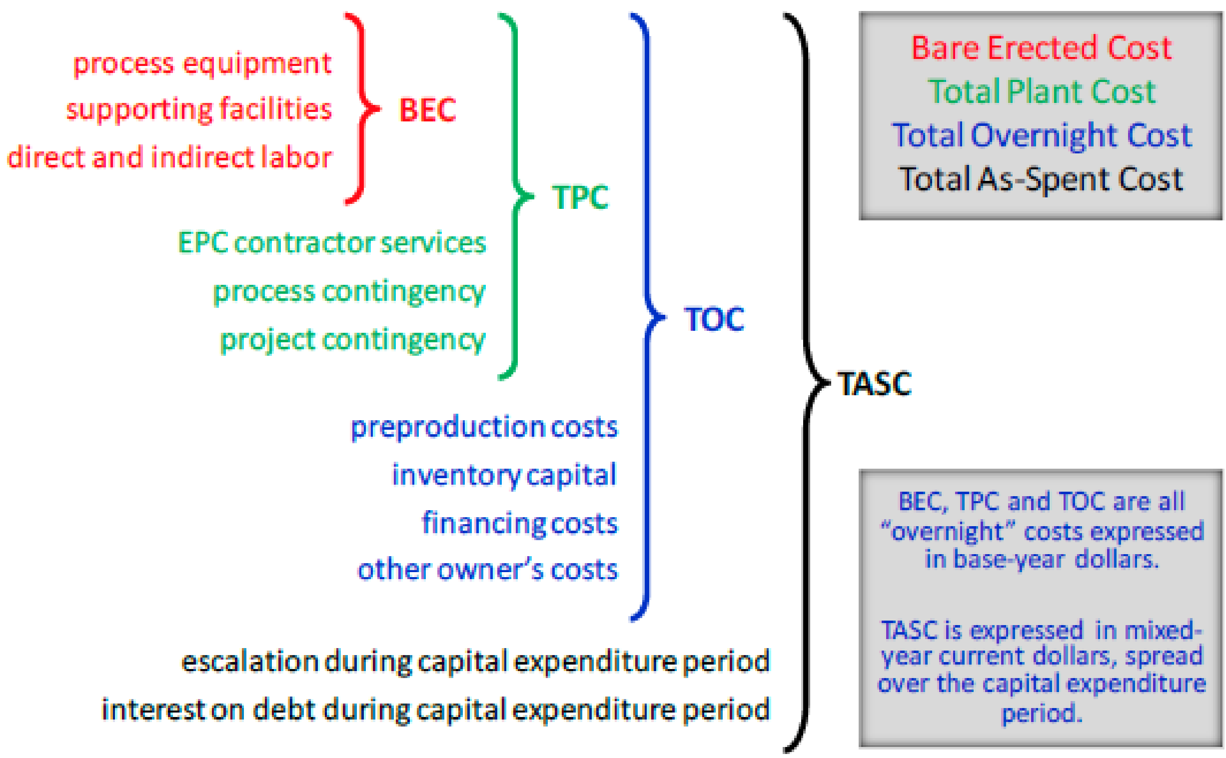



**Figure 7-1**
**Capital Cost Levels and Their Elements**

TOC comprises the TPC plus owner's costs. TOC is an "overnight" cost, expressed in base-year dollars and as such does not include escalation during construction or interest during construction. TOC is calculated using a simple multiplier on TPC. The multiplier used for this study was 1.23. TASC is the sum of all CAPEX as they are incurred during the CAPEX period including their escalation. TASC also includes interest during construction. Accordingly, TASC is expressed in mixed, current-year dollars over the CAPEX period. TASC is also calculated using a simple multiplier, this time on TOC. The multiplier used for this study was taken from NETL guidelines for high-risk investor-owned utility (IOU) projects as 1.14.

## Cost Estimate Classification

Recommended Practice 18R-97 of the AACE describes a Cost Estimate Classification System as applied in EPC for the process industries. The capital cost estimate done for this study is classified as an AACE Class 5 Conceptual/Screening Study. Typical accuracy ranges for AACE Class 5 estimates are -20% to -50% on the low side, and +30% to +100% on the high side.

Table 7-1 describes the characteristics of an AACE Class 5 Cost Estimate.[22]

**Table 7-1**
**AACE Class 5 Estimate Description**

| CLASS 5 ESTIMATE | |
|---|---|
| **Description:**<br>Class 5 estimates are generally prepared based on very limited information, and subsequently have wide accuracy ranges. As such, some companies and organizations have elected to determine that due to the inherent inaccuracies, such estimates cannot be classified in a conventional and systematic manner. Class 5 estimates, due to the requirements of end use, may be prepared within a very limited amount of time and with little effort expended—sometimes requiring less than an hour to prepare. Often, little more than proposed plant type, location, and capacity are known at the time of estimate preparation.<br><br>**Maturity Level of Project Definition Deliverables:**<br>Key deliverable and target status: Block flow diagram agreed by key stakeholders. 0% to 2% of full project definition.<br><br>**End Usage:**<br>Class 5 estimates are prepared for any number of strategic business planning purposes, such as but not limited to market studies, assessment of initial viability, evaluation of alternate schemes, project screening, project location studies, evaluation of resource needs and budgeting, long-range capital planning, etc. | **Estimating Methodology:**<br>Class 5 estimates generally use stochastic estimating methods such as cost/capacity curves and factors, scale of operations factors, Lang factors, Hand factors, Chilton factors, Peters-Timmerhaus factors, Guthrie factors, and other parametric and modeling techniques.<br><br>**Expected Accuracy Range:**<br>Typical accuracy ranges for Class 5 estimates are -20% to -50% on the low side, and +30% to +100% on the high side, depending on the technological complexity of the project, appropriate reference information and other risks ( after inclusion of an appropriate contingency determination). Ranges could exceed those shown if there are unusual risks.<br><br>**Alternate Estimate Names, Terms, Expressions, Synonyms:**<br>Ratio, ballpark, blue sky, seat-of-pants, ROM, idea study, prospect estimate, concession license estimate, guesstimate, rule-of-thumb. |

## System Code of Accounts

The costs are grouped according to a process/system-oriented code of accounts. Consistent with other NETL techno-economic studies, 14 accounts are used as shown in Table 7-2. This type of code-of-account structure has the advantage of grouping all reasonably allocable components together so they are included in the specific system account. In addition, costs for each code of account are further broken down into equipment, material, and labor cost. Labor cost includes both direct and indirect costs.

[22] "Cost Estimate Classification System – As Applied In Engineering, Procurement, and Construction for the Process Industries," AACE International Recommended Practice No. 18R-97.

**Table 7-2**
**Accounts for the Capital Costs**

| 1 COAL & SORBENT HANDLING |
|---|
| 1.1 Coal Receive & Unload<br>1.2 Coal Stackout & Reclaim<br>1.3 Coal Conveyors<br>1.4 Other Coal Handling<br>1.5 Sorbent Receive & Unload<br>1.6 Sorbent Stackout & Reclaim<br>1.7 Sorbent Conveyors<br>1.8 Other Sorbent Handling<br>1.9 Coal & Sorbent Hnd. Foundations |
| **2 COAL & SORBENT PREP & FEED** |
| 2.1 Coal Crushing & Drying<br>2.2 Coal Conveyor to Storage<br>2.3 Coal Injection System<br>2.4 Misc. Coal Prep & Feed<br>2.5 Sorbent Prep Equipment<br>2.6 Sorbent Storage & Feed<br>2.7 Sorbent Injection System<br>2.8 Booster Air Supply System<br>2.9 Coal & Sorbent Feed Foundation |
| **3 FEEDWATER & MISC. BALANCE-OF-PLANT (BOP) SYSTEMS** |
| 3.1 Feedwater System<br>3.2 Water Makeup & Pretreating<br>3.3 Other Feedwater Subsystems<br>3.4 Service Water Systems<br>3.5 Other Boiler Plant Systems<br>3.6 FO Supply Sys & Nat Gas<br>3.7 Waste Treatment Equipment<br>3.8 Misc. Equip. (Cranes, Air Comp., Comm.) |
| **4 PC BOILER & ACCESSORIES** |
| 4.1 PC Boiler<br>4.2 ASU/Oxidant Compression<br>4.4 Boiler BOP (w/ ID Fans)<br>4.5 Primary Air System<br>4.6 Secondary Air System<br>4.8 Major Component Rigging<br>4.9 PC Foundations |

| 5 FLUE GAS CLEANUP |
|---|
| 5.1 Absorber Vessels & Accessories<br>5.2 Other FGD<br>5.3 Bag House & Accessories<br>5.4 Other Particulate Removal Materials<br>5.5 Gypsum Dewatering System<br>5.6 Mercury Removal System |
| **5B $CO_2$ REMOVAL & COMPRESSION** |
| 5B.1 $CO_2$ Condensing Heat Exchanger<br>5B.2 $CO_2$ Compression & Drying |
| **6 COMBUSTION TURBINE/ ACCESSORIES** |
| **7 HRSG** |
| 7.1 Flue Gas Recycle Heat Exchanger<br>7.2 SCR System<br>7.3 Ductwork<br>7.4 Stack<br>7.9 HRSG, Duct & Stack Foundations |
| **8 STEAM TURBINE GENERATOR** |
| 8.1 Steam TG & Accessories<br>8.2 Turbine Plant Auxiliaries<br>8.3 Condenser & Auxiliaries<br>8.4 Steam Piping<br>8.9 TG Foundations |
| **9 COOLING WATER SYSTEM** |
| 9.1 Cooling Towers<br>9.2 Circulating Water Pumps<br>9.3 Circ. Water System Auxiliaries<br>9.4 Circ. Water Piping<br>9.5 Make-up Water System<br>9.6 Component Cooling Water System<br>9.9 Circ. Water System Foundations |
| **10 ASH/SPENT SORBENT HANDLING SYS** |
| 10.1 Ash Coolers<br>10.2 Cyclone Ash Letdown<br>10.3 HGCU Ash Letdown<br>10.4 High Temperature Ash Piping<br>10.5 Other Ash Recovery System<br>10.6 Ash Storage Silos<br>10.7 Ash Transport & Feed Equipment<br>10.8 Misc. Ash Handling Equipment<br>10.9 Ash/Spent Sorbent Foundation |

| 11 ACCESSORY ELECTRIC PLANT |
|---|
| 11.1 Generator Equipment<br>11.2 Station Service Equipment<br>11.3 Switchgear & Motor Control<br>11.4 Conduit & Cable Tray<br>11.5 Wire & Cable<br>11.6 Protective Equipment<br>11.7 Standby Equipment<br>11.8 Main Power Transformers<br>11.9 Electrical Foundations |
| **12 INSTRUMENTATION & CONTROL** |
| 12.1 PC Control Equipment<br>12.2 Combustion Turbine Control<br>12.3 Steam Turbine Control<br>12.4 Other Major Component Control<br>12.5 Signal Processing Equipment<br>12.6 Control Boards, Panels, & Racks<br>12.7 Distributed Control System Equipment<br>12.8 Instrument Wiring & Tubing<br>12.9 Other I & C Equipment |
| **13 IMPROVEMENTS TO SITE** |
| 13.1 Site Preparation<br>13.2 Site Improvements<br>13.3 Site Facilities |
| **14 BUILDINGS & STRUCTURES** |
| 14.1 Boiler Building<br>14.2 Turbine Building<br>14.3 Administration Building<br>14.4 Circulation Water Pumphouse<br>14.5 Water Treatment Buildings<br>14.6 Machine Shop<br>14.7 Warehouse<br>14.8 Other Buildings & Structures<br>14.9 Waste Treating Building & Str. |

## Plant Maturity

Cost estimates in this report reflect the cost of the next commercial offering for plants that include technologies that are not yet fully mature and/or which have not yet been deployed in a commercial context. These cost estimates for next commercial offerings do not include the unique cost premiums associated with first-of-a-kind plants that must demonstrate emerging technologies and resolve the cost and performance challenges associated with initial iterations. However, these estimates do utilize currently available cost bases for emerging technologies. Process contingencies applied to the appropriate subsystem levels were derived from the base case studies performed by NETL.

Cost estimates for all the plants and components, regardless of technology maturity, are based on design assumptions that affect costs, including the use of a favorable site with no unusual characteristics. The primary value of this report lies not in the absolute accuracy of cost estimates for the individual cases, but in the fact that all cases were evaluated using a common methodology with an internally consistent set of technical and economic assumptions. This consistency of approach allows meaningful comparisons of relative costs among the cases evaluated.

### Contracting Strategy

The estimates were based on an EPC approach utilizing multiple subcontracts. This approach provides the owner with greater control of the project, while minimizing, if not eliminating, most of the risk premiums typically included in an EPC contract price.

In a traditional lump-sum EPC contract, the contractor assumes all risk for performance, schedule, and cost. However, because of current market conditions, EPC contractors appear more reluctant to assume that overall level of risk. Rather, the current trend appears to be a modified EPC approach, where much of the risk remains with the owner. Where contractors are willing to accept the risk in EPC-type, lump-sum arrangements, it is reflected in the project cost. In today's market, contractor premiums for accepting these risks, particularly performance risk, can be substantial and increase the overall project costs dramatically.

This approach is anticipated to be the most cost-effective approach for the owner. While the owner retains the risks, the risks become reduced with time, as there is better scope definition at the time of contract award(s).

### Battery Limits for Capital Cost Estimate

The estimates represent a complete power plant facility on a generic site. The plant boundary or "battery" limit is defined as the total plant facility within the "fence line" including coal receiving and water supply system, but terminating at the high-voltage side of the main power transformers. Coal transportation cost is not included in the reported capital or O&M costs (storage and coal handling maintenance are, however). The cost of transporting, storing, and monitoring $CO_2$ is also not included in the costs for the cases that capture $CO_2$, but is treated separately and added to the COE by adding \$10/tonne-$CO_2$.

### Time Escalation of Costs

For this study, the cost basis is in January 2019 dollars. Prior-year costs for the relevant NETL baseline cases were escalated to June 2018 dollars by an EPRI engineering contractor in a recent techno-economic study. The Chemical Engineering Plant Cost Index (CEPCI) was then used to escalate these June 2018 costs to January 2019 dollars. Figure 7-2 shows the CEPCI from June 2002 to June 2019.

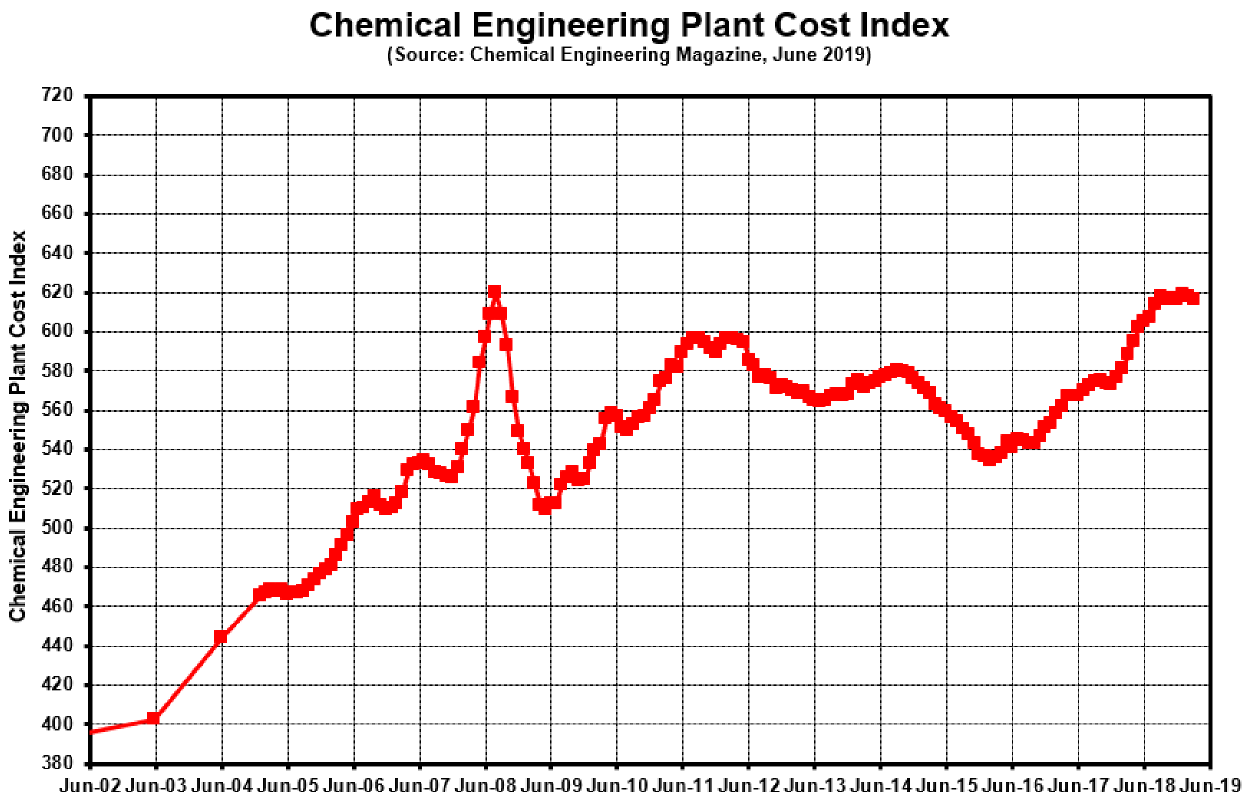



**Figure 7-2**
**Chemical Engineering Plant Cost Index**

## Labor Rates

The all-in union construction craft labor rate for the Montana site was assumed to be $62.87/hour. The craft labor rate is based on a competitive bidding environment with adequate skilled craft labor available locally. Labor is based on a 50-hour work week (five x 10-hour days).

## Exclusions

The capital cost estimate includes all anticipated costs for equipment and materials, installation labor, professional services (engineering and construction management), and contingency. The following items are excluded from the capital costs:

- All taxes except for payroll and property
- Site specific considerations – including, but not limited to, seismic zone, accessibility, local regulatory requirements, excessive rock, piles, laydown space, etc.
- Labor incentives
- Additional premiums associated with an EPC contracting approach

## Contingency

Process and project contingencies are included in estimates to account for unknown costs that are omitted or unforeseen due to a lack of complete project definition and engineering. Contingencies are added because experience has shown that such costs are expected to be incurred even though they cannot be explicitly determined at the time the estimate is prepared. Capital cost contingencies do not cover uncertainties or risks associated with:

- Scope changes
- Changes in labor availability or productivity
- Delays in equipment deliveries
- Changes in regulatory requirements
- Unexpected cost escalation
- Performance of the plant after startup (e.g., availability, efficiency)

### Process Contingency

Process contingency is intended to compensate for uncertainty in costs caused by performance uncertainties associated with the development status of a technology. Process contingency is applied to each component based on its current technology status.

As shown in Table 7-3, AACE International Recommended Practice 16R-90 provides guidelines for estimating process contingencies.

**Table 7-3**
**AACE Guidelines for Process Contingency**

| Technology Status | Process Contingency (% of Associated Process Capital) |
|---|---|
| New Concept with Limited Data | 40+ |
| Concept with Bench-Scale Data | 30–70 |
| Small Pilot Plant Data | 20–35 |
| Full-sized Modules Have Been Operated | 5–20 |
| Process is Used Commercially | 0–10 |

### Project Contingency

The project contingency is a capital cost contingency factor covering the cost of additional equipment or other costs that would result from a more detailed design of a definitive project at an actual site. AACE 16R-90 states that project contingency for a “budget-type” estimate (AACE Class 5) should be 15 to 30% of the sum of BEC, EPC fees, and process contingency.

## Owner’s Costs

Owner’s costs include:

- Prepaid royalties or license fees

- Preproduction (or startup) costs
- Inventory capital (fuel storage, consumables, etc.)
- Initial cost for catalyst and chemicals
- Land

Royalty charges or license fees may apply to some portions of generating units incorporating new technologies. If known, royalty charges must be included in the capital requirement.

Preproduction costs cover operator training, equipment checkout, major changes in unit equipment, extra maintenance, and inefficient use of fuel and other materials during startup. For this project's purposes, preproduction costs were estimated as follows:

- One month fixed operating costs (O&M labor, administrative and support labor, and maintenance materials). In some cases, this could be as high as two years of fixed operating costs due to new staff being hired two years before commissioning the plant.
- One to three months of variable operating costs (consumables) at full capacity, excluding fuel. (These variable operating costs include chemicals, water, and other consumables plus waste disposal charges.)
- 25% of full-capacity fuel cost for one month. This charge covers inefficient operation that occurs during the startup period.
- 2% of TPC. This charge covers expected changes and modifications to equipment that will be needed to bring the unit up to full capacity.

The following should be included:

- Value of inventories of fuels, consumables, and by-products was capitalized
- An allowance for spare parts of 0.5% of the total plant cost
- The initial cost of any catalyst or chemicals contained in the process equipment (but not in storage, which is covered in inventory capital)
- A nominal cost of $7413/hectare ($3000/acre) for land

Table 7-4 summarizes the procedure for estimating owner's costs. The methodology is defined by the DOE Cost Estimation Methodology[23] and mostly follows the guidelines from Sections 12.4.7 to 12.4.12 of AACE International Recommended Practice No. 16R-90.[24]

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[23] "Cost Estimation Methodology for NETL Assessments of Power Plant Performance," DOE/NETL-2011/1455, April 2011.

[24] "Conducting Technical and Economic Evaluations – As Applied for the Process and Utility Industries," AACE International Recommended Practice No. 16R-90.

**Table 7-4**
**Estimation Method for Owner's Costs**

| Owner's Cost | Estimate Basis |
|---|---|
| Prepaid Royalties | Any technology royalties are assumed to be included in the associated equipment cost, and thus are not included as an owner's cost. |
| Preproduction (Start-Up) Costs | • 6 months operating labor<br>• 1-month maintenance materials at full capacity<br>• 1-month non-fuel consumables at full capacity<br>• 1-month waste disposal<br>• 25% of one month's fuel cost at full capacity<br>• 2% of TPC<br><br>Compared to AACE 16R-90, this includes additional costs for operating labor (6 months versus 1 month) to cover the cost of training the plant operators, including their participation in startup, and involving them occasionally during the design and construction. AACE 16R-90 and EPRI Technical Assessment Guide (TAG)® differ on the amount of fuel cost to include; this estimate follows EPRI. |
| Working Capital | Although inventory capital (see below) is accounted for, no additional costs are included for working capital. |
| Inventory Capital | • 0.5% of TPC for spare parts<br>• 60-day supply (at full capacity) of fuel. Not applicable for natural gas.<br>• 60-day supply (at full capacity) of non-fuel consumables (e.g., chemicals and catalysts) that are stored on site. Does not include catalysts and adsorbents that are batch replacements such as selective catalytic reduction catalysts and activated carbon.<br><br>AACE 16R-90 does not include an inventory cost for fuel, but EPRI TAG® does. |
| Land | ($7413/hectare) ($3000/acre) (121.4 hectares [300 acres] for IGCC and PC) |
| Financing Cost | • 2.7% of TPC<br><br>This financing cost (not included by AACE 16R-90) covers the cost of securing financing, including fees and closing costs but not including interest during construction. The "rule of thumb" estimate (2.7% of TPC) is based on a 2008 private communication with a capital services firm. |

<table>
<tr><th>Owner's Cost</th><th>Estimate Basis</th></tr>
<tr><td>Other Owners Costs</td><td>• 15% of TPC<br><br>This additional lumped cost is not included by AACE 16R-90 or EPRI TAG®. The "rule of thumb" estimate (15% of TPC) is based on a 2009 private communication with Worley-Parsons. The lumped cost includes:<br>o Preliminary feasibility studies, including a front-end engineering design study<br>o Economic development (costs for incentivizing local collaboration and support)<br>o Construction and/or improvement of roads and/or railroad spurs outside of site boundary<br>o Legal fees<br>o Permitting costs<br>o Owner's engineering (staff paid by owner to give third-party advice and to help the owner oversee/evaluate the work of the EPC contractor and other contractors)<br>o Owner's contingency (sometimes called "management reserve", these are funds to cover costs relating to delayed startup, fluctuations in equipment costs, and unplanned labor incentives more than a five-day/ten-hour-per-day work week. Owner's contingency is NOT a part of project contingency.)<br>This lumped cost does NOT include:<br>o EPC risk premiums (costs estimates are based on an EPC management approach utilizing multiple subcontracts, in which the owner assumes project risks for performance, schedule, and cost)<br>o Transmission interconnection: the cost of interconnecting with power transmission infrastructure beyond the plant busbar.<br>o Taxes on capital costs: all capital costs are assumed to be exempt from state and local taxes.<br>o Unusual site improvements: normal costs associated with improvements to the plant site are included in the BEC, if the site is level and requires no environmental remediation. Unusual costs associated with the following design parameters are excluded: flood plain considerations, existing soil/site conditions, water discharges and reuse, rainfall/snowfall criteria, seismic design, buildings/enclosures, fire protection, local code height requirements, and noise regulations.</td></tr>
</table>

### O&M Costs

O&M costs are to be estimated for a year of normal operation and presented in the base-year dollars. O&M costs for a generating unit are generally allocated as fixed and variable O&M costs.

Fixed O&M costs are essentially independent of actual capacity factor, number of hours of operation, or the number of kilowatts produced, and are expressed in $/kW-year. Fixed O&M costs are composed of the following components:

- Operating labor
- Total maintenance costs (may also have a variable component)
- Overhead charges

Taxes and insurance are considered as fixed O&M costs and are estimated as 2% of the total plant cost.

Variable O&M costs and consumables are directly proportional to the number of kilowatts produced. They are generally in mills/kW-hour.

The estimation of these cost components is discussed below.

### Operating Labor

Operating labor is based on the number of personnel required to operate the plant per shift. The total operating cost is based on the labor rate, supervision, and overhead.

### Total Maintenance Costs

Annual maintenance costs for new technologies were estimated as a percentage of the installed capital cost of the facilities. The percentage varies widely, depending on the nature of the processing conditions and the type of design. The ranges shown in Table 7-5 are representative.

**Table 7-5**
**Maintenance as a Percentage of TPC**

| Type of Processing Conditions | Maintenance % of Total Plant Capital Cost/Year* |
|---|---|
| Corrosive and Abrasive Slurries | 5–10+ |
| Severe (Solids, High-Pressure, and Temperature) | 3–6+ |
| Clean (Liquids and Gases Only) | 1.5–4 |
| General Facilities and Steam Electrical Systems | 1–3 |

* Minimum capital cost plants will generally experience maintenance costs at the high end of the range.

Maintenance cost estimates can be developed separately for different sections of the plant. Estimates should be separately expressed as maintenance labor and maintenance materials. A maintenance labor-to-materials ratio of 40:60 was used for this breakdown if other information is not available.

Table 7-6 shows the percentages that were used for each Account area in the plant.

**Table 7-6**
**Maintenance as a Percentage of Plant Account Cost**

| Account Description | % Maintenance | Account No. |
|---|---|---|
| Solid Handling and Storage | 2.5% | 1, 2, 10 |
| Feedwater and Miscellaneous BOP Systems | 2.0% | 3 |
| Boiler and Flue Gas Cleanup | 2.5% | 4, 5 |
| $CO_2$ Condensing and Compression | 1.5% | 5B |
| Heat Recovery Steam Generator | 2.0% | 7 |
| Power Cycle | 2.0% | 8 |
| Cooling Water | 2.0% | 9 |
| BOP | 1.5% | 11, 12, 13, 14 |

The percentage approach described above is recommended for use when vendor-specific O&M data are not available.

### Overhead Charges

The only overhead charge to be included in power plant studies is a charge for administrative and support labor, which is taken as 30% of the O&M labor.

### Consumables

Consumables are the principal components of variable O&M costs. These include water, catalysts, chemicals, solid waste disposal, and other materials that are consumed in proportion to energy output. Costs for consumable items are shown in Table 7-7.

**Table 7-7**
**Cost Data for Consumable Items**

| Consumables and Variable Cost Items | Unit Cost |
|---|---|
| **$H_2O$ and Chemicals** | |
| Raw Water, $/1000 liters | 0.45 |
| Ammonia (aqueous 29.4 wt %), $/tonne | 194 |
| **Sorbent (Delivered)** | |
| Lime, $/tonne | 155 |
| Limestone, $/tonne | 45 |
| **Dry Disposal** | |
| Bottom and Fly Ash, $/tonne | 15 |
| **Other** | |
| Activated Carbon, $/tonne | 1455 |
| Urea, $/tonne | 454 |

### Financial Structure Selection

The financial structure for this study was based on an IOU financial structure with a 5-year capital expenditure period, as specified in the DOE Cost Estimation Methodology report.[25] The financial structure for both low- and high-risk cases is shown in Table 7-8.

**Table 7-8**
**Financial Structure for Investor Owned Utility High- and Low-Risk Projects**

| Type of Security | % of Total | Current (Nominal) Dollar Cost | Weighted Current (Nominal) Cost | After Tax Weighted Cost of Capital |
|---|---|---|---|---|
| | | LOW RISK | | |
| Debt | 50 | 4.50% | 2.25% | |
| Equity | 50 | 12% | 6% | |
| Total | | | 8.25% | 7.39% |
| | | HIGH RISK | | |
| Debt | 45 | 5.50% | 2.48% | |
| Equity | 55 | 12% | 6.60% | |
| Total | | | 9.08% | 8.13% |

### Global Economic Assumptions

Table 7-9 summarizes the global economic assumptions that were used for evaluating the economic performances of the cases in this study. The assumptions are specified in the DOE Cost Estimation Methodology.

[25] "Cost Estimation Methodology for NETL Assessments of Power Plant Performance," DOE/NETL-2011/1455, April 2011.

**Table 7-9**
**Global Economic Assumptions**

| Parameter | Value |
|---|---|
| TAXES | |
| | |
| Income Tax Rate | 38% Effective (34% Federal, 6% State) |
| Capital Depreciation | 20 years, 150% declining balance |
| Investment Tax Credit | 0% |
| Tax Holiday | 0 years |
| CONTRACTING AND FINANCING TERMS | |
| Contracting Strategy | Engineering Procurement Construction Management (owner assumes project risks for performance, schedule and cost) |
| Type of Debt Financing | Non-Recourse (collateral that secures debt is limited to the real assets of the project) |
| Repayment Term of Debt | 15 years |
| Grace Period on Debt Repayment | 0 years |
| Debt Reserve Fund | None |
| ANALYSIS TIME PERIODS | |
| Capital Expenditure Period | 5 Years |
| Operational Period | 30 years |
| Economic Analysis Period (used for IRROE) | 35 Years (capital expenditure period plus operational period) |
| TREATMENT OF CAPITAL COSTS | |
| Capital Cost Escalation During Capital Expenditure Period (nominal annual rate) | 3.6%[1] |
| Distribution of Total Overnight Capital over the Capital Expenditure Period (before escalation) | 5-Year Period: 10%, 30%, 25%, 20%, 15% |
| Working Capital | zero for all parameters |
| % of Total Overnight Capital that is Depreciated | 100% (this assumption introduces a very small error even if a substantial amount of TOC is actually non-depreciable) |
| ESCALATION OF OPERATING REVENUES AND COSTS | |
| Escalation of COE (revenue), O&M Costs, Fuel Costs (nominal annual rate) | 3.0%[2] |

[1] A nominal average annual rate of 3.6% is assumed for escalation of capital costs during construction. This rate is equivalent to the nominal average annual escalation rate for process plant construction costs between 1947 and 2008 according to the Chemical Engineering Plant Cost Index.

[2] An average annual inflation rate of 3.0% is assumed. This rate is equivalent to the average annual escalation rate between 1947 and 2008 for the U.S. Department of Labor's Producer Price Index for Finished Goods, the so-called "headline" index of the various Producer Price Indices. (The Producer Price Index for the Electric Power Generation Industry may be more applicable, but that data does not provide a long-term historical perspective since it only dates back to December 2003.)

## Cost of Electricity

The first-year COE (or power cost) is the revenue received by the generator per net MW-hr during the first year of operation assuming that the COE escalates at a nominal annual rate equal to the general inflation rate (i.e., remains constant in real terms over the operational period of the plant). The LCOE is the revenue received by the generator per net MW-hr during the first year of operation assuming that the first year of operation COE escalates at a nominal annual rate of 0% (i.e., remains constant in nominal terms over the operation period of the plant). NETL's Power Systems Financial Model (PSFM) provides a reference for COE calculations. The model accepts all of the economic assumptions outlined in Table 7-8 and Table 7-9, along with specific information on the capital cost and fixed/variable O&M costs.

The approaches used to calculate both first-year power costs and LCOE are described below.

### First-Year Power Cost

A simplified method provided in the DOE Financial Model User's Guide was used to calculate the first-year power cost.[26] A first-year capital charge factor (CCF) can be used to calculate the COE with this simplified equation:

$$COE = [\ (CCF)(TOC) + OC_{FIX} + (CF)\ OC_{VAR}\ ]\ /\ (CF)\ (MW\text{-}hr)$$

where:

- COE = revenue received by the generator ($/MW-hr) during the power plant's first year of operation (expressed in 2019 dollars), assuming that the COE escalates at a nominal annual rate equal to the general inflation rate; i.e., that it remains constant in real terms over the operational period of the power plant
- CCF = is the first-year CCF that matches the applicable finance structure and capital expenditure period
- TOC = Total Overnight Capital in 2019 dollars
- $OC_{FIX}$ = the sum of all fixed annual operating costs in 2019 dollars
- $OC_{VAR}$ = the sum of all variable annual operating costs, including fuel at 100% capacity factor, in 2019 dollars
- CF = plant capacity factor, assumed to be constant over the operational period
- MW-hr = annual net megawatt-hours of power generated at 100% capacity factor

Based on the economic factors specified by the DOE, the CCF for a low-risk IOU and five-year capital expenditure period is 0.116 (such as a commercial project like a supercritical pulverized coal plant without $CO_2$ capture). The CCF for a high-risk IOU and five-year capital expenditure

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[26] "Power Systems Financial Model Version 6.6 User's Guide," DOE/NETL-2011/1492, May 2011.

period is 0.124 (such as a novel system like post-combustion $CO_2$ capture, atmospheric oxy-combustion, or SPOC).

LCOE

The PSFM provides the LCOE on a current-dollar basis over a levelization period equal to the plants operational life; i.e., the LCOE is constant in current dollars over this period. The model provides a levelization factor that can be multiplied by the COE to give the LCOE in base-year dollars. The levelization factor for NETL-defined economic inputs is 1.268.

### *Costs of $CO_2$ Captured and Avoided*

The cost of $CO_2$ captured was calculated both from the standpoint of the cost of $CO_2$ removed and the cost of $CO_2$ avoided.

The cost of $CO_2$ captured or removed in $/tonne is given by:

$$\text{Cost of } CO_2 \text{ Captured} = (COE_{\text{with removal}} - COE_{\text{w/o removal}}) / (CO_2 \text{ Captured})$$

where:

- COE = cost of electricity ($/MW-$hr_{net}$)
- $CO_2$ Captured = $CO_2$ captured for case (tonnes/MW-$hr_{net}$ or tons/MW-$hr_{net}$)

Note that for cost of $CO_2$ captured, the COE does not include the cost of $CO_2$ transportation and storage (T&S).

The equation used to calculate the cost of $CO_2$ avoided in $/tonne is given by:

$$\text{Cost of } CO_2 \text{ Avoided} = (COE_{\text{with removal}} - COE_{\text{w/o removal}}) / (CO_{2\,\text{w/o removal}} - CO_{2\,\text{with removal}})$$

where:

- COE = cost of electricity ($/MW-$hr_{net}$)
- $CO_2$ = $CO_2$ emissions for case (tonnes/MW-$hr_{net}$ or tons/MW-$hr_{net}$).

### Costs of $CO_2$ Transport and Storage

The cost of $CO_2$ T&S is included in the COE to derive the complete cost of capturing and storing $CO_2$. The updated DOE Baseline Report[27] specified the conditions and T&S costs to be used for DOE system studies. The costs are based on transporting high-pressure (151.7 bara [2200 psia]) $CO_2$ from the power plant through a 100-km (62.1 mile) pipeline to the sequestration or EOR site. The $CO_2$ leaves the pipeline at a pressure of 82.7 bara (1200 psia) still in a SC state. For the Montana plant location used for this study, the T&S value specified by DOE is $10/tonne-$CO_2$.

[27] "Updated Costs (June 2011 Basis) for Selection Bituminous Baseline Cases," DOE/NETL-341/082312, August 2012.

## Baseline Cases and SPOC

This section provides details on how the specific costs were estimated for the baseline and the SPOC cases (baseline and flexible). These descriptions are then followed by the presentation of the capital and O&M costs for each case along with the first-year power cost, LCOE, and $CO_2$ captured and avoided cost.

### SPOC Baseline Case

NETL Low-Rank Coal Baseline Case S12F (Oxy-Fuel Supercritical PC w/$CO_2$ Capture) provided the basis for developing factored cost estimates for many of the SPOC plant systems. The S12F costs were factored based on the capacity of the given SPOC system relative to the capacity of the S12F system. Scaling exponents from the January 2013 NETL QGESS Capital Cost Scaling Methodology report were used.

Costs for the SPOC coal preparation, pressurization (lock-hopper system), and feeding system were factored from NETL Baseline Case S1B (Shell Gasification IGCC w/CCS). The cost for the SPOC HP ASU was developed by AL however the costs have been combined into Account 4.1.

The SPOC boiler equipment and installation labor costs were provided by DBL. The cost for SPOC boiler foundations were also included in the DBL costs.

The SPOC base case was consistent with the NETL Low-Rank Coal Baseline cases in applying percentage factors for the home office engineering and procurement services as well as field construction management cost estimates.

### SPOC Flexible Case

The SPOC flexible case is identical to the baseline case for the boiler, turbine, and BOP equipment as these components are capable of a high degree of turndown and a 6% per minute ramping rate. The principal difference is in the ASU system, where smaller compressor units and additional associated interconnecting pipework and manifolds are needed to deliver the flexibility required to match the SPOC boilers.

**Table 7-10**
**Capital Costs for Base Case S12A**

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 COAL & SORBENT HANDLING | | | | | | | | | | | | | |
| 1.1 Coal Receive & Unload | $5,285.67 | $0 | $2,381 | $0 | $7,666 | 10% | $767 | 0% | $0 | 15% | $1,265 | $9,698 | 18 |
| 1.2 Coal Stackout & Reclaim | $6,831 | $0 | $1,527 | $0 | $8,358 | 10% | $836 | 0% | $0 | 15% | $1,379 | $10,574 | 19 |
| 1.3 Coal Conveyors | $6,352 | $0 | $1,510 | $0 | $7,861 | 10% | $786 | 0% | $0 | 15% | $1,297 | $9,945 | 18 |
| 1.4 Other Coal Handling | $1,661 | $0 | $349 | $0 | $2,010 | 10% | $201 | 0% | $0 | 15% | $332 | $2,543 | 5 |
| 1.5 Sorbent Receive & Unload | $64 | $0 | $19 | $0 | $83 | 10% | $8 | 0% | $0 | 15% | $14 | $105 | 0 |
| 1.6 Sorbent Stackout & Reclaim | $1,039 | $0 | $187 | $0 | $1,227 | 10% | $123 | 0% | $0 | 15% | $202 | $1,552 | 3 |
| 1.7 Sorbent Conveyors | $371 | $81 | $90 | $0 | $542 | 10% | $54 | 0% | $0 | 15% | $89 | $686 | 1 |
| 1.8 Other Sorbent Handling | $225 | $53 | $116 | $0 | $394 | 10% | $39 | 0% | $0 | 15% | $65 | $498 | 1 |
| 1.9 Coal & Sorbent Hnd. Foundations | $0 | $6,126 | $8,076 | $0 | $14,202 | 10% | $1,420 | 0% | $0 | 15% | $2,343 | $17,966 | 33 |
| SUBTOTAL 1. | $21,829 | $6,260 | $14,255 | $0 | $42,344 | 10% | $4,234 | 0% | $0 | 15% | $6,987 | $53,567 | 97 |
| 2 COAL & SORBENT PREP & FEED | | | | | | | | | | | | | |
| 2.1 Coal Crushing & Drying | $3,066 | $0 | $590 | $0 | $3,656 | 10% | $366 | 0% | $0 | 15% | $603 | $4,625 | 8 |
| 2.2 Coal Conveyor to Storage | $7,852 | $0 | $1,692 | $0 | $9,544 | 10% | $954 | 0% | $0 | 15% | $1,575 | $12,073 | 22 |
| 2.3 Coal Injection System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.4 Misc. Coal Prep & Feed | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.5 Sorbent Prep Equipment | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0.0% | 0 | $0 | 0 |
| 2.6 Sorbent Storage & Feed | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0.0% | 0 | $0 | 0 |
| 2.7 Sorbent Injection System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.8 Booster Air Supply System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.9 Coal & Sorbent Feed Foundation | $0 | $827 | $727 | $0 | $1,553 | 10% | $155 | 0% | $0 | 15% | $256 | $1,965 | 4 |
| SUBTOTAL 2. | $10,919 | $827 | $3,008 | $0 | $14,754 | 10% | $1,475 | 0% | $0 | 15% | $2,434 | $18,664 | 34 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 3 FEEDWATER & MISC. BOP SYSTEMS | | | | | | | | | | | | | |
| 3.1 Feedwater System | $23,433 | $0 | $7,555 | $0 | $30,988 | 10% | $3,099 | 0% | $0 | 15% | $5,113 | $39,200 | 71 |
| 3.2 Water Makeup & Pretreating | $3,528 | $0 | $1,116 | $0 | $4,644 | 10% | $464 | 0% | $0 | 20% | $1,022 | $6,131 | 11 |
| 3.3 Other Feedwater Subsystems | $7,372 | $0 | $3,027 | $0 | $10,398 | 10% | $1,040 | 0% | $0 | 15% | $1,716 | $13,154 | 24 |
| 3.4 Service Water Systems | $707 | $0 | $369 | $0 | $1,076 | 10% | $108 | 0% | $0 | 20% | $237 | $1,420 | 3 |
| 3.5 Other Boiler Plant Systems | $9,336 | $0 | $8,825 | $0 | $18,161 | 10% | $1,816 | 0% | $0 | 15% | $2,997 | $22,974 | 42 |
| 3.6 FO Supply Sys & Nat Gas | $347 | $0 | $405 | $0 | $752 | 10% | $75 | 0% | $0 | 15% | $124 | $952 | 2 |
| 3.7 Waste Treatment Equipment | $2,314 | $0 | $1,339 | $0 | $3,654 | 10% | $365 | 0% | $0 | 20% | $804 | $4,823 | 9 |
| 3.8 Misc. Equip. (Cranes, Air Comp., Comm.) | $3,394 | $0 | $1,049 | $0 | $4,443 | 10% | $444 | 0% | $0 | 20% | $977 | $5,865 | 11 |
| SUBTOTAL 3. | $50,430 | $0 | $23,686 | $0 | $74,117 | 10% | $7,412 | 0% | $0 | 16% | $12,989 | $94,520 | 172 |
| 4 PC BOILER & ACCESSORIES | | | | | | | | | | | | | |
| 4.1 PC Boiler | $233,166 | $0 | $115,987 | $0 | $349,153 | 10% | $34,915 | 0% | $0 | 10% | $38,407 | $422,475 | 768 |
| 4.2 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.3 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.4 Boiler BOP (w/ ID Fans) | w/4.1 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.5 Primary Air System | w/4.1 | $0 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.6 Secondary Air System | w/4.1 | $0 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.8 Major Component Rigging | $0 | w/4.1 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.9 PC Foundations | $0 | w/14.1 | w/14.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| SUBTOTAL 4. | $233,166 | $0 | $115,987 | $0 | $349,153 | 10% | $34,915 | 0% | $0 | 10% | $38,407 | $422,475 | 768 |
| 5 FLUE GAS CLEANUP | | | | | | | | | | | | | |
| 5.1 Absorber Vessels & Accessories | $101,981 | $0 | $27,590 | $0 | $129,571 | | $12,957 | | $0 | | $14,253 | $156,781 | 285 |
| 5.2 Other FGD | $1,316 | $0 | $848 | $0 | $2,164 | | $216 | | $0 | | $238 | $2,619 | 5 |

| Project: Montana Rosebud PRB Coal<br>TOTAL PLANT COST SUMMARY<br>Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
| 5.3 Bag House & Accessories | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 5.4 Other Particulate Removal Materials | $24,365 | $0 | $16,508 | $0 | $40,873 | | $4,087 | | $0 | | $4,496 | $49,456 | 90 |
| 5.5 Gypsum Dewatering System | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 5.6 Mercury Removal System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 5.9 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| SUBTOTAL 5. | $127,662 | $0 | $44,946 | $0 | $172,608 | | $17,261 | | $0 | | $18,987 | $208,856 | 380 |
| 5B CO2 REMOVAL & COMPRESSION | | | | | | | | | | | | | |
| 5B.1 CO2 Condensing Heat Exchanger | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 5B.2 CO2 Compression & Drying | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| SUBTOTAL 5B. | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 6 COMBUSTION TURBINE/ACCESSORIES | | | | | | | | | | | | | |
| SUBTOTAL 6. | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 7 HRSG | | | | | | | | | | | | | |
| 7.1 Flue Gas Recycle Heat Exchanger | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 7.2 SCR System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 15% | 0 | $0 | 0 |
| 7.3 Ductwork | $13,311 | $0 | $8,401 | $0 | $21,713 | 10% | $2,171 | 0% | $0 | 15% | $3,583 | $27,467 | 50 |
| 7.4 Stack | $13,236 | $0 | $7,694 | $0 | $20,930 | 10% | $2,093 | 0% | $0 | 10% | $2,302 | $25,325 | 46 |
| 7.9 HRSG, Duct & Stack Foundations | $0 | $1,443 | $1,713 | $0 | $3,156 | 10% | $316 | 0% | $0 | 20% | $694 | $4,166 | 8 |
| SUBTOTAL 7. | $26,548 | $1,443 | $17,808 | $0 | $45,799 | 10% | $4,580 | 0% | $0 | 13% | $6,579 | $56,958 | 104 |
| 8 STEAM TURBINE GENERATOR | | | | | | | | | | | | | |
| 8.1 Steam TG & Accessories | $70,602 | $0 | $8,711 | $0 | $79,313 | 10% | $7,931 | 0% | $0 | 10% | $8,724 | $95,969 | 174 |
| 8.2 Turbine Plant Auxiliaries | $444 | $0 | $944 | $0 | $1,388 | 10% | $139 | 0% | $0 | 10% | $153 | $1,679 | 3 |
| 8.3a Condenser & Auxiliaries | $5,142 | $0 | $2,906 | $0 | $8,048 | 10% | $805 | 0% | $0 | 10% | $885 | $9,738 | 18 |

| Project: Montana Rosebud PRB Coal<br>TOTAL PLANT COST SUMMARY<br>Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 8.3b Air Cooled Condenser | $47,123 | $0 | $9,385 | $0 | $56,508 | 10% | $5,651 | 0% | $0 | 20% | $12,432 | $74,591 | 136 |
| 8.4 Steam Piping | $23,996 | $0 | $10,662 | $0 | $34,657 | 10% | $3,466 | 0% | $0 | 15% | $5,718 | $43,842 | 80 |
| 8.9 TG Foundations | $0 | $1,323 | $2,184 | $0 | $3,507 | 10% | $351 | 0% | $0 | 20% | $772 | $4,630 | 8 |
| SUBTOTAL 8. | $147,306 | $1,323 | $34,792 | $0 | $183,421 | 10% | $18,342 | 0% | $0 | 14% | $28,684 | $230,449 | 419 |
| 9 COOLING WATER SYSTEM | | | | | | | | | | | | | |
| 9.1 Cooling Towers | $7,187 | $0 | $2,223 | $0 | $9,409 | 10% | $941 | 0% | $0 | 10% | $1,035 | $11,385 | 21 |
| 9.2 Circulating Water Pumps | $1,447 | $0 | $74 | $0 | $1,521 | 10% | $152 | 0% | $0 | 10% | $167 | $1,841 | 3 |
| 9.3 Circ. Water System Auxiliaries | $425 | $0 | $56 | $0 | $481 | 10% | $48 | 0% | $0 | 10% | $53 | $582 | 1 |
| 9.4 Circ. Water Piping | $0 | $3,582 | $3,243 | $0 | $6,825 | 10% | $683 | 0% | $0 | 15% | $1,126 | $8,634 | 16 |
| 9.5 Make-up Water System | $382 | $0 | $491 | $0 | $873 | 10% | $87 | 0% | $0 | 15% | $144 | $1,104 | 2 |
| 9.6 Component Cooling Water System | $346 | $0 | $266 | $0 | $612 | 10% | $61 | 0% | $0 | 15% | $101 | $775 | 1 |
| 9.9 Circ. Water System Foundations | $0 | $1,888 | $3,135 | $0 | $5,024 | 10% | $502 | 0% | $0 | 20% | $1,105 | $6,631 | 12 |
| SUBTOTAL 9. | $9,786 | $5,470 | $9,489 | $0 | $24,745 | 10% | $2,475 | 0% | $0 | 14% | $3,732 | $30,953 | 56 |
| 10 ASH/SPENT SORBENT HANDLING SYS | | | | | | | | | | | | | |
| 10.1 Ash Coolers | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.2 Cyclone Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.3 HGCU Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.4 High Temperature Ash Piping | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.5 Other Ash Recovery System | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.6 Ash Storage Silos | $979 | $0 | $2,994 | $0 | $3,973 | 10% | $397 | 0% | $0 | 10% | $437 | $4,807 | 9 |
| 10.7 Ash Transport & Feed Equipment | $6,501 | $0 | $6,445 | $0 | $12,947 | 10% | $1,295 | 0% | $0 | 10% | $1,424 | $15,666 | 28 |
| 10.8 Misc. Ash Handling Equipment | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.9 Ash/Spent Sorbent Foundation | $0 | $221 | $272 | $0 | $492 | 10% | $49 | 0% | $0 | 20% | $108 | $650 | 1 |
| SUBTOTAL 10. | $7,480 | $221 | $9,711 | $0 | $17,412 | 10% | $1,741 | 0% | $0 | 10% | $1,969 | $21,123 | 38 |
| 11 ACCESSORY ELECTRIC PLANT | | | | | | | | | | | | | |
| 11.1 Generator Equipment | $2,059 | $0 | $329 | $0 | $2,389 | 10% | $239 | 0% | $0 | 8% | $210 | $2,838 | 5 |
| 11.2 Station Service Equipment | $3,607 | $0 | $1,210 | $0 | $4,817 | 10% | $482 | 0% | $0 | 8% | $424 | $5,723 | 10 |
| 11.3 Switchgear & Motor Control | $4,141 | $0 | $719 | $0 | $4,860 | 10% | $486 | 0% | $0 | 10% | $535 | $5,881 | 11 |
| 11.4 Conduit & Cable Tray | $0 | $2,839 | $9,175 | $0 | $12,015 | 10% | $1,201 | 0% | $0 | 15% | $1,982 | $15,199 | 28 |
| 11.5 Wire & Cable | $0 | $5,407 | $9,666 | $0 | $15,073 | 10% | $1,507 | 0% | $0 | 15% | $2,487 | $19,068 | 35 |
| 11.6 Protective Equipment | $335 | $0 | $1,166 | $0 | $1,502 | 10% | $150 | 0% | $0 | 10% | $165 | $1,817 | 3 |
| 11.7 Standby Equipment | $1,586 | $0 | $37 | $0 | $1,623 | 10% | $162 | 0% | $0 | 10% | $179 | $1,964 | 4 |
| 11.8 Main Power Transformers | $11,090 | $0 | $218 | $0 | $11,307 | 10% | $1,131 | 0% | $0 | 10% | $1,244 | $13,682 | 25 |
| 11.9 Electrical Foundations | $0 | $380 | $968 | $0 | $1,348 | 10% | $135 | 0% | $0 | 20% | $297 | $1,780 | 3 |
| SUBTOTAL 11. | $22,819 | $8,627 | $23,488 | $0 | $54,934 | 10% | $5,493 | 0% | $0 | 12% | $7,522 | $67,952 | 124 |
| 12 INSTRUMENTATION & CONTROL | | | | | | | | | | | | | |
| 12.1 PC Control Equipment | w/12.7 | $0 | w/12.7 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.2 Combustion Turbine Control | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.3 Steam Turbine Control | w/8.1 | $0 | w/8.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.4 Other Major Component Control | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.5 Signal Processing Equipment | W/12.7 | $0 | w/12.7 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.6 Control Boards, Panels, & Racks | $558 | $0 | $340 | $0 | $898 | 10% | $90 | 0% | $0 | 15% | $148 | $1,137 | 2 |
| 12.7 Distributed Control System Equipment | $5,630 | $0 | $1,004 | $0 | $6,634 | 10% | $663 | 0% | $0 | 10% | $730 | $8,027 | 15 |
| 12.8 Instrument Wiring & Tubing | $3,394 | $0 | $6,176 | $0 | $9,569 | 10% | $957 | 0% | $0 | 15% | $1,579 | $12,106 | 22 |
| 12.9 Other I & C Equipment | $1,590 | $0 | $3,683 | $0 | $5,273 | 10% | $527 | 0% | $0 | 10% | $580 | $6,381 | 12 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12A Air-Fired Supercritical PC w/o $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12A TOTAL PLANT Cost | Case S12A COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SUBTOTAL 12. | $11,171 | $0 | $11,203 | $0 | $22,375 | 10% | $2,237 | 0% | $0 | 12% | $3,037 | $27,650 | 50 |
| 13 IMPROVEMENTS TO SITE | | | | | | | | | | | | | |
| 13.1 Site Preparation | $0 | $59 | $1,266 | $0 | $1,325 | 10% | $133 | 0% | $0 | 20% | $292 | $1,749 | 3 |
| 13.2 Site Improvements | $0 | $1,975 | $2,610 | $0 | $4,585 | 10% | $458 | 0% | $0 | 20% | $1,009 | $6,052 | 11 |
| 13.3 Site Facilities | $3,540 | $0 | $3,714 | $0 | $7,254 | 10% | $725 | 0% | $0 | 20% | $1,596 | $9,575 | 17 |
| SUBTOTAL 13. | $3,540 | $2,034 | $7,590 | $0 | $13,164 | 10% | $1,316 | 0% | $0 | 20% | $2,896 | $17,377 | 32 |
| 14 BUILDINGS & STRUCTURES | | | | | | | | | | | | | |
| 14.1 Boiler Building | $0 | $11,558 | $10,156 | $0 | $21,714 | 10% | $2,171 | 0% | $0 | 15% | $3,583 | $27,469 | 50 |
| 14.2 Turbine Building | $0 | $15,011 | $13,980 | $0 | $28,991 | 10% | $2,899 | 0% | $0 | 15% | $4,784 | $36,674 | 67 |
| 14.3 Administration Building | $0 | $744 | $786 | $0 | $1,530 | 10% | $153 | 0% | $0 | 15% | $252 | $1,936 | 4 |
| 14.4 Circulation Water Pumphouse | $0 | $212 | $170 | $0 | $382 | 10% | $38 | 0% | $0 | 15% | $63 | $483 | 1 |
| 14.5 Water Treatment Buildings | $0 | $440 | $401 | $0 | $841 | 10% | $84 | 0% | $0 | 15% | $139 | $1,064 | 2 |
| 14.6 Machine Shop | $0 | $498 | $334 | $0 | $831 | 10% | $83 | 0% | $0 | 15% | $137 | $1,052 | 2 |
| 14.7 Warehouse | $0 | $336 | $338 | $0 | $674 | 10% | $67 | 0% | $0 | 15% | $111 | $853 | 2 |
| 14.8 Other Buildings & Structures | $0 | $275 | $234 | $0 | $509 | 10% | $51 | 0% | $0 | 15% | $84 | $644 | 1 |
| 14.9 Waste Treating Building & Str. | $0 | $527 | $1,599 | $0 | $2,126 | 10% | $213 | 0% | $0 | 15% | $351 | $2,689 | 5 |
| SUBTOTAL 14. | $0 | $29,601 | $27,997 | $0 | $57,598 | 10% | $5,760 | 0% | $0 | 15% | $9,504 | $72,864 | 132 |
| TOTAL COST | $672,655 | $55,805 | $343,961 | $0 | $1,072,422 | 10% | $107,242 | 0% | $0 | 12% | $143,727 | $1,323,408 | 2,406 |

**Table 7-11**
**Capital Costs for Base Case S12B**

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 COAL & SORBENT HANDLING | | | | | | | | | | | | | |
| 1.1 Coal Receive & Unload | $6,608.69 | $0 | $2,977 | $0 | $9,586 | 10% | $959 | 0% | $0 | 15% | $1,582 | $12,126 | 22 |
| 1.2 Coal Stackout & Reclaim | $8,542 | $0 | $1,909 | $0 | $10,452 | 10% | $1,045 | 0% | $0 | 15% | $1,725 | $13,221 | 24 |
| 1.3 Coal Conveyors | $7,942 | $0 | $1,888 | $0 | $9,830 | 10% | $983 | 0% | $0 | 15% | $1,622 | $12,435 | 23 |
| 1.4 Other Coal Handling | $2,077 | $0 | $436 | $0 | $2,513 | 10% | $251 | 0% | $0 | 15% | $415 | $3,179 | 6 |
| 1.5 Sorbent Receive & Unload | $80 | $0 | $24 | $0 | $104 | 10% | $10 | 0% | $0 | 15% | $17 | $131 | 0 |
| 1.6 Sorbent Stackout & Reclaim | $1,293 | $0 | $234 | $0 | $1,527 | 10% | $153 | 0% | $0 | 15% | $252 | $1,932 | 4 |
| 1.7 Sorbent Conveyors | $462 | $101 | $112 | $0 | $674 | 10% | $67 | 0% | $0 | 15% | $111 | $853 | 2 |
| 1.8 Other Sorbent Handling | $278 | $66 | $144 | $0 | $488 | 10% | $49 | 0% | $0 | 15% | $81 | $618 | 1 |
| 1.9 Coal & Sorbent Hnd. Foundations | $0 | $7,660 | $10,099 | $0 | $17,759 | 10% | $1,776 | 0% | $0 | 15% | $2,930 | $22,465 | 41 |
| SUBTOTAL 1. | $27,283 | $7,827 | $17,823 | $0 | $52,932 | 10% | $5,293 | 0% | $0 | 15% | $8,734 | $66,959 | 122 |
| 2 COAL & SORBENT PREP & FEED | | | | | | | | | | | | | |
| 2.1 Coal Crushing & Drying | $3,890 | $0 | $748 | $0 | $4,638 | 10% | $464 | 0% | $0 | 15% | $765 | $5,867 | 11 |
| 2.2 Coal Conveyor to Storage | $9,961 | $0 | $2,145 | $0 | $12,106 | 10% | $1,211 | 0% | $0 | 15% | $1,997 | $15,314 | 28 |
| 2.3 Coal Injection System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.4 Misc. Coal Prep & Feed | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.5 Sorbent Prep Equipment | $0 | $0 | $0 | $0 | $0 | 8.7% | $0 | 0% | $0 | 15% | 0 | $0 | 0 |
| 2.6 Sorbent Storage & Feed | $0 | $0 | $0 | $0 | $0 | 8.9% | $0 | 0% | $0 | 15% | 0 | $0 | 0 |
| 2.7 Sorbent Injection System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.8 Booster Air Supply System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 2.9 Coal & Sorbent Feed Foundation | $0 | $1,050 | $921 | $0 | $1,971 | 10% | $197 | 0% | $0 | 15% | $325 | $2,493 | 5 |
| SUBTOTAL 2. | $13,851 | $1,050 | $3,815 | $0 | $18,715 | 10% | $1,871 | 0% | $0 | 15% | $3,088 | $23,674 | 43 |

| Project: Montana Rosebud PRB Coal<br>TOTAL PLANT COST SUMMARY<br>Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 3 FEEDWATER & MISC. BOP SYSTEMS | | | | | | | | | | | | | |
| 3.1 Feedwater System | $29,382 | $0 | $9,474 | $0 | $38,855 | 10% | $3,886 | 0% | $0 | 15% | $6,411 | $49,152 | 89 |
| 3.2 Water Makeup & Pretreating | $8,120 | $0 | $2,568 | $0 | $10,688 | 10% | $1,069 | 0% | $0 | 20% | $2,351 | $14,109 | 26 |
| 3.3 Other Feedwater Subsystems | $9,243 | $0 | $3,795 | $0 | $13,038 | 10% | $1,304 | 0% | $0 | 15% | $2,151 | $16,493 | 30 |
| 3.4 Service Water Systems | $1,626 | $0 | $850 | $0 | $2,476 | 10% | $248 | 0% | $0 | 20% | $545 | $3,268 | 6 |
| 3.5 Other Boiler Plant Systems | $12,231 | $0 | $11,565 | $0 | $23,796 | 10% | $2,380 | 0% | $0 | 15% | $3,926 | $30,102 | 55 |
| 3.6 FO Supply Sys & Nat Gas | $378 | $0 | $440 | $0 | $819 | 10% | $82 | 0% | $0 | 15% | $135 | $1,036 | 2 |
| 3.7 Waste Treatment Equipment | $5,327 | $0 | $3,084 | $0 | $8,411 | 10% | $841 | 0% | $0 | 20% | $1,850 | $11,102 | 20 |
| 3.8 Misc. Equip. (Cranes, Air Comp., Comm.) | $3,696 | $0 | $1,143 | $0 | $4,839 | 10% | $484 | 0% | $0 | 20% | $1,065 | $6,388 | 12 |
| SUBTOTAL 3. | $70,003 | $0 | $32,919 | $0 | $102,922 | 10% | $10,292 | 0% | $0 | 16% | $18,435 | $131,649 | 239 |
| 4 PC BOILER & ACCESSORIES | | | | | | | | | | | | | |
| 4.1 PC Boiler | $297,084 | $0 | $147,781 | $0 | $444,865 | 10% | $44,487 | 0% | $0 | 10% | $48,935 | $538,287 | 979 |
| 4.2 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.3 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.4 Boiler BOP (w/ ID Fans) | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.5 Primary Air System | w/4.1 | $0 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.6 Secondary Air System | w/4.1 | $0 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.8 Major Component Rigging | $0 | w/4.1 | w/4.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 4.9 PC Foundations | $0 | w/14.1 | w/14.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| SUBTOTAL 4. | $297,084 | $0 | $147,781 | $0 | $444,865 | 10% | $44,487 | 0% | $0 | 10% | $48,935 | $538,287 | 979 |
| 5 FLUE GAS CLEANUP | | | | | | | | | | | | | |
| 5.1 Absorber Vessels & Accessories | $130,907 | $0 | $35,415 | $0 | $166,322 | 10% | $16,632 | 0% | $0 | 10% | $18,295 | $201,250 | 366 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.2 Other FGD | $1,690 | $0 | $1,089 | $0 | $2,778 | 10% | $278 | 0% | $0 | 10% | $306 | $3,362 | 6 |
| 5.3 Bag House & Accessories | w/5.1 | $0 | w/5.1 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 5.4 Other Particulate Removal Materials | $31,276 | $0 | $21,189 | $0 | $52,465 | 10% | $5,247 | 0% | $0 | 10% | $5,771 | $63,483 | 115 |
| 5.5 Gypsum Dewatering System | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 5.6 Mercury Removal System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 5.9 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| SUBTOTAL 5. | $163,873 | $0 | $57,693 | $0 | $221,566 | 10% | $22,157 | 0% | $0 | 10% | $24,372 | $268,095 | 487 |
| 5B CO2 REMOVAL & COMPRESSION | | | | | | | | | | | | | |
| 5B.1 CO2 Removal System | $282,586 | $0 | $85,154 | $0 | $367,740 | 10% | $36,774 | 20% | $72,813 | 24% | $95,465 | $572,792 | 1,041 |
| 5B.2 CO2 Compression & Drying | $54,911 | $0 | $20,398 | $0 | $75,309 | 10% | $7,531 | 0% | $0 | 20% | $16,568 | $99,408 | 181 |
| SUBTOTAL 5B. | $337,496 | $0 | $105,553 | $0 | $443,049 | 10% | $44,305 | 16% | $72,813 | 23% | $112,033 | $672,200 | 1,222 |
| 6 COMBUSTION TURBINE/ACCESSORIES | | | | | | | | | | | | | |
| SUBTOTAL 6. | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 7 HRSG | | | | | | | | | | | | | |
| 7.1 Flue Gas Recycle Heat Exchanger | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 7.2 SCR System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 7.3 Ductwork | $13,335 | $0 | $8,416 | $0 | $21,751 | 10% | $2,175 | 0% | $0 | 15% | $3,589 | $27,515 | 50 |
| 7.4 Stack | $12,055 | $0 | $7,006 | $0 | $19,061 | 10% | $1,906 | 0% | $0 | 10% | $2,097 | $23,064 | 42 |
| 7.9 HRSG, Duct & Stack Foundations | $0 | $1,314 | $1,560 | $0 | $2,875 | 10% | $287 | 0% | $0 | 20% | $632 | $3,794 | 7 |
| SUBTOTAL 7. | $25,389 | $1,314 | $16,983 | $0 | $43,687 | 10% | $4,369 | 0% | $0 | 13% | $6,318 | $54,373 | 99 |
| 8 STEAM TURBINE GENERATOR | | | | | | | | | | | | | |
| 8.1 Steam TG & Accessories | $78,297 | $0 | $9,645 | $0 | $87,942 | 10% | $8,794 | 0% | $0 | 10% | $9,674 | $106,410 | 193 |

| Project: Montana Rosebud PRB Coal<br>TOTAL PLANT COST SUMMARY<br>Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 8.2 Turbine Plant Auxiliaries | $493 | $0 | $1,049 | $0 | $1,542 | 10% | $154 | 0% | $0 | 10% | $170 | $1,866 | 3 |
| 8.3a Condenser & Auxiliaries | $4,137 | $0 | $2,600 | $0 | $6,737 | 10% | $674 | 0% | $0 | 10% | $741 | $8,152 | 15 |
| 8.3b Air Cooled Condenser | $37,905 | $0 | $7,549 | $0 | $45,454 | 10% | $4,545 | 0% | $0 | 20% | $10,000 | $60,000 | 109 |
| 8.4 Steam Piping | $30,575 | $0 | $13,585 | $0 | $44,160 | 10% | $4,416 | 0% | $0 | 15% | $7,286 | $55,862 | 102 |
| 8.9 TG Foundations | $0 | $1,471 | $2,427 | $0 | $3,898 | 10% | $390 | 0% | $0 | 20% | $858 | $5,146 | 9 |
| SUBTOTAL 8. | $151,407 | $1,471 | $36,856 | $0 | $189,734 | 10% | $18,973 | 0% | $0 | 14% | $28,728 | $237,436 | 432 |
| 9 COOLING WATER SYSTEM | | | | | | | | | | | | | |
| 9.1 Cooling Towers | $18,360 | $0 | $5,678 | $0 | $24,038 | 10% | $2,404 | 0% | $0 | 10% | $2,644 | $29,086 | 53 |
| 9.2 Circulating Water Pumps | $3,683 | $0 | $284 | $0 | $3,967 | 10% | $397 | 0% | $0 | 10% | $436 | $4,800 | 9 |
| 9.3 Circ. Water System Auxiliaries | $948 | $0 | $126 | $0 | $1,074 | 10% | $107 | 0% | $0 | 10% | $118 | $1,299 | 2 |
| 9.4 Circ. Water Piping | $0 | $7,974 | $7,222 | $0 | $15,196 | 10% | $1,520 | 0% | $0 | 15% | $2,507 | $19,223 | 35 |
| 9.5 Make-up Water System | $772 | $0 | $993 | $0 | $1,765 | 10% | $177 | 0% | $0 | 15% | $291 | $2,233 | 4 |
| 9.6 Component Cooling Water System | $771 | $0 | $592 | $0 | $1,364 | 10% | $136 | 0% | $0 | 15% | $225 | $1,725 | 3 |
| 9.9 Circ. Water System Foundations | $0 | $4,218 | $7,005 | $0 | $11,223 | 10% | $1,122 | 0% | $0 | 20% | $2,469 | $14,815 | 27 |
| SUBTOTAL 9. | $24,534 | $12,192 | $21,901 | $0 | $58,626 | 10% | $5,863 | 0% | $0 | 13% | $8,691 | $73,180 | 133 |
| 10 ASH/SPENT SORBENT HANDLING SYS | | | | | | | | | | | | | |
| 10.1 Ash Coolers | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.2 Cyclone Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.3 HGCU Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.4 High Temperature Ash Piping | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.5 Other Ash Recovery System | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.6 Ash Storage Silos | $1,194 | $0 | $3,654 | $0 | $4,848 | 10% | $485 | 0% | $0 | 10% | $533 | $5,866 | 11 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.7 Ash Transport & Feed Equipment | $7,934 | $0 | $7,864 | $0 | $15,798 | 10% | $1,580 | 0% | $0 | 10% | $1,738 | $19,115 | 35 |
| 10.8 Misc. Ash Handling Equipment | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.9 Ash/Spent Sorbent Foundation | $0 | $270 | $331 | $0 | $602 | 10% | $60 | 0% | $0 | 20% | $132 | $794 | 1 |
| SUBTOTAL 10. | $9,127 | $270 | $11,849 | $0 | $21,247 | 10% | $2,125 | 0% | $0 | 10% | $2,403 | $25,775 | 47 |
| 11 ACCESSORY ELECTRIC PLANT | | | | | | | | | | | | | |
| 11.1 Generator Equipment | $2,241 | $0 | $358 | $0 | $2,599 | 10% | $260 | 0% | $0 | 7% | $200 | $3,059 | 6 |
| 11.2 Station Service Equipment | $6,399 | $0 | $2,145 | $0 | $8,544 | 10% | $854 | 0% | $0 | 7% | $658 | $10,056 | 18 |
| 11.3 Switchgear & Motor Control | $7,343 | $0 | $1,276 | $0 | $8,619 | 10% | $862 | 0% | $0 | 10% | $948 | $10,429 | 19 |
| 11.4 Conduit & Cable Tray | $0 | $5,037 | $16,272 | $0 | $21,309 | 10% | $2,131 | 0% | $0 | 15% | $3,516 | $26,956 | 49 |
| 11.5 Wire & Cable | $0 | $9,590 | $17,143 | $0 | $26,733 | 10% | $2,673 | 0% | $0 | 15% | $4,411 | $33,817 | 61 |
| 11.6 Protective Equipment | $335 | $0 | $1,166 | $0 | $1,502 | 10% | $150 | 0% | $0 | 10% | $165 | $1,817 | 3 |
| 11.7 Standby Equipment | $1,699 | $0 | $39 | $0 | $1,739 | 10% | $174 | 0% | $0 | 10% | $191 | $2,104 | 4 |
| 11.8 Main Power Transformers | $15,157 | $0 | $242 | $0 | $15,398 | 10% | $1,540 | 0% | $0 | 10% | $1,694 | $18,632 | 34 |
| 11.9 Electrical Foundations | $0 | $421 | $1,072 | $0 | $1,492 | 10% | $149 | 0% | $0 | 20% | $328 | $1,970 | 4 |
| SUBTOTAL 11. | $33,174 | $15,047 | $39,713 | $0 | $87,935 | 10% | $8,793 | 0% | $0 | 13% | $12,112 | $108,840 | 198 |
| 12 INSTRUMENTATION & CONTROL | | | | | | | | | | | | | |
| 12.1 PC Control Equipment | w/12.7 | $0 | w/12.7 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.2 Combustion Turbine Control | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.3 Steam Turbine Control | w/8.1 | $0 | w/8.1 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.4 Other Major Component Control | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.5 Signal Processing Equipment | W/12.7 | $0 | w/12.7 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | 0 | $0 | 0 |
| 12.6 Control Boards, Panels, & Racks | $637 | $0 | $390 | $0 | $1,027 | 10% | $103 | 6% | $56 | 16% | $178 | $1,364 | 2 |

Project: Montana Rosebud PRB Coal
TOTAL PLANT COST SUMMARY
Case: S12B Air-Fired Supercritical PC with Econamine-Based $CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12B TOTAL PLANT Cost | Case S12B COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12.7 Distributed Control System Equipment | $6,443 | $0 | $1,150 | $0 | $7,593 | 10% | $759 | 6% | $418 | 11% | $877 | $9,647 | 18 |
| 12.8 Instrument Wiring & Tubing | $3,884 | $0 | $7,068 | $0 | $10,951 | 10% | $1,095 | 6% | $602 | 16% | $1,897 | $14,546 | 26 |
| 12.9 Other I & C Equipment | $1,821 | $0 | $4,215 | $0 | $6,035 | 10% | $604 | 6% | $332 | 11% | $697 | $7,668 | 14 |
| SUBTOTAL 12. | $12,785 | $0 | $12,822 | $0 | $25,607 | 10% | $2,561 | 6% | $1,408 | 13% | $3,649 | $33,226 | 60 |
| 13 IMPROVEMENTS TO SITE | | | | | | | | | | | | | |
| 13.1 Site Preparation | $0 | $66 | $1,424 | $0 | $1,490 | 10% | $149 | 0% | $0 | 20% | $328 | $1,967 | 4 |
| 13.2 Site Improvements | $0 | $2,221 | $2,935 | $0 | $5,157 | 10% | $516 | 0% | $0 | 20% | $1,134 | $6,807 | 12 |
| 13.3 Site Facilities | $3,980 | $0 | $4,176 | $0 | $8,156 | 10% | $816 | 0% | $0 | 20% | $1,794 | $10,766 | 20 |
| SUBTOTAL 13. | $3,980 | $2,288 | $8,535 | $0 | $14,803 | 10% | $1,480 | 0% | $0 | 20% | $3,257 | $19,540 | 36 |
| 14 BUILDINGS & STRUCTURES | | | | | | | | | | | | | |
| 14.1 Boiler Building | $0 | $12,426 | $10,920 | $0 | $23,345 | 10% | $2,335 | 0% | $0 | 15% | $3,852 | $29,532 | 54 |
| 14.2 Turbine Building | $0 | $16,370 | $15,247 | $0 | $31,617 | 10% | $3,162 | 0% | $0 | 15% | $5,217 | $39,996 | 73 |
| 14.3 Administration Building | $0 | $820 | $866 | $0 | $1,686 | 10% | $169 | 0% | $0 | 15% | $278 | $2,133 | 4 |
| 14.4 Circulation Water Pumphouse | $0 | $375 | $299 | $0 | $674 | 10% | $67 | 0% | $0 | 15% | $111 | $853 | 2 |
| 14.5 Water Treatment Buildings | $0 | $1,013 | $923 | $0 | $1,936 | 10% | $194 | 0% | $0 | 15% | $320 | $2,450 | 4 |
| 14.6 Machine Shop | $0 | $547 | $368 | $0 | $915 | 10% | $91 | 0% | $0 | 15% | $151 | $1,157 | 2 |
| 14.7 Warehouse | $0 | $370 | $372 | $0 | $742 | 10% | $74 | 0% | $0 | 15% | $122 | $939 | 2 |
| 14.8 Other Buildings & Structures | $0 | $303 | $258 | $0 | $561 | 10% | $56 | 0% | $0 | 15% | $92 | $709 | 1 |
| 14.9 Waste Treating Building & Str. | $0 | $581 | $1,761 | $0 | $2,342 | 10% | $234 | 0% | $0 | 15% | $386 | $2,963 | 5 |
| SUBTOTAL 14. | $0 | $32,807 | $31,012 | $0 | $63,819 | 10% | $6,382 | 0% | $0 | 15% | $10,530 | $80,731 | 147 |
| TOTAL COST | $1,169,987 | $74,265 | $545,255 | $0 | $1,789,507 | 10% | $178,951 | 4% | $74,221 | 15% | $291,286 | $2,333,965 | 4,243 |

**Table 7-12**
**Capital Costs for Base Case S12F**

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 1 COAL & SORBENT HANDLING | | | | | | | | | | | | | |
| 1.1 Coal Receive & Unload | 6,247 | | 2,853 | | 9,100 | 9% | 813 | 0% | | 15% | 1,487 | 11,401 | 21 |
| 1.2 Coal Stackout & Reclaim | 8,074 | | 1,830 | | 9,904 | 9% | 867 | 0% | | 15% | 1,616 | 12,387 | 23 |
| 1.3 Coal Conveyors | 7,507 | | 1,810 | | 9,317 | 9% | 817 | 0% | | 15% | 1,520 | 11,655 | 21 |
| 1.4 Other Coal Handling | 1,963 | | 419 | | 2,383 | 9% | 209 | 0% | | 15% | 389 | 2,980 | 5 |
| 1.5 Sorbent Receive & Unload | 78 | | 24 | | 102 | 9% | 9 | 0% | | 15% | 17 | 128 | 0 |
| 1.6 Sorbent Stackout & Reclaim | 1,259 | | 230 | | 1,489 | 9% | 130 | 0% | | 15% | 243 | 1,862 | 3 |
| 1.7 Sorbent Conveyors | 450 | 97 | 110 | | 656 | 9% | 57 | 0% | | 15% | 107 | 820 | 1 |
| 1.8 Other Sorbent Handling | 271 | 63 | 143 | | 477 | 9% | 42 | 0% | | 15% | 78 | 598 | 1 |
| 1.9 Coal & Sorbent Hnd. Foundations | 0 | 7,676 | 9,683 | | 17,360 | 9% | 1,622 | 0% | | 15% | 2,848 | 21,830 | 40 |
| SUBTOTAL 1. | 25,849 | 7,836 | 17,102 | 0 | 50,788 | 9% | 4,567 | 0% | 0 | 15% | 8,306 | 63,663 | 116 |
| 2 COAL & SORBENT PREP & FEED | | | | | | | | | | | | | |
| 2.1 Coal Crushing & Drying | 3,646 | | 710 | | 4,357 | 9% | 380 | 0% | | 15% | 710 | 5,447 | 10 |
| 2.2 Coal Conveyor to Storage | 9,337 | | 2,038 | | 11,375 | 9% | 995 | 0% | | 15% | 1,855 | 14,225 | 26 |
| 2.3 Coal Injection System | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.4 Misc. Coal Prep & Feed | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.5 Sorbent Prep Equipment | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.6 Sorbent Storage & Feed | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.7 Sorbent Injection System | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.8 Booster Air Supply System | $0 | $0 | $0 | $0 | $0 | 9% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.9 Coal & Sorbent Feed Foundation | 0 | 1,047 | 878 | | 1,925 | 9% | 177 | 0% | | 15% | 315 | 2,416 | 4 |
| SUBTOTAL 2. | 12,983 | 1,047 | 3,626 | 0 | 17,656 | 9% | 1,551 | 0% | 0 | 15% | 2,880 | 22,088 | 40 |

| Project: Montana Rosebud PRB<br>TOTAL PLANT COST SUMMARY<br>Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 3 FEEDWATER & MISC. BOP SYSTEMS | | | | | | | | | | | | | |
| 3.1 Feedwater System | 29,613 | | 9,566 | | 39,179 | 9% | 3,431 | 0% | | 15% | 6,391 | 49,001 | 89 |
| 3.2 Water Makeup & Pretreating | 5,978 | | 1,924 | | 7,902 | 9% | 741 | 0% | | 20% | 1,728 | 10,372 | 19 |
| 3.3 Other Feedwater Subsystems | 9,066 | | 3,831 | | 12,897 | 9% | 1,150 | 0% | | 15% | 2,107 | 16,154 | 29 |
| 3.4 Service Water Systems | 1,172 | | 637 | | 1,809 | 9% | 168 | 0% | | 20% | 395 | 2,373 | 4 |
| 3.5 Other Boiler Plant Systems | 11,761 | | 11,610 | | 23,371 | 9% | 2,192 | 0% | | 15% | 3,834 | 29,397 | 53 |
| 3.6 FO Supply Sys & Nat Gas | 368 | | 459 | | 827 | 9% | 77 | 0% | | 15% | 135 | 1,039 | 2 |
| 3.7 Waste Treatment Equipment | 0 | | 0 | | 0 | | 0 | | | | 0 | 0 | 0 |
| 3.8 Misc. Equip. (Cranes, Air Comp., Comm.) | 3,905 | | 1,192 | | 5,097 | 10% | 490 | 0% | | 20% | 1,117 | 6,704 | 12 |
| SUBTOTAL 3. | 61,862 | 0 | 29,220 | 0 | 91,082 | 9% | 8,248 | 0% | 0 | 16% | 15,708 | 115,040 | 209 |
| 4 PC BOILER & ACCESSORIES | | | | | | | | | | | | | |
| 4.1 PC Oxy-Boiler/ Accessories | 286,917 | | 140,011 | | 426,928 | 10% | 41,353 | 15% | 64,039 | 11% | 53,232 | 585,552 | 1,065 |
| 4.2 ASU/O2 Compress | 214,651 | | 175,624 | | 390,275 | 10% | 37,802 | 0% | | 10% | 42,808 | 470,885 | 856 |
| 4.3 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.4 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.5 Primary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.6 Secondary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.8 Major Component Rigging | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.9 Boiler Foundations | | | | | 0 | | | | | | | 0 | 0 |
| SUBTOTAL 4. | 501,569 | 0 | 315,635 | 0 | 817,204 | 10% | 79,155 | 8% | 64,039 | 11% | 96,039 | 1,056,437 | 1,921 |
| 5 FLUE GAS CLEANUP | | | | | | | | | | | | | |
| 5.1 FGD System | 85,700 | | 14,415 | | 100,115 | 9% | 9,475 | 0% | | 10% | 10,960 | 120,550 | 219 |
| 5.2 Other FGD | 1,364 | | 546 | | 1,911 | 10% | 184 | 0% | | 10% | 209 | 2,304 | 4 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.3 Baghouse & Accessories | | | | | 0 | | | | | | | 0 | 0 |
| 5.4 Other Particulate Removal Materials | 24,699 | | 10,406 | | 35,105 | 10% | 3,379 | 0% | | 10% | 3,848 | 42,333 | 77 |
| 5.5 Gypsum Dewatering | | | | | 0 | | | | | | | 0 | 0 |
| 5.6 Mercury Removal | | | | | 0 | | | | | | | 0 | 0 |
| SUBTOTAL 5. | 111,763 | 0 | 25,368 | 0 | 137,131 | 10% | 13,039 | 0% | 0 | 10% | 15,017 | 165,187 | 300 |
| 5B CO2 REMOVAL & COMPRESSION | | | | | | | | | | | | | |
| 5B.1 CO2 Condensing Heat Exchanger | 7,758 | | 648 | | 8,406 | 10% | 841 | 0% | | 15% | 1,387 | 10,635 | 19 |
| 5B.2 CO2 Compression & Drying | 84,523 | | 69,156 | | 153,679 | 10% | 15,369 | 0% | | 20% | 33,809 | 202,857 | 369 |
| SUBTOTAL 5B. | 92,281 | 0 | 69,804 | 0 | 162,086 | 10% | 16,210 | 0% | 0 | 20% | 35,195 | 213,492 | 388 |
| 6 COMBUSTION TURBINE/ACCESSORIES | | | | | | | | | | | | | |
| SUBTOTAL 6. | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0 |
| 7 HRSG | | | | | | | | | | | | | |
| 7.1 Flue Gas Recycle Heat Exchanger | 51,205 | | 4,276 | | 55,481 | 10% | 5,548 | 0% | | 15% | 9,154 | 70,184 | 128 |
| 7.2 HRSG Accessories | | | | | 0 | | | | | | | 0 | 0 |
| 7.3 Ductwork | 11,385 | | 7,314 | | 18,699 | 9% | 1,633 | 0% | | 15% | 3,050 | 23,383 | 43 |
| 7.4 Stack | 1,820 | | 1,065 | | 2,885 | 10% | 276 | 0% | | 10% | 316 | 3,477 | 6 |
| 7.9 Duct & Stack Foundations | | 987 | 1,120 | | 2,107 | 9% | 196 | 0% | | 20% | 461 | 2,764 | 5 |
| SUBTOTAL 7. | 64,411 | 987 | 13,776 | 0 | 79,173 | 10% | 7,653 | 0% | 0 | 15% | 12,981 | 99,808 | 181 |
| 8 STEAM TURBINE GENERATOR | | | | | | | | | | | | | |
| 8.1 Steam TG & Accessories | 89,043 | | 11,826 | | 100,869 | 10% | 9,658 | 0% | | 10% | 11,052 | 121,580 | 221 |
| 8.2 Turbine Plant Auxiliaries | 601 | | 1,287 | | 1,888 | 10% | 183 | 0% | | 10% | 207 | 2,278 | 4 |
| 8.3a Condenser & Auxiliaries | 7,454 | | 4,497 | | 11,951 | 9% | 1,135 | 0% | | 10% | 1,309 | 14,396 | 26 |
| 8.3b Air Cooled Condenser | | | | | 0 | | | | | | | 0 | 0 |

| Project: Montana Rosebud PRB<br>TOTAL PLANT COST SUMMARY<br>Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 8.4 Steam Piping | 35,222 | | 17,367 | | 52,589 | 8% | 4,389 | 0% | | 15% | 8,547 | 65,525 | 119 |
| 8.9 TG Foundations | | 1,881 | 2,970 | | 4,851 | 9% | 456 | 0% | | 20% | 1,061 | 6,369 | 12 |
| SUBTOTAL 8. | 132,320 | 1,881 | 37,947 | 0 | 172,147 | 9% | 15,821 | 0% | 0 | 12% | 22,177 | 210,146 | 382 |
| 9 COOLING WATER SYSTEM | | | | | | | | | | | | | |
| 9.1 Cooling Towers | 11,033 | | 3,436 | | 14,468 | 9% | 1,373 | 0% | | 10% | 1,584 | 17,425 | 32 |
| 9.2 Circulating Water Pumps | 3,237 | | 308 | | 3,545 | 9% | 304 | 0% | | 10% | 385 | 4,234 | 8 |
| 9.3 Circ. Water System Auxiliaries | 907 | | 122 | | 1,029 | 9% | 97 | 0% | | 10% | 112 | 1,239 | 2 |
| 9.4 Circ. Water Piping | | 7,198 | 6,976 | | 14,174 | 9% | 1,306 | 0% | | 15% | 2,322 | 17,803 | 32 |
| 9.5 Make-up Water System | 715 | | 954 | | 1,669 | 10% | 159 | 0% | | 15% | 274 | 2,102 | 4 |
| 9.6 Component Cooling Water Sys | 718 | | 572 | | 1,290 | 9% | 122 | 0% | | 15% | 211 | 1,623 | 3 |
| 9.9 Circ. Water System Foundations & Structures | | 4,272 | 6,788 | | 11,060 | 9% | 1,041 | 0% | | 20% | 2,420 | 14,523 | 26 |
| SUBTOTAL 9. | 16,610 | 11,470 | 19,155 | 0 | 47,235 | 9% | 4,402 | 0% | 0 | 14% | 7,309 | 58,947 | 107 |
| 10 ASH/SPENT SORBENT HANDLING SYS | | | | | | | | | | | | | |
| 10.1 Ash Coolers | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.2 Cyclone Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.3 HGCU Ash Letdown | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.4 High Temperature Ash Piping | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.5 Other Ash Recovery System | N/A | $0 | N/A | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.6 Ash Storage Silos | 1,155 | | 3,557 | | 4,712 | 10% | 458 | 0% | | 10% | 517 | 5,687 | 10 |
| 10.7 Ash Transport & Feed Equipment | 7,472 | | 7,653 | | 15,125 | 9% | 1,431 | 0% | | 10% | 1,656 | 18,212 | 33 |
| 10.8 Misc. Ash Handling Equipment | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 10% | 0 | $0 | 0 |
| 10.9 Ash/Spent Sorbent Foundation | | 275 | 322 | | 597 | 9% | 55 | 0% | | 20% | 131 | 784 | 1 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SUBTOTAL 10. | 8,627 | 275 | 11,532 | 0 | 20,434 | 10% | 1,945 | 0% | 0 | 10% | 2,303 | 24,683 | 45 |
| 11 ACCESSORY ELECTRIC PLANT | | | | | | | | | | | | | |
| 11.1 Generator Equipment | 442 | | 72 | | 514 | 9% | 48 | 0% | | 7% | 42 | 604 | 1 |
| 11.2 Station Service Equipment | 7,477 | | 2,457 | | 9,933 | 10% | 950 | 0% | | 7% | 816 | 11,700 | 21 |
| 11.3 Switchgear & Motor Control | 8,596 | | 1,461 | | 10,057 | 9% | 931 | 0% | | 10% | 1,098 | 12,086 | 22 |
| 11.4 Conduit & Cable Tray | | 5,389 | 18,634 | | 24,023 | 10% | 2,299 | 0% | | 15% | 3,949 | 30,271 | 55 |
| 11.5 Wire & Cable | | 10,169 | 19,631 | | 29,800 | 8% | 2,511 | 0% | | 15% | 4,847 | 37,159 | 68 |
| 11.6 Protective Equipment | 313 | | 1,068 | | 1,382 | 10% | 135 | 0% | | 10% | 152 | 1,669 | 3 |
| 11.7 Standby Equipment | 457 | | 10 | | 468 | 9% | 44 | 0% | | 10% | 51 | 563 | 1 |
| 11.8 Main Power Transformers | 1,098 | | 34 | | 1,132 | 8% | 86 | 0% | | 10% | 122 | 1,340 | 2 |
| 11.9 Electrical Foundations | | 62 | 150 | | 211 | 9% | 20 | 0% | | 20% | 46 | 278 | 1 |
| SUBTOTAL 11. | 18,384 | 15,620 | 43,516 | 0 | 77,521 | 9% | 7,023 | 0% | 0 | 13% | 11,123 | 95,669 | 174 |
| 12 INSTRUMENTATION & CONTROL | | | | | | | | | | | | | |
| 12.1 PC Control Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.2 Combustion Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.3 Steam Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.4 Other Major Component Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.5 Signal Processing Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.6 Control Boards, Panels, & Racks | 694 | | 416 | | 1,110 | 10% | 106 | 0% | | 15% | 182 | 1,399 | 3 |
| 12.7 Distributed Control System Equipment | 7,012 | | 1,225 | | 8,237 | 10% | 785 | 0% | | 10% | 903 | 9,925 | 18 |
| 12.8 Instrument Wiring & Tubing | 3,802 | | 7,542 | | 11,343 | 9% | 966 | 0% | | 15% | 1,846 | 14,155 | 26 |
| 12.9 Other I & C Equipment | 1,981 | | 4,496 | | 6,477 | 10% | 631 | 0% | | 10% | 711 | 7,819 | 14 |
| SUBTOTAL 12. | 13,489 | 0 | 13,679 | 0 | 27,167 | 9% | 2,488 | 0% | 0 | 12% | 3,641 | 33,298 | 61 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: S12F Oxy-Fuel Supercritical PC w/$CO_2$ Capture
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | CASE S12F TOTAL PLANT Cost | Case S12F COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 13 IMPROVEMENTS TO SITE | | | | | | | | | | | | | |
| 13.1 Site Preparation | | 64 | 1,286 | | 1,350 | 10% | 133 | 0% | | 20% | 297 | 1,780 | 3 |
| 13.2 Site Improvements | | 2,135 | 2,651 | | 4,786 | 10% | 470 | 0% | | 20% | 1,051 | 6,307 | 11 |
| 13.3 Site Facilities | 3,826 | | 3,773 | | 7,599 | 10% | 746 | 0% | | 20% | 1,668 | 10,014 | 18 |
| SUBTOTAL 13. | 3,826 | 2,199 | 7,710 | 0 | 13,735 | 10% | 1,349 | 0% | 0 | 20% | 3,016 | 18,100 | 33 |
| 14 BUILDINGS & STRUCTURES | | | | | | | | | | | | | |
| 14.1 Boiler Building | | 10,986 | 9,662 | | 20,648 | 9% | 1,854 | 0% | | 15% | 3,376 | 25,878 | 47 |
| 14.2 Turbine Building | | 14,469 | 13,486 | | 27,955 | 9% | 2,518 | 0% | | 15% | 4,570 | 35,043 | 64 |
| 14.3 Administration Building | | 724 | 765 | | 1,489 | 9% | 134 | 0% | | 15% | 243 | 1,867 | 3 |
| 14.4 Circulation Water Pumphouse | | 239 | 189 | | 428 | 9% | 38 | 0% | | 15% | 69 | 536 | 1 |
| 14.5 Water Treatment Buildings | | 666 | 548 | | 1,213 | 9% | 109 | 0% | | 15% | 198 | 1,521 | 3 |
| 14.6 Machine Shop | | 484 | 325 | | 809 | 9% | 72 | 0% | | 15% | 132 | 1,013 | 2 |
| 14.7 Warehouse | | 328 | 329 | | 658 | 9% | 59 | 0% | | 15% | 108 | 825 | 1 |
| 14.8 Other Buildings & Structures | | 268 | 229 | | 496 | 9% | 45 | 0% | | 15% | 81 | 622 | 1 |
| 14.9 Waste Treating Building & Str. | | 495 | 1,504 | | 1,999 | 9% | 189 | 0% | | 15% | 328 | 2,517 | 5 |
| SUBTOTAL 14. | 0 | 28,659 | 27,036 | 0 | 55,695 | 9% | 5,018 | 0% | 0 | 15% | 9,106 | 69,822 | 127 |
| TOTAL COST | 1,063,973 | 69,973 | 635,107 | 0 | 1,769,053 | 10% | 168,469 | 4% | 64,039 | 13% | 244,802 | 2,246,379 | 4,084 |

**Table 7-13**
**Capital Costs for Baseline SPOC Case**

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Base Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 1 COAL & SORBENT HANDLING | | | | | | | | | | | | | |
| 1.1 Coal Receive & Unload | 5,842 | | 2,668 | | 8,511 | 9% | 760 | 0% | | 15% | 1,391 | 10,663 | 19 |
| 1.2 Coal Stackout & Reclaim | 7,551 | | 1,711 | | 9,263 | 9% | 811 | 0% | | 15% | 1,511 | 11,585 | 21 |
| 1.3 Coal Conveyors | 7,021 | | 1,693 | | 8,714 | 9% | 764 | 0% | | 15% | 1,422 | 10,900 | 20 |
| 1.4 Other Coal Handling | 1,836 | | 392 | | 2,228 | 9% | 195 | 0% | | 15% | 364 | 2,787 | 5 |
| 1.5 Sorbent Receive & Unload | 73 | | 22 | | 95 | 9% | 9 | 0% | | 15% | 16 | 120 | 0 |
| 1.6 Sorbent Stackout & Reclaim | 1,175 | | 215 | | 1,389 | 9% | 121 | 0% | | 15% | 227 | 1,737 | 3 |
| 1.7 Sorbent Conveyors | 420 | 90 | 102 | | 612 | 9% | 53 | 0% | | 15% | 100 | 765 | 1 |
| 1.8 Other Sorbent Handling | 253 | 59 | 133 | | 445 | 9% | 39 | 0% | | 15% | 73 | 558 | 1 |
| 1.9 Coal & Sorbent Hnd. Foundations | 0 | 7,179 | 9,056 | | 16,235 | 9% | 1,517 | 0% | | 15% | 2,663 | 20,416 | 37 |
| SUBTOTAL 1. | 24,171 | 7,328 | 15,993 | 0 | 47,492 | 9% | 4,270 | 0% | 0 | 15% | 7,767 | 59,532 | 108 |
| 2 COAL & SORBENT PREP & FEED | | | | | | | | | | | | | |
| 2.1 Coal Crushing & Drying | 65,655 | 3,945 | 9,539 | | 79,139 | 9% | 6,831 | 0% | | 20% | 17,199 | 103,169 | 188 |
| 2.2 Coal Storage & Feed | 97,427 | 2,998 | 12,801 | | 113,226 | 9% | 9,789 | 0% | | 20% | 24,602 | 147,618 | 268 |
| 2.3 Coal Injection System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.4 Misc. Coal Prep & Feed | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.5 Sorbent Prep Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.6 Sorbent Storage & Feed | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.7 Sorbent Injection System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.8 Booster Air Supply System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.9 Coal & Sorbent Feed Foundation | 0 | 6,647 | 5,457 | | 12,104 | 9% | 1,121 | 0% | | 20% | 2,645 | 15,870 | 29 |
| SUBTOTAL 2. | 163,082 | 13,591 | 27,797 | 0 | 204,469 | 9% | 17,740 | 0% | 0 | 20% | 44,446 | 266,657 | 485 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Base Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 3 FEEDWATER & MISC. BOP SYSTEMS | | | | | | | | | | | | | |
| 3.1 Feedwater System | 23,956 | | 7,739 | | 31,695 | 9% | 2,775 | 0% | | 15% | 5,170 | 39,641 | 72 |
| 3.2 Water Makeup & Pretreating | 5,541 | | 1,783 | | 7,324 | 9% | 687 | 0% | | 20% | 1,602 | 9,613 | 17 |
| 3.3 Other Feedwater Subsystems | 8,430 | | 3,563 | | 11,992 | 9% | 1,069 | 0% | | 15% | 1,959 | 15,021 | 27 |
| 3.4 Service Water Systems | 1,086 | | 591 | | 1,677 | 9% | 156 | 0% | | 20% | 366 | 2,199 | 4 |
| 3.5 Other Boiler Plant Systems | 10,854 | | 10,716 | | 21,570 | 9% | 2,023 | 0% | | 15% | 3,539 | 27,132 | 49 |
| 3.6 FO Supply Sys & Nat Gas | 358 | | 447 | | 805 | 9% | 75 | 0% | | 15% | 132 | 1,012 | 2 |
| 3.7 Waste Treatment Equipment | 0 | | 0 | | 0 | | 0 | | | | 0 | 0 | 0 |
| 3.8 Misc. Equip. (Cranes, Air Comp., Comm.) | 3,802 | | 1,161 | | 4,963 | 10% | 477 | 0% | | 20% | 1,088 | 6,528 | 12 |
| SUBTOTAL 3. | 54,028 | 0 | 25,999 | 0 | 80,027 | 9% | 7,262 | 0% | 0 | 16% | 13,856 | 101,147 | 184 |
| 4 PC BOILER & ACCESSORIES | | | | | | | | | | | | | |
| 4.1 SPOC Oxy-Boiler/ ASU / Aux | 323,650 | | 229,986 | | 553,636 | 10% | 54,441 | 15% | 83,045 | 11% | 69,112 | 760,235 | 1,382 |
| 4.2 Open | - | | - | | - | - | - | - | - | - | - | - | - |
| 4.3 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.4 Boiler BOP (w/ ID Fans) | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.5 Primary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.6 Secondary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.8 Major Component Rigging | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.9 Boiler Foundations | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| SUBTOTAL 4. | 323,650 | | 229,986 | | 553,636 | 10% | 54,441 | 15% | 83,045 | 11% | 69,112 | 760,235 | 1,382 |
| 5 FLUE GAS CLEANUP | | | | | | | | | | | | | |
| 5.1 FGD System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.2 Other FGD | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Base Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.3 Baghouse & Accessories | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.4 Other Particulate Removal Materials | 10,241 | | 4,315 | | 14,556 | 10% | 1,401 | 0% | | 10% | 1,596 | 17,553 | 32 |
| 5.5 Gypsum Dewatering | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.6 Mercury Removal | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.9 Mercury Removal System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| SUBTOTAL 5. | 10,241 | | 4,315 | | 14,556 | 10% | 1,401 | 0% | | 10% | 1,596 | 17,553 | 32 |
| 5B CO2 REMOVAL & COMPRESSION | | | | | | | | | | | | | |
| 5B.1 CO2 Condensing Heat Exchanger | 7,272 | | 607 | | 7,879 | 10% | 789 | 0% | | 15% | 1,300 | 9,967 | 18 |
| 5B.2 CO2 Compression & Drying | 79,133 | | 64,746 | | 143,879 | 10% | 14,389 | 0% | | 20% | 31,653 | 189,921 | 345 |
| SUBTOTAL 5B. | 86,405 | 0 | 65,353 | 0 | 151,758 | 10% | 15,177 | 0% | 0 | 20% | 32,952 | 199,888 | 363 |
| 6 COMBUSTION TURBINE/ACCESSORIES | | | | | | | | | | | | | |
| SUBTOTAL 6. | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0.0 |
| 7 HRSG | | | | | | | | | | | | | |
| 7.1 Flue Gas Recycle Heat Exchanger | 47,476 | | 3,965 | | 51,441 | 10% | 5,144 | 0% | | 15% | 8,488 | 65,073 | 118 |
| 7.2 HRSG Accessories | | | | | 0 | | | | | | | 0 | 0 |
| 7.3 Ductwork | 10,556 | | 6,781 | | 17,338 | 9% | 1,514 | 0% | | 15% | 2,828 | 21,680 | 39 |
| 7.4 Stack | 1,688 | | 988 | | 2,675 | 10% | 256 | 0% | | 10% | 293 | 3,224 | 6 |
| 7.9 Duct & Stack Foundations | | 915 | 1,039 | | 1,954 | 9% | 182 | 0% | | 20% | 427 | 2,563 | 5 |
| SUBTOTAL 7. | 59,720 | 915 | 12,772 | 0 | 73,407 | 10% | 7,096 | 0% | 0 | 15% | 12,035 | 92,539 | 168 |
| 8 STEAM TURBINE GENERATOR | | | | | | | | | | | | | |
| 8.1 Steam TG & Accessories | 87,077 | 0 | 11,565 | | 98,642 | 10% | 9,445 | 0% | | 10% | 10,808 | 118,895 | 216 |
| 8.2 Turbine Plant Auxiliaries | 588 | 0 | 1,258 | | 1,846 | 10% | 179 | 0% | | 10% | 202 | 2,227 | 4 |
| 8.3a Condenser & Auxiliaries | 7,297 | 0 | 4,402 | | 11,698 | 9% | 1,111 | 0% | | 10% | 1,282 | 14,091 | 26 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Base Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 8.3b Air Cooled Condenser | 0 | 0 | 0 | | 0 | | 0 | | | | 0 | 0 | 0 |
| 8.4 Steam Piping | 34,444 | 0 | 16,984 | | 51,427 | 8% | 4,292 | 0% | | 15% | 8,358 | 64,078 | 117 |
| 8.9 TG Foundations | 0 | 1,838 | 2,904 | | 4,742 | 9% | 446 | 0% | | 20% | 1,038 | 6,226 | 11 |
| SUBTOTAL 8. | 129,405 | 1,838 | 37,112 | 0 | 168,355 | 9% | 15,473 | 0% | 0 | 12% | 21,688 | 205,517 | 374 |
| 9 COOLING WATER SYSTEM | | | | | | | | | | | | | |
| 9.1 Cooling Towers | 10,775 | | 3,356 | | 14,131 | 9% | 1,341 | 0% | | 10% | 1,547 | 17,019 | 31 |
| 9.2 Circulating Water Pumps | 3,162 | | 301 | | 3,463 | 9% | 297 | 0% | | 10% | 376 | 4,136 | 8 |
| 9.3 Circ. Water System Auxiliaries | 889 | | 119 | | 1,009 | 9% | 95 | 0% | | 10% | 110 | 1,214 | 2 |
| 9.4 Circ. Water Piping | | 7,055 | 6,837 | | 13,892 | 9% | 1,280 | 0% | | 15% | 2,276 | 17,448 | 32 |
| 9.5 Make-up Water System | 700 | | 934 | | 1,635 | 10% | 155 | 0% | | 15% | 269 | 2,059 | 4 |
| 9.6 Component Cooling Water Sys | 704 | | 560 | | 1,264 | 9% | 119 | 0% | | 15% | 207 | 1,590 | 3 |
| 9.9 Circ. Water System Foundations & Structures | | 4,194 | 6,664 | | 10,858 | 9% | 1,022 | 0% | | 20% | 2,376 | 14,256 | 26 |
| SUBTOTAL 9. | 16,231 | 11,249 | 18,771 | 0 | 46,251 | 9% | 4,310 | 0% | 0 | 14% | 7,161 | 57,723 | 105 |
| 10 ASH/SPENT SORBENT HANDLING SYS | | | | | | | | | | | | | |
| 10.1 Rotary Ash Coolers | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.2 Cyclone Ash Letdown | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.3 HGCU Ash Letdown | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.4 High Temperature Ash Piping | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.5 Reducer Baghouse Ash Recycle System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.6 Ash Storage Silos | 1,087 | | 3,348 | | 4,435 | 10% | 432 | 0% | | 10% | 486 | 5,353 | 10 |
| 10.7 Ash Transport & Feed Equipment | 7,033 | | 7,204 | | 14,237 | 9% | 1,347 | 0% | | 10% | 1,558 | 17,143 | 31 |
| 10.8 Misc. Ash Handling Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |

| Project: Montana Rosebud PRB<br>TOTAL PLANT COST SUMMARY<br>Case: SPOC Base Case<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 10.9 Ash/Spent Sorbent Foundation | | 259 | 303 | | 562 | 9% | 52 | 0% | | 20% | 123 | 738 | 1 |
| SUBTOTAL 10. | 8,120 | 259 | 10,855 | 0 | 19,235 | 10% | 1,831 | 0% | 0 | 10% | 2,168 | 23,234 | 42 |
| 11 ACCESSORY ELECTRIC PLANT | | | | | | | | | | | | | |
| 11.1 Generator Equipment | 434 | 0 | 71 | | 505 | 9% | 47 | 0% | | 7% | 41 | 593 | 1 |
| 11.2 Station Service Equipment | 7,375 | 0 | 2,423 | | 9,798 | 10% | 937 | 0% | | 7% | 805 | 11,540 | 21 |
| 11.3 Switchgear & Motor Control | 8,479 | 0 | 1,441 | | 9,920 | 9% | 918 | 0% | | 10% | 1,083 | 11,921 | 22 |
| 11.4 Conduit & Cable Tray | 0 | 5,316 | 18,380 | | 23,696 | 10% | 2,267 | 0% | | 15% | 3,895 | 29,858 | 54 |
| 11.5 Wire & Cable | 0 | 10,031 | 19,364 | | 29,394 | 8% | 2,477 | 0% | | 15% | 4,781 | 36,653 | 67 |
| 11.6 Protective Equipment | 309 | 0 | 1,054 | | 1,363 | 10% | 133 | 0% | | 10% | 150 | 1,646 | 3 |
| 11.7 Standby Equipment | 451 | 0 | 10 | | 462 | 9% | 44 | 0% | | 10% | 50 | 556 | 1 |
| 11.8 Main Power Transformers | 1,082 | 0 | 33 | | 1,115 | 8% | 85 | 0% | | 10% | 120 | 1,320 | 2 |
| 11.9 Electrical Foundations | 0 | 60 | 147 | | 207 | 9% | 19 | 0% | | 20% | 45 | 272 | 0 |
| SUBTOTAL 11. | 18,131 | 15,407 | 42,922 | 0 | 76,459 | 9% | 6,927 | 0% | 0 | 13% | 10,971 | 94,359 | 172 |
| 12 INSTRUMENTATION & CONTROL | | | | | | | | | | | | | |
| 12.1 PC Control Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.2 Combustion Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.3 Steam Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.4 Other Major Component Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.5 Signal Processing Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.6 Control Boards, Panels, & Racks | 683 | | 409 | | 1,092 | 10% | 104 | 0% | | 15% | 179 | 1,376 | 3 |
| 12.7 Distributed Control System Equipment | 6,898 | | 1,205 | | 8,103 | 10% | 772 | 0% | | 10% | 888 | 9,764 | 18 |
| 12.8 Instrument Wiring & Tubing | 3,740 | | 7,419 | | 11,159 | 9% | 950 | 0% | | 15% | 1,816 | 13,925 | 25 |
| 12.9 Other I & C Equipment | 1,949 | | 4,423 | | 6,372 | 10% | 621 | 0% | | 10% | 699 | 7,692 | 14 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Base Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| SUBTOTAL 12. | 13,270 | 0 | 13,456 | 0 | 26,726 | 9% | 2,448 | 0% | 0 | 12% | 3,582 | 32,756 | 60 |
| 13 IMPROVEMENTS TO SITE | | | | | | | | | | | | | |
| 13.1 Site Preparation | | 63 | 1,258 | | 1,321 | 10% | 130 | 0% | | 20% | 290 | 1,742 | 3 |
| 13.2 Site Improvements | | 2,089 | 2,595 | | 4,684 | 10% | 460 | 0% | | 20% | 1,028 | 6,172 | 11 |
| 13.3 Site Facilities | 3,744 | | 3,693 | | 7,437 | 10% | 730 | 0% | | 20% | 1,633 | 9,800 | 18 |
| SUBTOTAL 13. | 3,744 | 2,152 | 7,545 | 0 | 13,441 | 10% | 1,320 | 0% | 0 | 20% | 2,951 | 17,713 | 32 |
| 14 BUILDINGS & STRUCTURES | | | | | | | | | | | | | |
| 14.1 Boiler Building | | 10,986 | 9,662 | | 20,648 | 9% | 1,854 | 0% | | 15% | 3,376 | 25,878 | 47 |
| 14.2 Turbine Building | | 14,414 | 13,434 | | 27,848 | 9% | 2,508 | 0% | | 15% | 4,553 | 34,909 | 63 |
| 14.3 Administration Building | | 716 | 757 | | 1,473 | 9% | 133 | 0% | | 15% | 241 | 1,847 | 3 |
| 14.4 Circulation Water Pumphouse | | 234 | 186 | | 420 | 9% | 37 | 0% | | 15% | 68 | 526 | 1 |
| 14.5 Water Treatment Buildings | | 652 | 537 | | 1,189 | 9% | 106 | 0% | | 15% | 194 | 1,489 | 3 |
| 14.6 Machine Shop | | 479 | 321 | | 800 | 9% | 71 | 0% | | 15% | 131 | 1,002 | 2 |
| 14.7 Warehouse | | 325 | 326 | | 651 | 9% | 59 | 0% | | 15% | 106 | 816 | 1 |
| 14.8 Other Buildings & Structures | | 265 | 226 | | 491 | 9% | 44 | 0% | | 15% | 80 | 615 | 1 |
| 14.9 Waste Treating Building & Str. | | 494 | 1,500 | | 1,994 | 9% | 189 | 0% | | 15% | 328 | 2,511 | 5 |
| SUBTOTAL 14. | 0 | 28,565 | 26,949 | 0 | 55,514 | 9% | 5,002 | 0% | 0 | 15% | 9,076 | 69,594 | 127 |
| TOTAL COST | 910,197 | 81,303 | 539,837 | 0 | 1,531,327 | 11% | 133,697 | 3% | 83,045 | 16% | 239,361 | 1,998,447 | 3,634 |

**Table 7-14**
**Capital Costs for Flexible SPOC Case**

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Flexible Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 COAL & SORBENT HANDLING | | | | | | | | | | | | | |
| 1.1 Coal Receive & Unload | 5,842 | | 2,668 | | 8,511 | 9% | 760 | 0% | | 15% | 1,391 | 10,663 | 19 |
| 1.2 Coal Stackout & Reclaim | 7,551 | | 1,711 | | 9,263 | 9% | 811 | 0% | | 15% | 1,511 | 11,585 | 21 |
| 1.3 Coal Conveyors | 7,021 | | 1,693 | | 8,714 | 9% | 764 | 0% | | 15% | 1,422 | 10,900 | 20 |
| 1.4 Other Coal Handling | 1,836 | | 392 | | 2,228 | 9% | 195 | 0% | | 15% | 364 | 2,787 | 5 |
| 1.5 Sorbent Receive & Unload | 73 | | 22 | | 95 | 9% | 9 | 0% | | 15% | 16 | 120 | 0 |
| 1.6 Sorbent Stackout & Reclaim | 1,175 | | 215 | | 1,389 | 9% | 121 | 0% | | 15% | 227 | 1,737 | 3 |
| 1.7 Sorbent Conveyors | 420 | 90 | 102 | | 612 | 9% | 53 | 0% | | 15% | 100 | 765 | 1 |
| 1.8 Other Sorbent Handling | 253 | 59 | 133 | | 445 | 9% | 39 | 0% | | 15% | 73 | 558 | 1 |
| 1.9 Coal & Sorbent Hnd. Foundations | 0 | 7,179 | 9,056 | | 16,235 | 9% | 1,517 | 0% | | 15% | 2,663 | 20,416 | 37 |
| SUBTOTAL 1. | 24,171 | 7,328 | 15,993 | 0 | 47,492 | 9% | 4,270 | 0% | 0 | 15% | 7,767 | 59,532 | 108 |
| 2 COAL & SORBENT PREP & FEED | | | | | | | | | | | | | |
| 2.1 Coal Crushing & Drying | 65,655 | 3,945 | 9,539 | | 79,139 | 9% | 6,831 | 0% | | 20% | 17,199 | 103,169 | 188 |
| 2.2 Coal Storage & Feed | 97,427 | 2,998 | 12,801 | | 113,226 | 9% | 9,789 | 0% | | 20% | 24,602 | 147,618 | 268 |
| 2.3 Coal Injection System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.4 Misc. Coal Prep & Feed | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.5 Sorbent Prep Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.6 Sorbent Storage & Feed | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.7 Sorbent Injection System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.8 Booster Air Supply System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 2.9 Coal & Sorbent Feed Foundation | 0 | 6,647 | 5,457 | | 12,104 | 9% | 1,121 | 0% | | 20% | 2,645 | 15,870 | 29 |
| SUBTOTAL 2. | 163,082 | 13,591 | 27,797 | 0 | 204,469 | 9% | 17,740 | 0% | 0 | 20% | 44,446 | 266,657 | 485 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Flexible Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 3 FEEDWATER & MISC. BOP SYSTEMS | | | | | | | | | | | | | |
| 3.1 Feedwater System | 23,956 | | 7,739 | | 31,695 | 9% | 2,775 | 0% | | 15% | 5,170 | 39,641 | 72 |
| 3.2 Water Makeup & Pretreating | 5,541 | | 1,783 | | 7,324 | 9% | 687 | 0% | | 20% | 1,602 | 9,613 | 17 |
| 3.3 Other Feedwater Subsystems | 8,430 | | 3,563 | | 11,992 | 9% | 1,069 | 0% | | 15% | 1,959 | 15,021 | 27 |
| 3.4 Service Water Systems | 1,086 | | 591 | | 1,677 | 9% | 156 | 0% | | 20% | 366 | 2,199 | 4 |
| 3.5 Other Boiler Plant Systems | 10,854 | | 10,716 | | 21,570 | 9% | 2,023 | 0% | | 15% | 3,539 | 27,132 | 49 |
| 3.6 FO Supply Sys & Nat Gas | 358 | | 447 | | 805 | 9% | 75 | 0% | | 15% | 132 | 1,012 | 2 |
| 3.7 Waste Treatment Equipment | 0 | | 0 | | 0 | | 0 | | | | 0 | 0 | 0 |
| 3.8 Misc. Equip. (Cranes, Air Comp., Comm.) | 3,802 | | 1,161 | | 4,963 | 10% | 477 | 0% | | 20% | 1,088 | 6,528 | 12 |
| SUBTOTAL 3. | 54,028 | 0 | 25,999 | 0 | 80,027 | 9% | 7,262 | 0% | 0 | 16% | 13,856 | 101,147 | 184 |
| 4 PC BOILER & ACCESSORIES | | | | | | | | | | | | | |
| 4.1 SPOC Oxy-Boiler/ ASU / Aux | 338,650 | | 237,896 | | 576,546 | 10% | 56,732 | 15% | 86,481 | 17% | 71,976 | 791,735 | 1,440 |
| 4.2 Open | - | | - | | - | - | - | - | - | - | - | - | - |
| 4.3 Open | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.4 Boiler BOP (w/ ID Fans) | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.5 Primary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.6 Secondary Air System | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.8 Major Component Rigging | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 4.9 Boiler Foundations | $0 | $0 | $0 | $0 | $0 | 0.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| SUBTOTAL 4. | 338,650 | | 237,896 | | 576,546 | 10% | 56,732 | 15% | 86,481 | 17% | 71,976 | 791,735 | 1,440 |
| 5 FLUE GAS CLEANUP | | | | | | | | | | | | | |
| 5.1 FGD System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.2 Other FGD | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Flexible Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 5.3 Baghouse & Accessories | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.4 Other Particulate Removal Materials | 10,241 | | 4,315 | | 14,556 | 10% | 1,401 | 0% | | 10% | 1,596 | 17,553 | 32 |
| 5.5 Gypsum Dewatering | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.6 Mercury Removal | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 5.9 Mercury Removal System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| SUBTOTAL 5. | 10,241 | | 4,315 | | 14,556 | 10% | 1,401 | 0% | | 10% | 1,596 | 17,553 | 32 |
| 5B CO2 REMOVAL & COMPRESSION | | | | | | | | | | | | | |
| 5B.1 CO2 Condensing Heat Exchanger | 7,272 | | 607 | | 7,879 | 10% | 789 | 0% | | 15% | 1,300 | 9,967 | 18 |
| 5B.2 CO2 Compression & Drying | 79,133 | | 64,746 | | 143,879 | 10% | 14,389 | 0% | | 20% | 31,653 | 189,921 | 345 |
| SUBTOTAL 5B. | 86,405 | 0 | 65,353 | 0 | 151,758 | 10% | 15,177 | 0% | 0 | 20% | 32,952 | 199,888 | 363 |
| 6 COMBUSTION TURBINE/ACCESSORIES | | | | | | | | | | | | | |
| SUBTOTAL 6. | $0 | $0 | $0 | $0 | $0 | | $0 | | $0 | | $0 | $0 | 0.0 |
| 7 HRSG | | | | | | | | | | | | | |
| 7.1 Flue Gas Recycle Heat Exchanger | 47,476 | | 3,965 | | 51,441 | 10% | 5,144 | 0% | | 15% | 8,488 | 65,073 | 118 |
| 7.2 HRSG Accessories | | | | | 0 | | | | | | | 0 | 0 |
| 7.3 Ductwork | 10,556 | | 6,781 | | 17,338 | 9% | 1,514 | 0% | | 15% | 2,828 | 21,680 | 39 |
| 7.4 Stack | 1,688 | | 988 | | 2,675 | 10% | 256 | 0% | | 10% | 293 | 3,224 | 6 |
| 7.9 Duct & Stack Foundations | | 915 | 1,039 | | 1,954 | 9% | 182 | 0% | | 20% | 427 | 2,563 | 5 |
| SUBTOTAL 7. | 59,720 | 915 | 12,772 | 0 | 73,407 | 10% | 7,096 | 0% | 0 | 15% | 12,035 | 92,539 | 168 |
| 8 STEAM TURBINE GENERATOR | | | | | | | | | | | | | |
| 8.1 Steam TG & Accessories | 87,077 | 0 | 11,565 | | 98,642 | 10% | 9,445 | 0% | | 10% | 10,808 | 118,895 | 216 |
| 8.2 Turbine Plant Auxiliaries | 588 | 0 | 1,258 | | 1,846 | 10% | 179 | 0% | | 10% | 202 | 2,227 | 4 |
| 8.3a Condenser & Auxiliaries | 7,297 | 0 | 4,402 | | 11,698 | 9% | 1,111 | 0% | | 10% | 1,282 | 14,091 | 26 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Flexible Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 8.3b Air Cooled Condenser | 0 | 0 | 0 | | 0 | | 0 | | | | 0 | 0 | 0 |
| 8.4 Steam Piping | 34,444 | 0 | 16,984 | | 51,427 | 8% | 4,292 | 0% | | 15% | 8,358 | 64,078 | 117 |
| 8.9 TG Foundations | 0 | 1,838 | 2,904 | | 4,742 | 9% | 446 | 0% | | 20% | 1,038 | 6,226 | 11 |
| SUBTOTAL 8. | 129,405 | 1,838 | 37,112 | 0 | 168,355 | 9% | 15,473 | 0% | 0 | 12% | 21,688 | 205,517 | 374 |
| 9 COOLING WATER SYSTEM | | | | | | | | | | | | | |
| 9.1 Cooling Towers | 10,775 | | 3,356 | | 14,131 | 9% | 1,341 | 0% | | 10% | 1,547 | 17,019 | 31 |
| 9.2 Circulating Water Pumps | 3,162 | | 301 | | 3,463 | 9% | 297 | 0% | | 10% | 376 | 4,136 | 8 |
| 9.3 Circ. Water System Auxiliaries | 889 | | 119 | | 1,009 | 9% | 95 | 0% | | 10% | 110 | 1,214 | 2 |
| 9.4 Circ. Water Piping | | 7,055 | 6,837 | | 13,892 | 9% | 1,280 | 0% | | 15% | 2,276 | 17,448 | 32 |
| 9.5 Make-up Water System | 700 | | 934 | | 1,635 | 10% | 155 | 0% | | 15% | 269 | 2,059 | 4 |
| 9.6 Component Cooling Water Sys | 704 | | 560 | | 1,264 | 9% | 119 | 0% | | 15% | 207 | 1,590 | 3 |
| 9.9 Circ. Water System Foundations & Structures | | 4,194 | 6,664 | | 10,858 | 9% | 1,022 | 0% | | 20% | 2,376 | 14,256 | 26 |
| SUBTOTAL 9. | 16,231 | 11,249 | 18,771 | 0 | 46,251 | 9% | 4,310 | 0% | 0 | 14% | 7,161 | 57,723 | 105 |
| 10 ASH/SPENT SORBENT HANDLING SYS | | | | | | | | | | | | | |
| 10.1 Rotary Ash Coolers | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.2 Cyclone Ash Letdown | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.3 HGCU Ash Letdown | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.4 High Temperature Ash Piping | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.5 Reducer Baghouse Ash Recycle System | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |
| 10.6 Ash Storage Silos | 1,087 | | 3,348 | | 4,435 | 10% | 432 | 0% | | 10% | 486 | 5,353 | 10 |
| 10.7 Ash Transport & Feed Equipment | 7,033 | | 7,204 | | 14,237 | 9% | 1,347 | 0% | | 10% | 1,558 | 17,143 | 31 |
| 10.8 Misc. Ash Handling Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 10% | $0 | $0 | 0 |

| Project: Montana Rosebud PRB<br>TOTAL PLANT COST SUMMARY<br>Case: SPOC Flexible Case<br>Plant Size: 550 MWnet<br>Cost Base: January 2019 ($x1000) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acct No. Item/Description | Equipment Cost | Material | Labor | | Bare Erected Cost $ | Eng'g CM H.O.& Fee | | Process Contingency | | Project Contingency | | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
| | | Cost | Direct | Indirect | | % | Total | % | Total | % | Total | | |
| 10.9 Ash/Spent Sorbent Foundation | | 259 | 303 | | 562 | 9% | 52 | 0% | | 20% | 123 | 738 | 1 |
| SUBTOTAL 10. | 8,120 | 259 | 10,855 | 0 | 19,235 | 10% | 1,831 | 0% | 0 | 10% | 2,168 | 23,234 | 42 |
| 11 ACCESSORY ELECTRIC PLANT | | | | | | | | | | | | | |
| 11.1 Generator Equipment | 434 | 0 | 71 | | 505 | 9% | 47 | 0% | | 7% | 41 | 593 | 1 |
| 11.2 Station Service Equipment | 7,375 | 0 | 2,423 | | 9,798 | 10% | 937 | 0% | | 7% | 805 | 11,540 | 21 |
| 11.3 Switchgear & Motor Control | 8,479 | 0 | 1,441 | | 9,920 | 9% | 918 | 0% | | 10% | 1,083 | 11,921 | 22 |
| 11.4 Conduit & Cable Tray | 0 | 5,316 | 18,380 | | 23,696 | 10% | 2,267 | 0% | | 15% | 3,895 | 29,858 | 54 |
| 11.5 Wire & Cable | 0 | 10,031 | 19,364 | | 29,394 | 8% | 2,477 | 0% | | 15% | 4,781 | 36,653 | 67 |
| 11.6 Protective Equipment | 309 | 0 | 1,054 | | 1,363 | 10% | 133 | 0% | | 10% | 150 | 1,646 | 3 |
| 11.7 Standby Equipment | 451 | 0 | 10 | | 462 | 9% | 44 | 0% | | 10% | 50 | 556 | 1 |
| 11.8 Main Power Transformers | 1,082 | 0 | 33 | | 1,115 | 8% | 85 | 0% | | 10% | 120 | 1,320 | 2 |
| 11.9 Electrical Foundations | 0 | 60 | 147 | | 207 | 9% | 19 | 0% | | 20% | 45 | 272 | 0 |
| SUBTOTAL 11. | 18,131 | 15,407 | 42,922 | 0 | 76,459 | 9% | 6,927 | 0% | 0 | 13% | 10,971 | 94,359 | 172 |
| 12 INSTRUMENTATION & CONTROL | | | | | | | | | | | | | |
| 12.1 PC Control Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.2 Combustion Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.3 Steam Turbine Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.4 Other Major Component Control | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.5 Signal Processing Equipment | $0 | $0 | $0 | $0 | $0 | 9.0% | $0 | 0% | $0 | 0% | $0 | $0 | 0 |
| 12.6 Control Boards, Panels, & Racks | 683 | | 409 | | 1,092 | 10% | 104 | 0% | | 15% | 179 | 1,376 | 3 |
| 12.7 Distributed Control System Equipment | 6,898 | | 1,205 | | 8,103 | 10% | 772 | 0% | | 10% | 888 | 9,764 | 18 |
| 12.8 Instrument Wiring & Tubing | 3,740 | | 7,419 | | 11,159 | 9% | 950 | 0% | | 15% | 1,816 | 13,925 | 25 |
| 12.9 Other I & C Equipment | 1,949 | | 4,423 | | 6,372 | 10% | 621 | 0% | | 10% | 699 | 7,692 | 14 |

Project: Montana Rosebud PRB
TOTAL PLANT COST SUMMARY
Case: SPOC Flexible Case
Plant Size: 550 MWnet
Cost Base: January 2019 ($x1000)

| Acct No. Item/Description | Equipment Cost | Material Cost | Labor Direct | Labor Indirect | Bare Erected Cost $ | Eng'g CM H.O.& Fee % | Eng'g CM H.O.& Fee Total | Process Contingency % | Process Contingency Total | Project Contingency % | Project Contingency Total | TOTAL BASE SPOC PLANT Cost | BASE SPOC COST $/kW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SUBTOTAL 12. | 13,270 | 0 | 13,456 | 0 | 26,726 | 9% | 2,448 | 0% | 0 | 12% | 3,582 | 32,756 | 60 |
| 13 IMPROVEMENTS TO SITE | | | | | | | | | | | | | |
| 13.1 Site Preparation | | 63 | 1,258 | | 1,321 | 10% | 130 | 0% | | 20% | 290 | 1,742 | 3 |
| 13.2 Site Improvements | | 2,089 | 2,595 | | 4,684 | 10% | 460 | 0% | | 20% | 1,028 | 6,172 | 11 |
| 13.3 Site Facilities | 3,744 | | 3,693 | | 7,437 | 10% | 730 | 0% | | 20% | 1,633 | 9,800 | 18 |
| SUBTOTAL 13. | 3,744 | 2,152 | 7,545 | 0 | 13,441 | 10% | 1,320 | 0% | 0 | 20% | 2,951 | 17,713 | 32 |
| 14 BUILDINGS & STRUCTURES | | | | | | | | | | | | | |
| 14.1 Boiler Building | | 10,986 | 9,662 | | 20,648 | 9% | 1,854 | 0% | | 15% | 3,376 | 25,878 | 47 |
| 14.2 Turbine Building | | 14,414 | 13,434 | | 27,848 | 9% | 2,508 | 0% | | 15% | 4,553 | 34,909 | 63 |
| 14.3 Administration Building | | 716 | 757 | | 1,473 | 9% | 133 | 0% | | 15% | 241 | 1,847 | 3 |
| 14.4 Circulation Water Pumphouse | | 234 | 186 | | 420 | 9% | 37 | 0% | | 15% | 68 | 526 | 1 |
| 14.5 Water Treatment Buildings | | 652 | 537 | | 1,189 | 9% | 106 | 0% | | 15% | 194 | 1,489 | 3 |
| 14.6 Machine Shop | | 479 | 321 | | 800 | 9% | 71 | 0% | | 15% | 131 | 1,002 | 2 |
| 14.7 Warehouse | | 325 | 326 | | 651 | 9% | 59 | 0% | | 15% | 106 | 816 | 1 |
| 14.8 Other Buildings & Structures | | 265 | 226 | | 491 | 9% | 44 | 0% | | 15% | 80 | 615 | 1 |
| 14.9 Waste Treating Building & Str. | | 494 | 1,500 | | 1,994 | 9% | 189 | 0% | | 15% | 328 | 2,511 | 5 |
| SUBTOTAL 14. | 0 | 28,565 | 26,949 | 0 | 55,514 | 9% | 5,002 | 0% | 0 | 15% | 9,076 | 69,594 | 127 |
| TOTAL COST | 925,197 | 81,303 | 547,736 | 0 | 1,554,236 | 9% | 146,988 | 3% | 86,481 | 14% | 242,225 | 2,029,947 | 3,691 |

**Table 7-15**
**O&M Costs for All Cases**

| | NETL Baseline Cases | | | SPOC Cases | |
|---|---|---|---|---|---|
| | **S12A** | **S12B** | **S12F** | **Baseline** | **Flexible** |
| Total Operating Jobs per Shift | 14 | 16 | 14 | 14 | 14 |
| **Fixed O&M Costs** | | | | | |
| Administrative & Support Labor | 3,994 | 5,876 | 5,523 | 5,488 | 5,577 |
| Operating Labor Costs | 6,476 | 7,540 | 6,476 | 6,476 | 6,476 |
| Maintenance Labor Costs | 9,500 | 15,965 | 15,616 | 15,476 | 15,834 |
| Property Taxes and Insurance | 26,468 | 46,697 | 44,927 | 44,527 | 44,559 |
| **Total Fixed O&M Costs, $1000/yr** | **46,438** | **76,060** | **72,541** | **71,967** | **73,447** |
| **Variable O&M Costs** | | | | | |
| Maintenance Material Cost | 14,250 | 23,947 | 23,423 | 23,214 | 23,752 |
| Consumables | | | | | |
| Bottom Ash Disposal | 988 | 1,424 | 1,229 | 1,103 | 1,103 |
| Chemicals | 5,918 | 14,178 | 7,158 | 3,194 | 3,194 |
| Fly Ash Disposal | 5,828 | 8,338 | 7,322 | 6,572 | 6,572 |
| Water | 1,131 | 3,264 | 4,133 | 4,004 | 4,004 |
| Other Consumables | 754 | 1,087 | 0 | 0 | 0 |
| **Total Variable O&M Costs, $1000/yr** | **28,870** | **52,238** | **43,265** | **38,087** | **38,087** |

**Table 7-16**
**First-Year Power Cost, LCOE, TPC, TOC, TASC, and $CO_2$ Captured and Avoided Cost for All Cases**

| **Case** | **S12A** | **S12B** | **S12F** | **Base-SPOC** | **Flex-SPOC** |
|---|---|---|---|---|---|
| Net Plant Output, MW | 550 | 550 | 550 | 550 | 550 |
| Efficiency, % | 38.8 | 27.0 | 31.0 | 34.5 | 34.5 |
| % Capture | 0 | 90 | 90 | 90 | 90 |
| $CO_2$ Captured, tonne/MW-hr (net) | 0.000 | 1.107 | 0.965 | 0.864 | 0.865 |
| $CO_2$ Emitted, tonne/MW-hr (net) | 0.858 | 0.123 | 0.107 | 0.095 | 0.095 |
| Fuel Type | PRB | PRB | PRB | PRB | PRB |
| Fuel Cost, $/MMBtu | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 |
| **Total Plant Cost, Total Overnight Cost, and Total As Spent Capital Cost** | | | | | |
| TPC, $/kW | 2,406 | 4,243 | 4,084 | 3,634 | 3,691 |
| TOC, $/kW | 2,936 | 5,174 | 4,967 | 4,425 | 4,494 |
| TASC, $/kW | 3,329 | 5,898 | 5,662 | 5,044 | 5,124 |
| **Power and $CO_2$ Costs** | | | | | |
| Capital, $/MW-hr | 45.7 | 86.2 | 82.7 | 73.7 | 74.8 |
| Fixed O&M, $/MW-hr | 11.3 | 18.6 | 17.7 | 16.0 | 16.2 |
| Variable O&M, $/MW-hr | 7.0 | 12.8 | 10.6 | 8.7 | 8.8 |
| Fuel Cost, $/MW-hr | 10.1 | 14.5 | 12.7 | 11.4 | 11.4 |
| $CO_2$ T&S Cost, $/MW-hr | 0.0 | 11.1 | 9.6 | 8.7 | 8.7 |
| First-Year Power Cost, $/MW-hr | 74.3 | 143.1 | 133.3 | 118.4 | 119.9 |
| Levelized Cost of Electricity, $/MW-hr | 94.2 | 181.4 | 169.0 | 150.1 | 152.0 |
| Cost of $CO_2$ Avoided, $/tonne | Base | 94 | 79 | 58 | 60 |
| Cost of $CO_2$ Captured, $/tonne | Base | 52 | 51 | 41 | 43 |

* "Cost and Performance of Low-Rank Pulverized Coal Oxycombustion Energy Plants: Final Report," DOE/NETL-401/093010, September 2010. † Updated Costs (June 2011 Basis) for Selection Bituminous Baseline Cases, DOE/NETL-341/082312, August 2012

## Comparison of Cost Results

The following section provides a summary of the cost results presented in a format where comparisons can more easily be made.

### *First-Year Power Costs and LCOE*

First-year power costs were calculated using the method prescribed by NETL, which uses this as its primary economic metric. The first-year power cost is the revenue received by the generator per net MW-hr during the first year of operation, if the first year of operation COE escalates at a nominal annual rate equal to the general inflation rate (i.e., remains constant in real terms over the operational period of the plant). The LCOE is the revenue received by the generator per net MW-hr during the first year of operation, if the first year of operation COE escalates at a nominal annual rate of 0% (i.e., remains constant in nominal terms over the operation period of the plant).

Figure 7-3 compares the first-year power costs, broken down into their components, for the NETL baseline cases and the SPOC baseline and flexible cases.

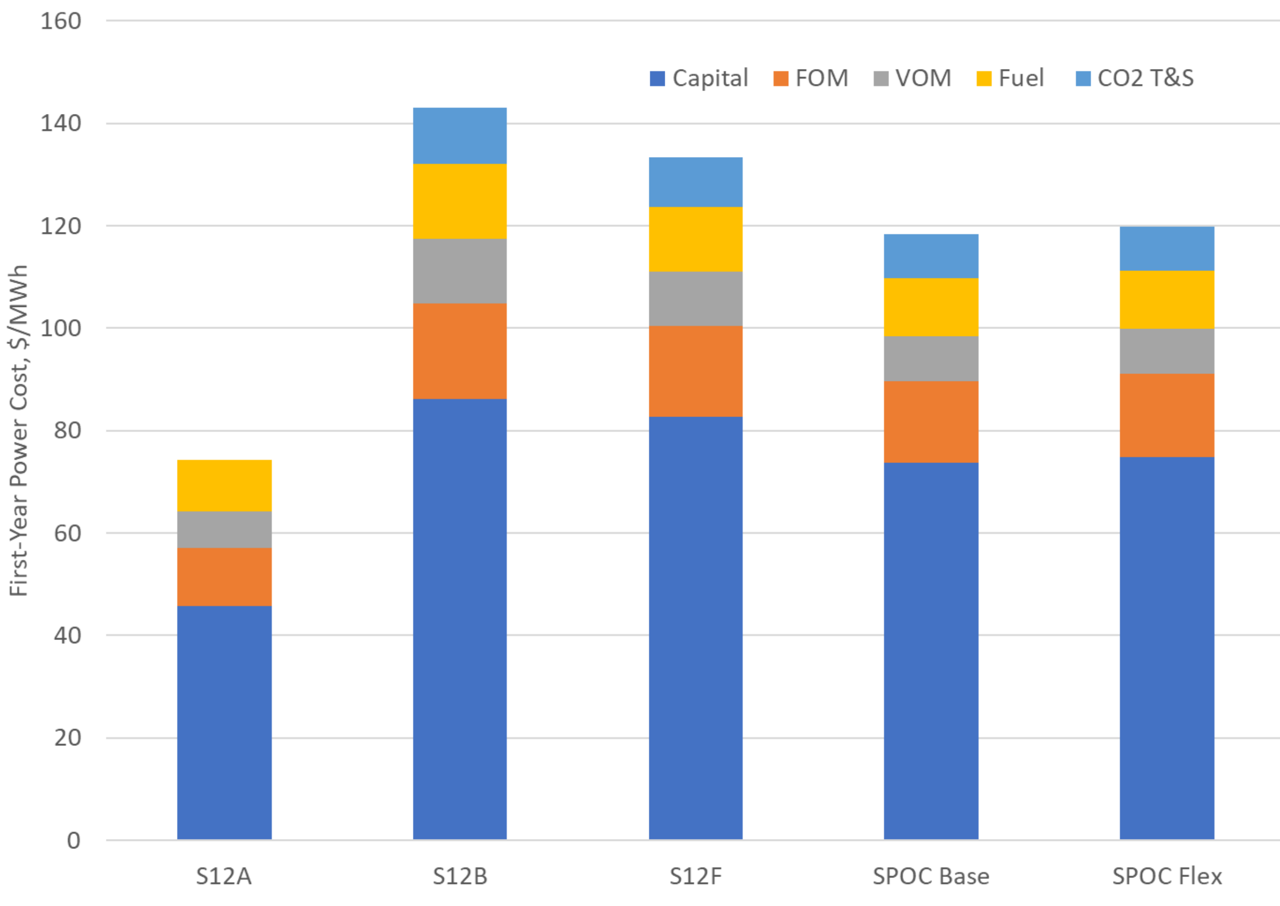


**Figure 7-3**
**First-Year Power Costs for All Cases**

Figure 7-4 compares the LCOE for the base and test cases.

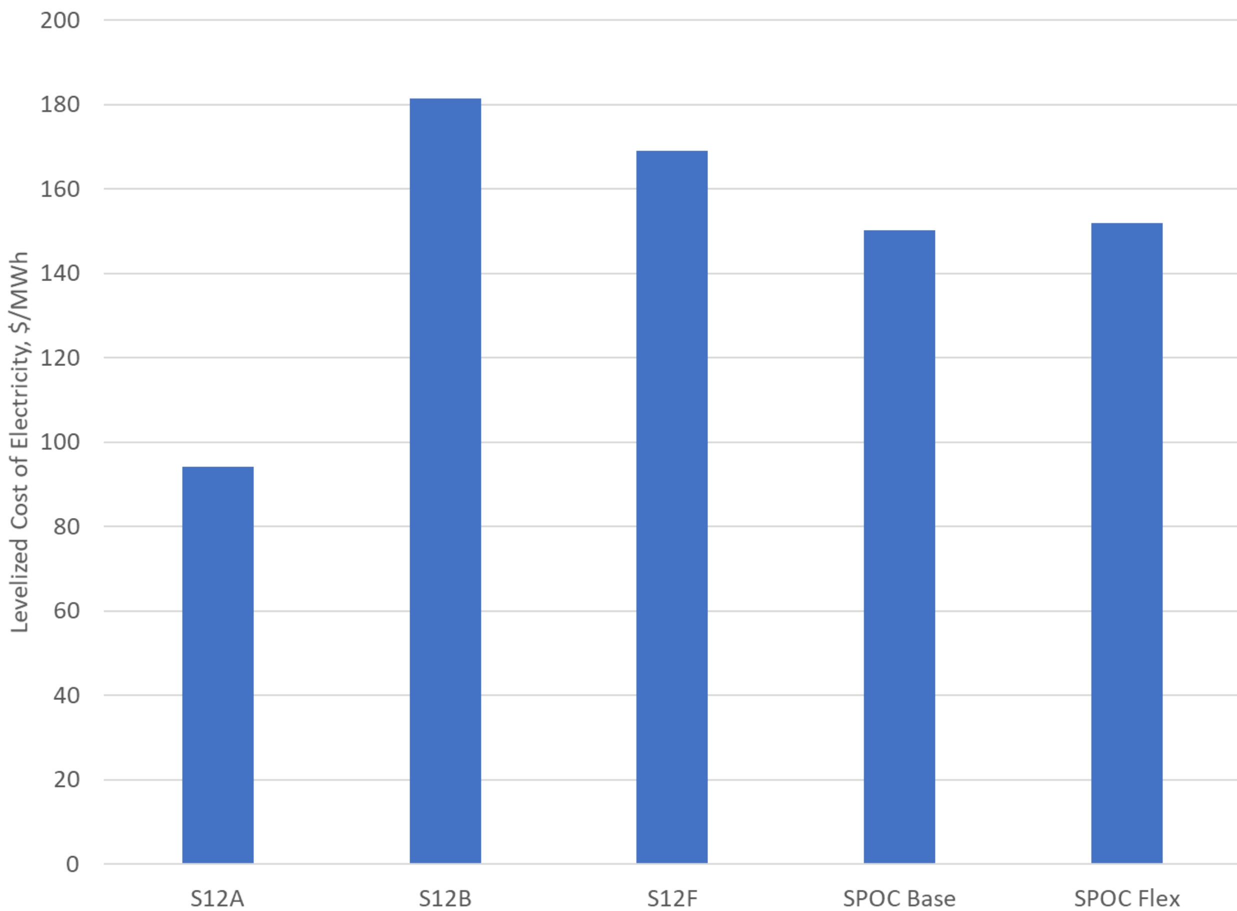


**Figure 7-4**
**LCOE for All Cases**

### *Cost of $CO_2$ Avoided and Captured*

Figure 7-5 shows the $CO_2$ avoided and captured costs for the baseline and flexible SPOC cases. The costs are relative to appropriate NETL baseline cases that capture $CO_2$. Note that the cost of $CO_2$ captured does not include T&S.

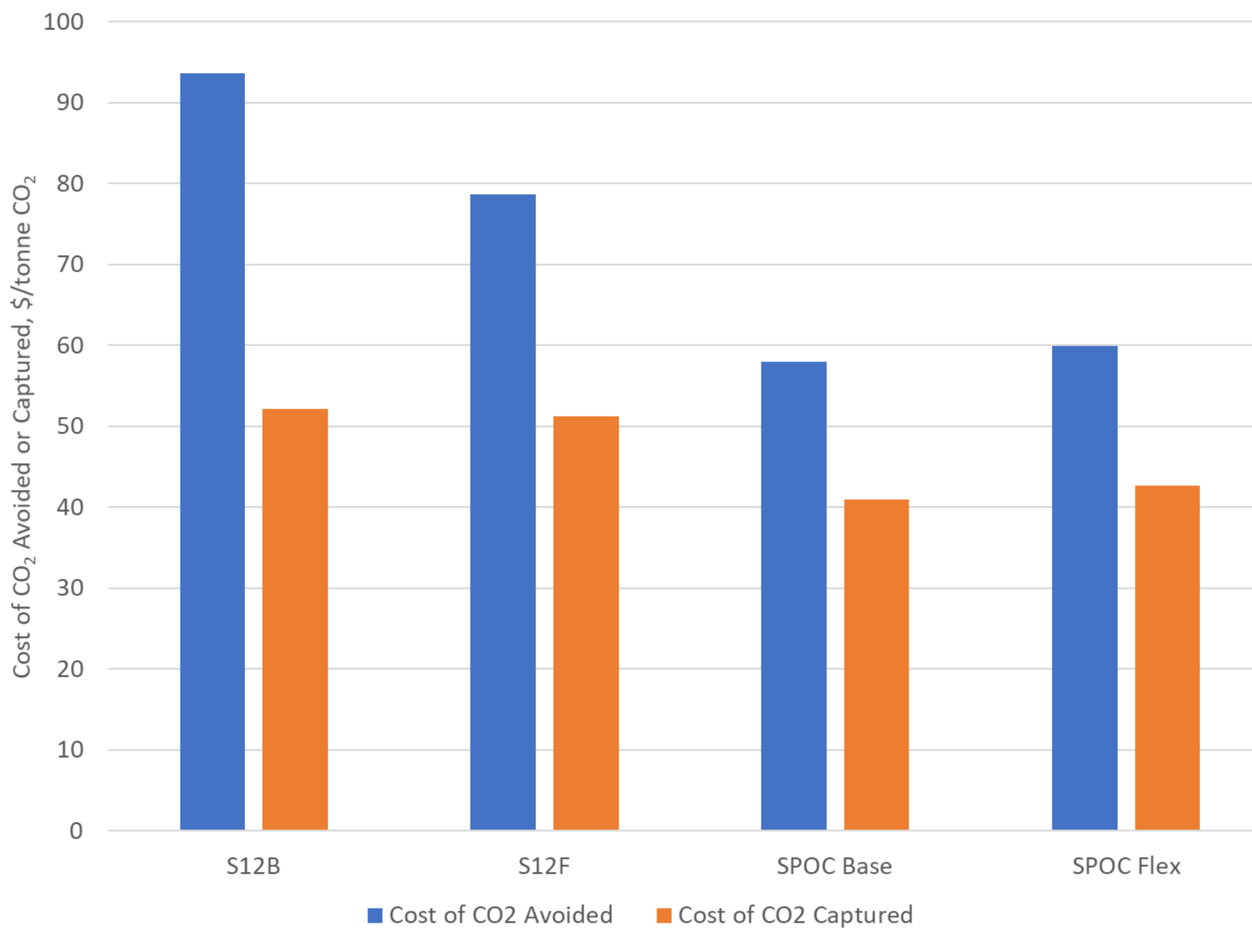


**Figure 7-5**
**$CO_2$ Avoided and Captured Costs for All Capture Cases**

## Flexibility Costs

Although the flexible ASU does add $57/kW to the plant cost, this is only a 1.6% increase on the baseline case, and the efficiency improvements at loads below 50% are significant. Subsequently, depending on the plant load-profile expectation, the flexible ASU would be beneficial if the plant spent a portion of the operating life below 50% load. This kind of operating profile is likely to be required for all fossil plants when more intermittent renewables are installed on the grid, particularly solar power that can be predicted ahead of time, allowing for appropriate pricing signals to be incorporated into the diurnal cycle.

# 8
# CONCLUSIONS AND RECOMENDATIONS

The goal of this chapter is to summarize the results of the project activities and to make recommendations for the next steps in the development of the SPOC technology.

## SPOC Process

The SPOC concept has undergone significant evolution throughout the execution of this project, following review of the constructability of the SPOC boiler stages, its ability to operate at part loads, and strategies for flexible pressurized oxygen delivery. A two-pass PV arrangement for each stage allows for road transportation to be feasible at the 400 MWth scale. This allows a 4-stage SPOC system to deliver 550 MWe with a high degree of modular factory manufacture, ensuring economic efficiency in the manufacture and construction process is attainable at this scale due to lower people hours and improved quality control over onsite construction methods.

Additionally, conventional heat transfer methods have been applied to the convective stages to ensure that heat is delivered to each of the water/steam circuits in appropriate proportions throughout the load range. Allowing bypassing of stages ensures that a significant degree of turndown is achievable on the steam turbine without incurring stage combustion turndown beyond 50%. Testing of the SPOC combustion showed that ultra-low firing rates are also possible, introducing the possibility of being able to sustain stages in a warm-standby condition in readiness for rapid ramping.

## Pilot Plant Testing

The 100 kWth pilot system represents a single SPOC stage using synthetic FGR and a down-fired, co-axial low-mixing flow design. The unit has been designed to replicate the environment where the main combustion reactions occur in the first 5 seconds of the full-scale SPOC boiler arrangement. Heated sample lines were installed to facilitate the evaluation of coal particle composition throughout the combustion process as well as the final carbon-in-ash levels at the outlet, allowing comparison with CFD modeling. Additionally, heat flux measurements were conducted to inform the full-scale design requirements. Testing was initially carried out at atmospheric pressure with methane support followed by high pressure operation on a coal only flame. Carbon monoxide and carbon-in-ash measurements showed that complete combustion was possible with ultra-low excess oxygen at 1 vol % in the product flue gas. This allowed the full-scale models to be calculated based on this level of excess oxygen, improving the performance of the system as lower feed oxygen is produced in the air separation unit (ASU), saving auxiliary power.

## Performance Summary

The SPOC process can achieve higher overall plant efficiency compared with atmospheric-pressure oxy-combustion due to heat recovery from the flue gases prior to $CO_2$ purification. The additional heat recovery delivers an improved steam turbine heat rate, which in turn allows for a lower overall steam flow requirement to deliver the required gross power. As lower steam generation requirements yield a lower fuel firing rate, additional auxiliary power savings can also be realized from reduced fuel handling, oxygen production, and $CO_2$ purification.

## Flexibility and Turndown

The Boiler and ASU OEM review of the SPOC process concluded that the system could deliver the targeted 6% load change per minute target. Additionally, with the ability to bypass stages, ultra-low load operation is feasible. Although the baseline case showed low load operation was possible, the process was inefficient at low load due to ASU compressor turndown limitations. The flexible-SPOC arrangement that had a combination of smaller compressors and shared manifolds for the air delivery to the cold boxes can operate at lower loads efficiently and so greatly improved the low-load performance.

## Economic Analysis

An economic assessment was carried out for both the baseline and flexible SPOC cases. The results show that both cases achieve a lower first-year power cost that the NETL baseline cases (with the flexible SPOC case being slightly higher due to the compounded impact of higher capital costs and lower efficiency at full load).

Because of the improved efficiency for the SPOC plants over the NETL baseline cases, the cost of $CO_2$ avoided is lower; however, the cost of $CO_2$ captured is slightly higher for SPOC vs. the atmospheric oxy-combustion case as lower $CO_2$ quantities are generated (and hence captured) and so this smaller quantity in effect amplifies the specific cost of capture.

## R&D Recommendations

Staged, pressurized oxy-combustion, while a promising technology, is a relatively recent concept and, as such, operability issues of combustor design and steam-side integration for such systems at a scale relevant to commercial deployment have not been evaluated. WUSTL has conducted extensive small pilot-scale (100 kWth) research to understand and advance pressurized oxy-combustion processes, including investigation of combustion and flame characteristics, radiative heat flux, burner operability, turn down, char burnout, ash characteristics, water-wash column operation, etc. for pressurized oxy-combustion systems. Nonetheless, at this stage in the development of the SPOC process, what is needed is a large-scale pilot plant that can serve to study pressurized oxy-combustion systems and components at a scale commensurate with the maturity of the technology.

A scale of 10 MWth, which includes steam-side integration and two stages would yield essential information with respect to heat transfer characteristics both in the radiative and convective sections of the pressure vessels, and the ability to operate the fuel staging process. In addition, while modeling results indicate that combustion and flame characteristics improve with scale, direct studies of the combustor at this scale will ensure that the models can be relied upon for scale up to commercial scale. Furthermore, a detailed analysis must be performed to understand the scaling aspects of key components and systems, including the DCC.

# A

## SPOC CONCEPT RISK MATRIX

**Table A-1**
**SPOC Concept Review Risk Matrix**

| Doosan Babcock | | | SPOC Concept Review Risk Matrix | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Risk Ref.** | **Discipline** | **Design Aspect / Consideration as Currently Proposed** | **Identified Risks** | **Possible Consequence(s)** | **Risk : Initial** | **Mitigation** | **Risk : Resultant** | **Further Mitigation** | **Risk : Resultant** |
| **CR-01** | - Layout<br>- Mechanical | Heating Surface Headers and Support | - Proposed concentric heating surface contained within each SPOC PV presents several significant mechanical design challenges.<br><br>**Risk: Complexity of design makes SPOC process uneconomic.** | - Costly solution to ensure structural and mechanical integrity. Particularly with respect to differential expansion and resistance to vibration.<br>- Location of headers and vessel penetrations a significant design challenge. | H | - Implement an alternate SPOC boiler configuration. A "two-pass" configuration comprising downward-fired radiant vessel and "upward-flow" convective boiler arrangement with heating surface arranged in cross flow. | M | - Carry out detailed engineering design.<br>- Manufacture and practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |
| **CR-02** | - Fuels and Chemistry<br>- Process and Systems<br>- Layout | Slagging and Fouling | - Extent of slagging and fouling within each SPOC PV and impact on design of pressure parts is not known. Concentric heating surface design proposed indicates a tight tube pitching.<br><br>**Risk: Potential for excessive slagging and fouling resulting in impaired process performance.** | - Excessive slagging and fouling will impact effectiveness of heating surfaces and hence the amount of heating surfaces required. In addition, excessive fouling and slagging could lead to significant gas-side pressure drops resulting in further operational issues and decreased availability/increased maintenance. | H | - Apply OEM design rules for tube pitching to minimize chance of slagging and fouling of heating surfaces.<br>- Include for excess effective heat transfer surface.<br>- Implement an alternate SPOC boiler configuration. A "two-pass" configuration comprising downward-fired radiant vessel and "upward-flow" convective boiler arrangement with heating surface arranged in cross flow allows a degree of ash/slag management before convective heating surface. | M | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |
| **CR-03** | - Fuels and Chemistry<br>- Process and Systems | Burner/Combustor Design | - Burner/combustor as proposed has significant thermal input. Performance at 550 MWe scale unknown.<br><br>**Risk: Burner/combustor performance at scale unknown resulting in significant differences in expected performance.** | - Unsuitable combustion performance obtained (particularly in later SPOC stages).<br>- An unstable flame. | H | - CFD performed and validated against 100 kWth rig data for all anticipated SPOC stage combustion conditions.<br>- Consideration of multiple burner arrangement to be made. | H | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |

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# SPOC Concept Review Risk Matrix

| Risk Ref. | Discipline | Design Aspect / Consideration as Currently Proposed | Identified Risks | Possible Consequence(s) | Risk : Initial | Mitigation | Risk : Resultant | Further Mitigation | Risk : Resultant |
|---|---|---|---|---|---|---|---|---|---|
| **CR-04** | - Layout<br>- Mechanical<br>- Process and Systems | Identical Vessels | - From a manufacturing, sparing, and economics viewpoint, having all vessels within the SPOC concept system identical in terms of sizing and heating surface would be beneficial. However, to provide the steam duty and flexibility of the system, it is unlikely that this will be possible.<br><br>**Risk: Higher CAPEX due to bespoke designs for each stage.** | - Increased vessel CAPEX cost.<br>- Increased design complexity. | L | - Ensure as much commonality as practical.<br>- Carry out detailed engineering design to minimize CAPEX, while ensuring flexible operation. | L | | |
| **CR-05** | - Fuels and Chemistry<br>- Process and Systems | Fuel Handling and Delivery System | - Novel SPOC concept requires development of a robust fuel delivery process.<br><br>**Risk: Unknown issues of application of gasifier fuel handling technology to novel SPOC concept.** | - Failure in fuel delivery system will be detrimental to performance, reliability, and availability.<br>- Fuel surface moisture has potential to cause issues with solids handling. | M | - Fuel delivery system proposed via lock-hopper arrangement. Process is analogous with commercially available gasifier technology, thus reducing potential technical risks.<br>- Surface drying of fuel by ASU nitrogen waste gas already proposed – requirements and fuel storage need to be considered during detailed design. | M | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |
| **CR-06** | - Fuels and Chemistry<br>- Process and Systems | Fuel Selection | - Montana Rosebud PRB selected as the design fuel.<br><br>**Technical Risk: Slagging and fouling characteristics less favorable than higher-rank coal.**<br>**Commercial Risk: Process economics likely to be considerably less favorable than a higher-rank coal.** | - Lower-rank coal has significant effect on plant sizing (plant ~7% greater than Illinois #6 coal from a heat input perspective alone).<br>- Slagging/fouling potential is greater, resulting in a need for increased tube pitching and online cleaning systems (soot blowers) and therefore cavities that increase PV sizing, and hence CAPEX, further.<br>- The increased flue gas flow results in increased auxiliary power and hence OPEX. | M | - Propose a higher-rank coal, such as Illinois #6, as the design coal. | L | | |

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# SPOC Concept Review Risk Matrix

| Risk Ref. | Discipline | Design Aspect / Consideration as Currently Proposed | Identified Risks | Possible Consequence(s) | Risk : Initial | Mitigation | Risk : Resultant | Further Mitigation | Risk : Resultant |
|---|---|---|---|---|---|---|---|---|---|
| **CR-07** | - Process and Systems | Particulate Removal | - Dust removal required at relatively high temperature compared to conventional power plant dust removal technologies.<br><br>**Risk: Requirement for high-temperature clean up vs. more conventional particulate removal technology.** | - Failure in particulate removal system will be detrimental to performance, reliability, and availability.<br>- In proposed concept, particulate removal from flue gas is to be carried out by candle filters. Ceramic candle filters are susceptible to breakage and hence have a negative impact on performance and availability.<br>- Potential for excessive pressure drop through filter blockage. | M | - Both metal and ceramic candle filter elements have been utilized in industry and are commercially proven. Capture efficiency much greater than hot electro-static precipitators.<br>- Potential to pair candle filters with an upstream cyclone separator to optimize cost/removal efficiency/equipment sizing.<br>- Implementation of metallic rather than ceramic candle filters likely to increase availability at the expense of CAPEX. | M | - CAPEX/OPEX (auxiliary power/DCC water treatment costs) vs. removal efficiency needs to be considered in determining optimum solution through detailed engineering design. | L |
| **CR-08** | - Process and Systems | Ash Handling | - Novel SPOC concept requires development of a robust ash handling process.<br><br>**Risk: Unknown issues of application of gasifier ash handling technology to novel SPOC concept.** | - Failure in ash handling system will be detrimental to performance, reliability, and availability.<br>- In proposed concept, flue gas is exposed to concentrically arranged convective heating surface prior to any ash removal resulting in increased fouling, slagging, and erosion potential. | M | - Wet bottom proposed for ash/slag removal. Process analogous with commercially available gasifier technology, thus reducing potential technical risks.<br>- Ash/slag removed via lock-hopper arrangement. Again, process is analogous with commercially available gasifier technology, thus reducing potential technical risks.<br>- Implement an alternate SPOC boiler configuration. A "two-pass" configuration comprising downward-fired radiant vessel and "upward-flow" convective boiler arrangement with heating surface arranged in cross flow allows a degree of ash/slag management before convective heating surface. | L | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |

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# SPOC Concept Review Risk Matrix

| Risk Ref. | Discipline | Design Aspect / Consideration as Currently Proposed | Identified Risks | Possible Consequence(s) | Risk : Initial | Mitigation | Risk : Resultant | Further Mitigation | Risk : Resultant |
|---|---|---|---|---|---|---|---|---|---|
| **CR-09** | - Fuels and Chemistry<br>- Process and Systems | Slagging and Fouling Management | - Extent of slagging and fouling within each SPOC PV may require the use of online cleaning system (e.g., sootblowers). Concentric heating surface design not conducive to typical online cleaning methods.<br><br>**Risk: Inability to manage slagging and fouling, impairing heating surface effectiveness.** | - Excessive slagging and fouling will impact effectiveness of heating surfaces and hence the amount of heating surfaces required. In addition, excessive fouling and slagging could lead to significant gas-side pressure drops resulting in further operational issues and decreased availability/increased maintenance. | H | - Include excess effective heat transfer surface.<br>- Implement an alternate SPOC boiler configuration. A "two-pass" configuration comprising downward-fired radiant vessel and "upward-flow" convective boiler arrangement with heating surface arranged in cross flow allows a degree of ash/slag management before convective heating surface. In addition, it allows for cavities to be incorporated, subject to vessel height limitations, for the installation of typical online cleaning methods. | M | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |
| **CR-10** | - Fuels and Chemistry<br>- Process and Systems<br>- Mechanical | Erosion and Corrosion | - Extent of anticipated erosion and corrosion through the SPOC system is not known.<br><br>**Risk: Design basis for erosion and corrosion is not robust enough resulting in under/over specification of equipment.** | - Adverse impact of erosion and corrosion on pressure parts and non-pressure parts inside the SPOC PV resulting in system performance issues and decreased availability/increased maintenance. | H | - Provide OEM analysis to determine propensity for erosion and corrosion.<br>- Apply OEM design rules and experience to make recommendations for acceptable materials of construction. | M | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | L |
| **CR-11** | - Process and Systems | Boiler Design (Pressure Parts) | - 100 kWth coal combustion test facility has no boiler heating surface and therefore model performance predictions cannot be validated.<br><br>**Risk: Design basis for boiler heating surface not validated resulting in under/over performance of boiler pressure parts.** | - Lack of a means to validate data may result in significant under or over estimates of boiler heating surface requirements. | H | - Apply OEM knowledge and experience to OEM design tools to predict plant performance. However, boiler performance predictions remain invalidated for novel SPOC application. | H | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | M |

Doosan Babcock

# SPOC Concept Review Risk Matrix

| Risk Ref. | Discipline | Design Aspect / Consideration as Currently Proposed | Identified Risks | Possible Consequence(s) | Risk : Initial | Mitigation | Risk : Resultant | Further Mitigation | Risk : Resultant |
|---|---|---|---|---|---|---|---|---|---|
| **CR-12** | - Process and Systems | Process Scale-Up | - Scale up of 100 kWth coal combustion test facility results to give indicative net 550 MWe SPOC plant performance.<br><br>**Risk: Design basis for scale-up not robust enough resulting in errors in system design.** | - Design rules for scale up not yet established; risk remains until full-scale, validated boiler performance is available. | H | - Apply OEM knowledge and experience to OEM design tools to predict plant performance. However, scale-up predictions remain invalidated for novel SPOC application. | H | - Carry out detailed engineering design.<br>- Practical demonstration of a complete SPOC boiler system at significant pilot plant scale. | |
| **CR-13** | - Process and Systems | Plant Flexibility | - Ensuring proposed design concept is capable of flexible operation.<br><br>**Risk: Lack of detailed design resulting in inability to fully assess plant flexibility and operational limits.** | - Without detailed design of the pressure parts, it will not be possible to properly assess the pressure parts scantlings in terms of maximum allowable ramp rates and operational flexibility against impact on design life. | H | - Apply OEM knowledge and experience to determine generally acceptable ramp rates for novel concept. | M | - Carry out detailed engineering design and finite-element analysis to ensure design concept is fit for purpose. | |
| **CR-14** | - Layout<br>- Mechanical<br>- Process and Systems | Vessel Sizing | - As the SPOC system operates under elevated pressure conditions (~16 bara [232 psia]), the combustion envelope and all downstream equipment (convective heat transfer banks, acid gas removal, cooling units, and driers) needs to be contained within PVs. These PVs need to be transportable.<br><br>**Risk: Design basis for vessel sizing not developed enough to determine optimized vessel sizing incorporating technical, logistical, and economic factors.** | - Required surface needs to be spread over more vessel stages increasing CAPEX and layout concerns.<br>- Increased design complexity. | M | - Gather information on design rules/as-built PVs to determine optimum vessel sizing.<br>- Carry out detailed engineering design to optimize number of stages and vessel heating surface arrangement to minimize CAPEX.<br>- Consider some site assembly based on offsetting higher transport costs. | L | | |

# B

# HEAT BALANCE DIAGRAMS

Heat balance diagrams are presented here for the following cases:

1) SPOC Design Case, Montana PRB Fuel, 100% Load
2) SPOC Check Coal Case, Illinois No.6 Fuel, 100% Load
3) SPOC Part-Load Case, Montana PRB Fuel, 75% Load
4) SPOC Part-Load Case, Montana PRB Fuel, 50% Load
5) SPOC Part-Load Case, Montana PRB Fuel, 25% Load
6) SPOC Part-Load Case, Montana PRB Fuel, 12% Load
7) NETL Baseline Case S12A, Montana PRB Fuel, 100% Load
8) NETL Baseline Case S12B, Montana PRB Fuel, 100% Load
9) NETL Baseline Case S12F, Montana PRB Fuel, 100% Load

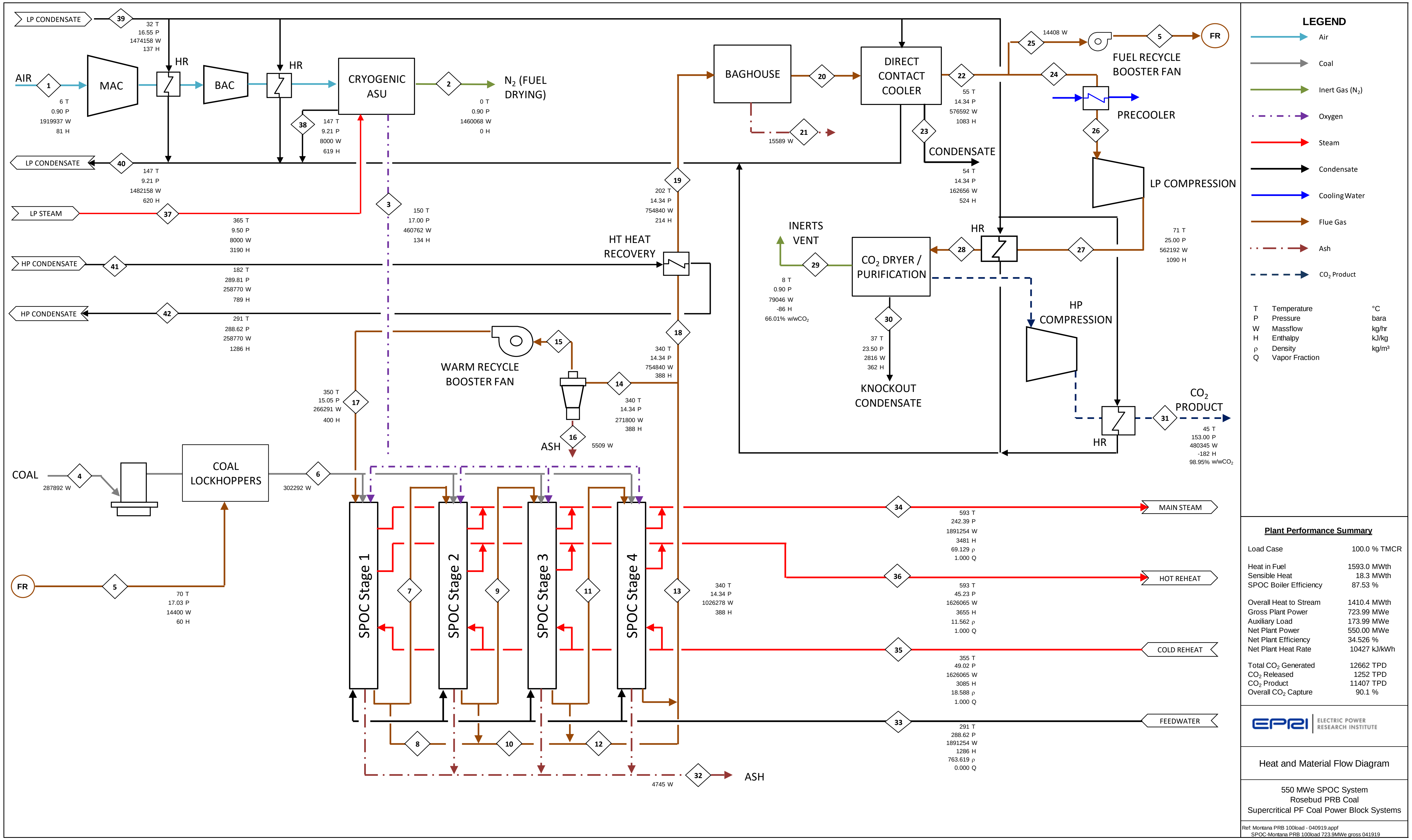



**Figure B-1**
**Design Case Montana PRB 100% Load – Boiler Island – SI Units**

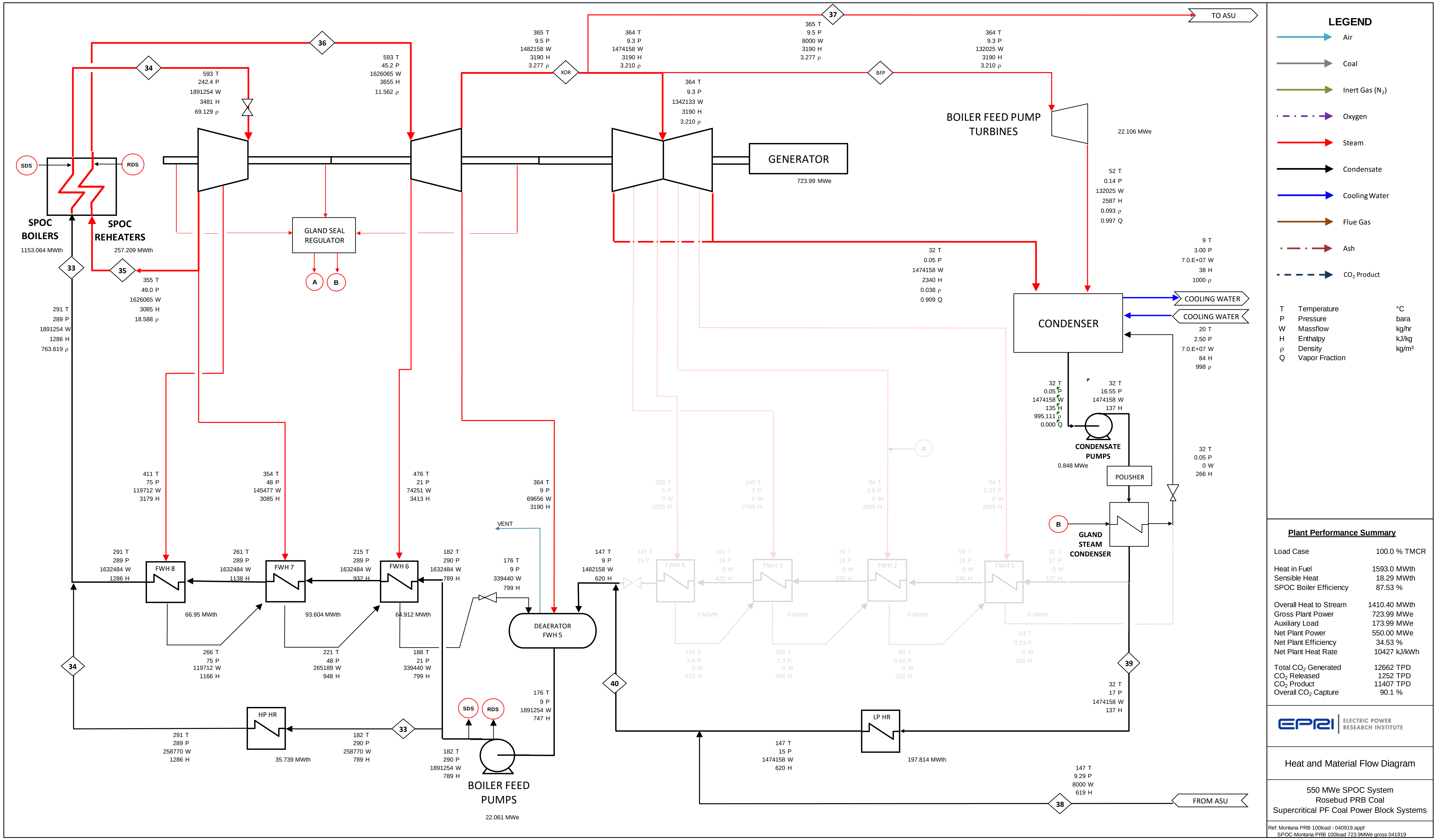



**Figure B-2**
**Design Case Montana PRB 100% Load – Steam Turbine Island – SI Units**

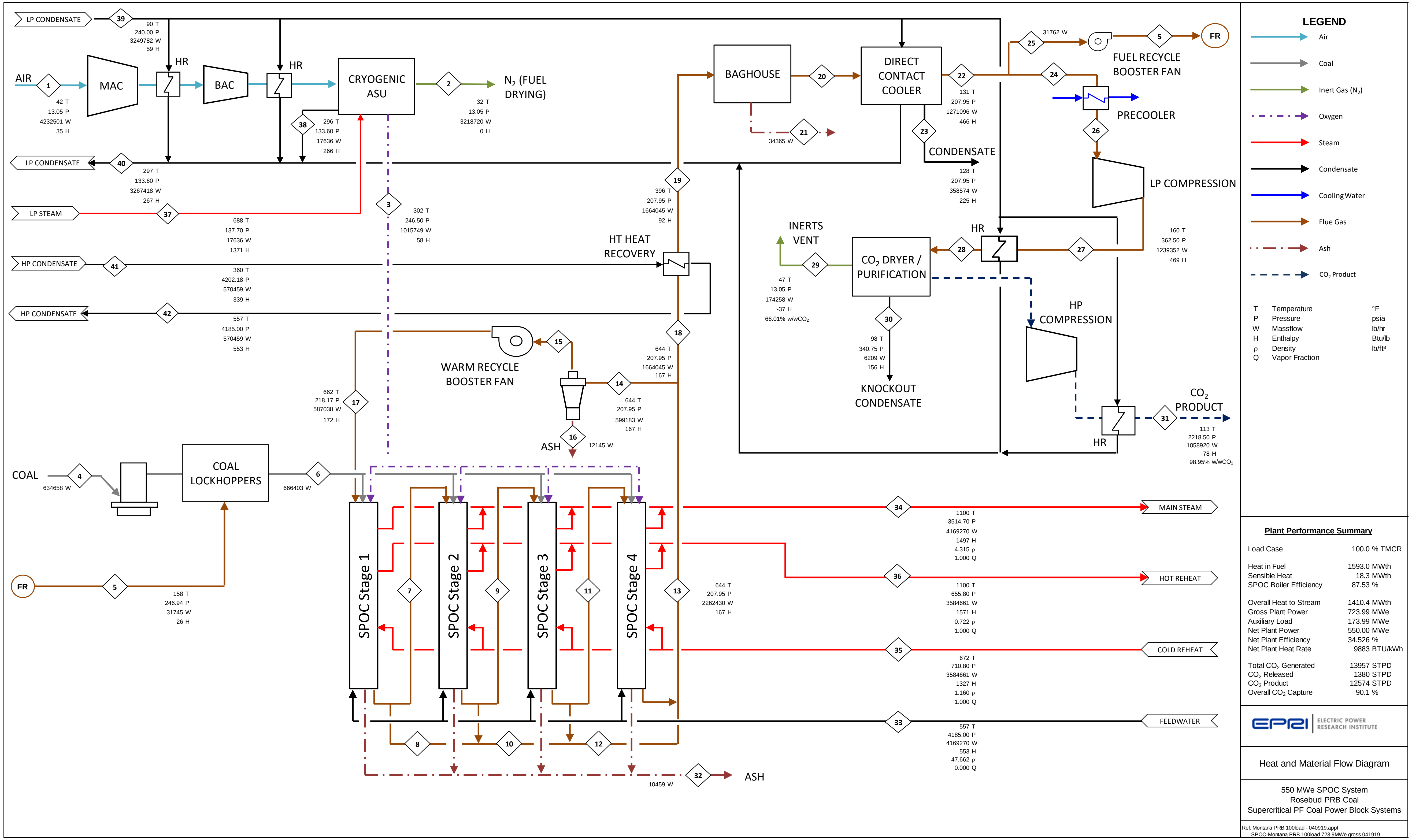



**Figure B-3**
**Design Case Montana PRB 100% Load – Boiler Island – English Units**

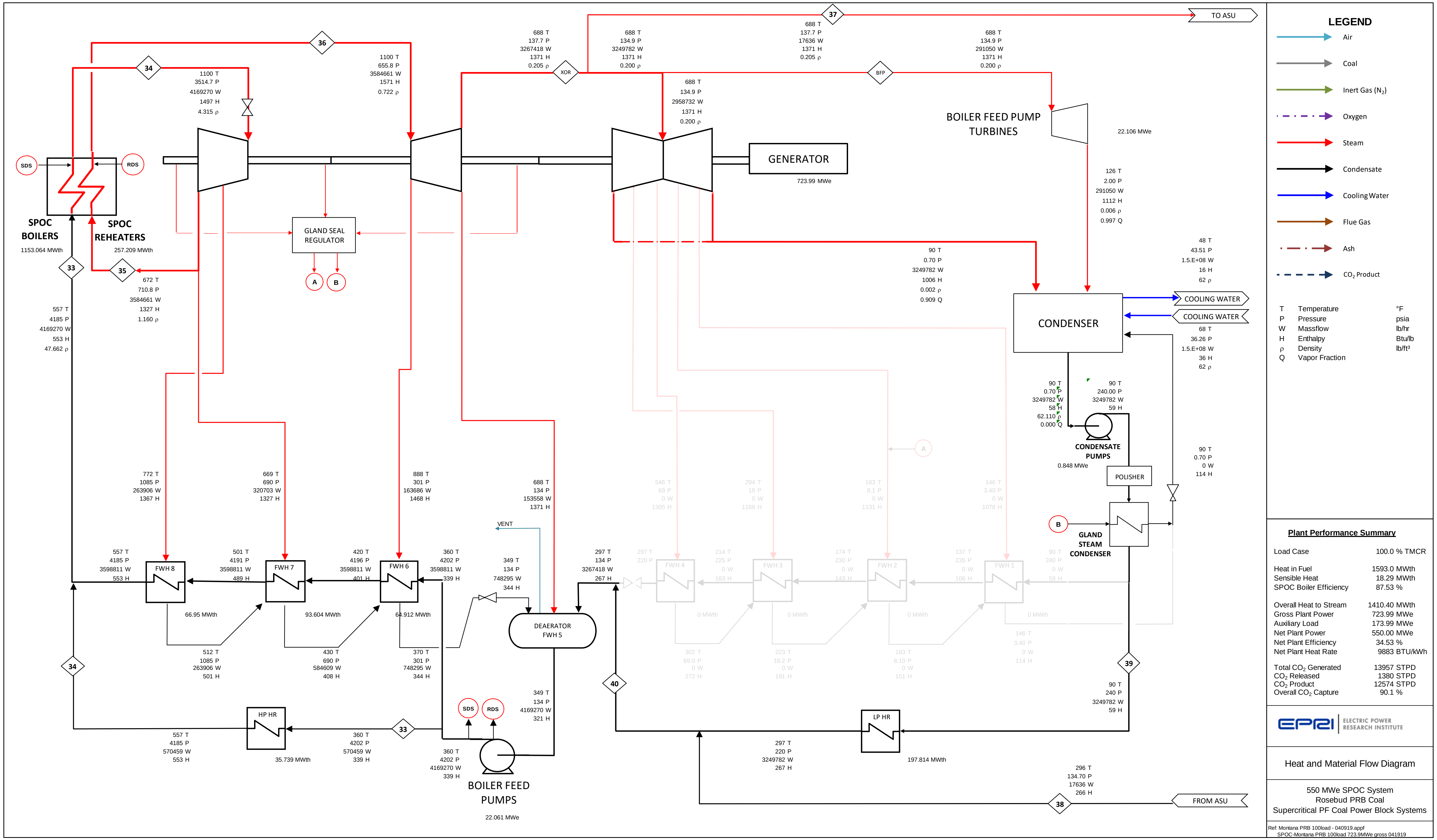



**Figure B-4**
**Design Case Montana PRB 100% Load – Steam Turbine Island – English Units**

**Table B-2**
**Design Case Montana PRB 100% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9205 | 0.9205 | 0.5537 | 0.5537 | 0.5537 | 0.5537 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0110 | 0.0110 | 0.4026 | 0.4026 | 0.4026 | 0.4026 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0110 | 0.0110 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0177 | 0.0177 | 0.0101 | 0.0101 | 0.0101 | 0.0101 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0395 | 0.0395 | 0.0237 | 0.0237 | 0.0237 | 0.0237 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 66,444 | 51,751 | 14,280 | - | 333 | 333 | 7907 | 5642 | 7839 | 11,261 |
| V-L Flowrate (kg/hr) | 1,919,937 | 1,451,753 | 460,762 | 0 | 14,400 | 14,400 | 263,135 | 187,762 | 260,864 | 374,751 |
| Solids Flowrate (kg/hr) | 0 | 8314 | 0 | 287,892 | 0 | 287,892 | 4081 | 2912 | 5140 | 6596 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 16 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.51 | 1.50 | 1.50 | 1.48 | 1.48 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 20.7 | 59.8 | 22.6 | 388.3 | 388.3 | 388.3 | 388.3 |
| Density (kg/m$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.297 | 763.191 | 9.460 | 9.460 | 9.460 | 9.460 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.180 | 43.180 | 33.279 | 33.279 | 33.279 | 33.279 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 146,475 | 114,085 | 31,481 | - | 735 | 735 | 17,431 | 12,438 | 17,280 | 24,825 |
| V-L Flowrate (lb/hr) | 4,232,501 | 3,200,391 | 1,015,749 | 0 | 31,745 | 31,745 | 580,081 | 413,922 | 575,075 | 826,140 |
| Solids Flowrate (lb/hr) | 0 | 18,329 | 0 | 634,658 | 0 | 634,658 | 8996 | 6419 | 11,332 | 14,542 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 61 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 218.4 | 217.6 | 217.6 | 215.2 | 215.2 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 8.9 | 25.7 | 9.7 | 166.9 | 166.9 | 166.9 | 166.9 |
| Density (lb/ft$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.297 | 763.191 | 9.460 | 9.460 | 9.460 | 9.460 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.5537 | 0.5537 | 0.5537 | 0.5537 | 0.5537 | 0.0000 | 0.5537 | 0.5535 | 0.5535 | 0.5535 |
| $H_2O$ | 0.4026 | 0.4026 | 0.4026 | 0.4026 | 0.4026 | 0.0000 | 0.4026 | 0.4024 | 0.4024 | 0.4024 |
| $N_2$ | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0000 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.0101 | 0.0101 | 0.0101 | 0.0101 | 0.0101 | 0.0000 | 0.0101 | 0.0106 | 0.0106 | 0.0106 |
| $SO_2$ | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0000 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0237 | 0.0237 | 0.0237 | 0.0237 | 0.0237 | 0.0000 | 0.0237 | 0.0237 | 0.0237 | 0.0237 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 7784 | 16,866 | 30,201 | 7998 | 7998 | - | 7998 | 22,214 | 22,214 | 22,214 |
| V-L Flowrate (kg/hr) | 259,047 | 561,287 | 1,005,052 | 266,179 | 266,179 | - | 266,179 | 739,236 | 739,236 | 739,236 |
| Solids Flowrate (kg/hr) | 5747 | 10,734 | 21,226 | 5621 | 112 | 5509 | 112 | 15,604 | 15,604 | 15.6 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.47 | 1.47 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 388.3 | 388.3 | 388.3 | 388.3 | 388.3 | 322.9 | 400.5 | 388.3 | 214.3 | 214.3 |
| Density (kg/m$^3$) | 9.460 | 9.460 | 9.460 | 9.460 | 9.324 | - | 9.768 | 9.460 | 12.432 | 12.432 |
| V-L Molecular Weight | 33.279 | 33.279 | 33.279 | 33.279 | 33.279 | - | 33.279 | 33.279 | 33.279 | 33.279 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 17,160 | 37,181 | 66,577 | 17,632 | 17,632 | - | 17,632 | 48,970 | 48,970 | 48,970 |
| V-L Flowrate (lb/hr) | 571,068 | 1,237,358 | 2,215,638 | 586,791 | 586,791 | - | 586,791 | 1,629,645 | 1,629,645 | 1,629,645 |
| Solids Flowrate (lb/hr) | 12,669 | 23,664 | 46,792 | 12,392 | 248 | 12,145 | 248 | 34,400 | 34,400 | 34.4 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 662 | 644 | 396 | 396 |
| Pressure (psia) | 212.8 | 212.8 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 166.9 | 166.9 | 166.9 | 166.9 | 166.9 | 138.8 | 172.2 | 166.9 | 92.2 | 92.2 |
| Density (lb/ft$^3$) | 9.460 | 9.460 | 9.460 | 9.460 | 9.324 | - | 9.768 | 9.460 | 12.432 | 12.432 |
| | | | | | | | | | | |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9205 | 0.0002 | 0.9205 | 0.9205 | 0.9205 | 0.9205 | 0.9205 | 0.6128 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0110 | 0.9923 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.9740 |
| $N_2$ | 0.0000 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0635 | 0.0000 |
| $O_2$ | 0.0000 | 0.0177 | 0.0000 | 0.0177 | 0.0177 | 0.0177 | 0.0177 | 0.0177 | 0.1039 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0002 | 0.0072 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0219 |
| Ar | 0.0000 | 0.0395 | 0.0000 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.2198 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0028 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0011 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 13,353 | 8860 | 13,353 | 333 | 13,020 | 13,020 | 13,020 | 1935 | 147 |
| V-L Flowrate (kg/hr) | - | 576,584 | 162,652 | 576,584 | 14,400 | 562,184 | 562,184 | 562,184 | 79,038 | 2,809 |
| Solids Flowrate (kg/hr) | 15,589 | 7.80 | 3.90 | 7.80 | 7.80 | 7.80 | 7.80 | 7.80 | 7.80 | 7.80 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 54 | 55 | 55 | 30 | 71 | 37 | 8 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.37 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 1082.7 | 524.1 | 1082.7 | 1082.7 | 1051.9 | 1090.0 | 1048.6 | -85.8 | 362.4 |
| Density (kg/m$^3$) | - | 24.025 | 930.320 | 24.025 | 24.025 | 25.370 | 41.070 | 45.664 | 2.624 | 811.855 |
| V-L Molecular Weight | - | 43.180 | 18.357 | 43.180 | 43.180 | 43.180 | 43.180 | 43.180 | 40.853 | 19.096 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 29,437 | 19,533 | 29,437 | 735 | 28,702 | 28,702 | 28,702 | 4265 | 324 |
| V-L Flowrate (lb/hr) | - | 1,271,079 | 358,566 | 1,271,079 | 31,745 | 1,239,334 | 1,239,334 | 1,239,334 | 174,240 | 6191 |
| Solids Flowrate (lb/hr) | 34,365 | 17.2 | 8.60 | 17.2 | 17.2 | 17.2 | 17.2 | 17.2 | 17.2 | 17.2 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 128 | 131 | 131 | 86 | 160 | 99 | 47 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 198.6 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 465.5 | 225.4 | 465.5 | 465.5 | 452.3 | 468.7 | 450.9 | -36.9 | 155.8 |
| Density (lb/ft$^3$) | - | 24.025 | 930.320 | 24.025 | 24.025 | 25.370 | 41.070 | 45.664 | 2.624 | 811.855 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9874 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0027 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0081 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 10,938 | - | 104,981 | 104,981 | 90,261 | 90,261 | 444 | 444 | 81,829 | 82,273 |
| V-L Flowrate (kg/hr) | 480,337 | - | 1,891,254 | 1,891,254 | 1,626,065 | 1,626,065 | 8,000 | 8,000 | 1,474,158 | 1,482,158 |
| Solids Flowrate (kg/hr) | 7.80 | 4,745 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 950 | 291 | 593 | 355 | 593 | 365 | 147 | 32 | 147 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 28.86 | 24.24 | 4.90 | 4.52 | 0.95 | 0.92 | 1.66 | 0.92 |
| Enthalpy (kJ/kg) | -182.2 | 902.5 | 1285.9 | 3480.7 | 3085.4 | 3654.9 | 3189.7 | 618.6 | 137.2 | 620.3 |
| Density (kg/$m^3$) | 731.555 | - | 763.619 | 69.129 | 18.588 | 11.562 | 3.277 | 920.459 | 995.796 | 920.088 |
| V-L Molecular Weight | 43.915 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 24,113 | - | 231,431 | 231,431 | 198,980 | 198,980 | 979 | 979 | 180,391 | 181,370 |
| V-L Flowrate (lb/hr) | 1,058,903 | - | 4,169,270 | 4,169,270 | 3,584,661 | 3,584,661 | 17,636 | 17,636 | 3,249,782 | 3,267,418 |
| Solids Flowrate (lb/hr) | 17.2 | 10,459 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 1742 | 557 | 1100 | 672 | 1100 | 688 | 296 | 90 | 297 |
| Pressure (psia) | 2218.5 | 13.1 | 4185.0 | 3514.7 | 710.8 | 655.8 | 137.7 | 133.6 | 240.0 | 133.6 |
| Enthalpy (Btu/lb) | -78.3 | 388.0 | 552.9 | 1496.6 | 1326.6 | 1571.5 | 1371.5 | 266.0 | 59.0 | 266.7 |
| Density (lb/$ft^3$) | 731.555 | - | 763.619 | 69.129 | 18.588 | 11.562 | 3.277 | 920.459 | 995.796 | 920.088 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 14,364 | 14,364 |
| V-L Flowrate (kg/hr) | 258,770 | 258,770 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 182 | 291 |
| Pressure (MPa, abs) | 28.98 | 28.86 |
| Enthalpy (kJ/kg) | 788.7 | 1285.9 |
| Density ($kg/m^3$) | 902.211 | 763.619 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 31,665 | 31,665 |
| V-L Flowrate (lb/hr) | 570,459 | 570,459 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 360 | 557 |
| Pressure (psia) | 4202.2 | 4185.0 |
| Enthalpy (Btu/lb) | 339.1 | 552.9 |
| Density ($lb/ft^3$) | 902.211 | 763.619 |

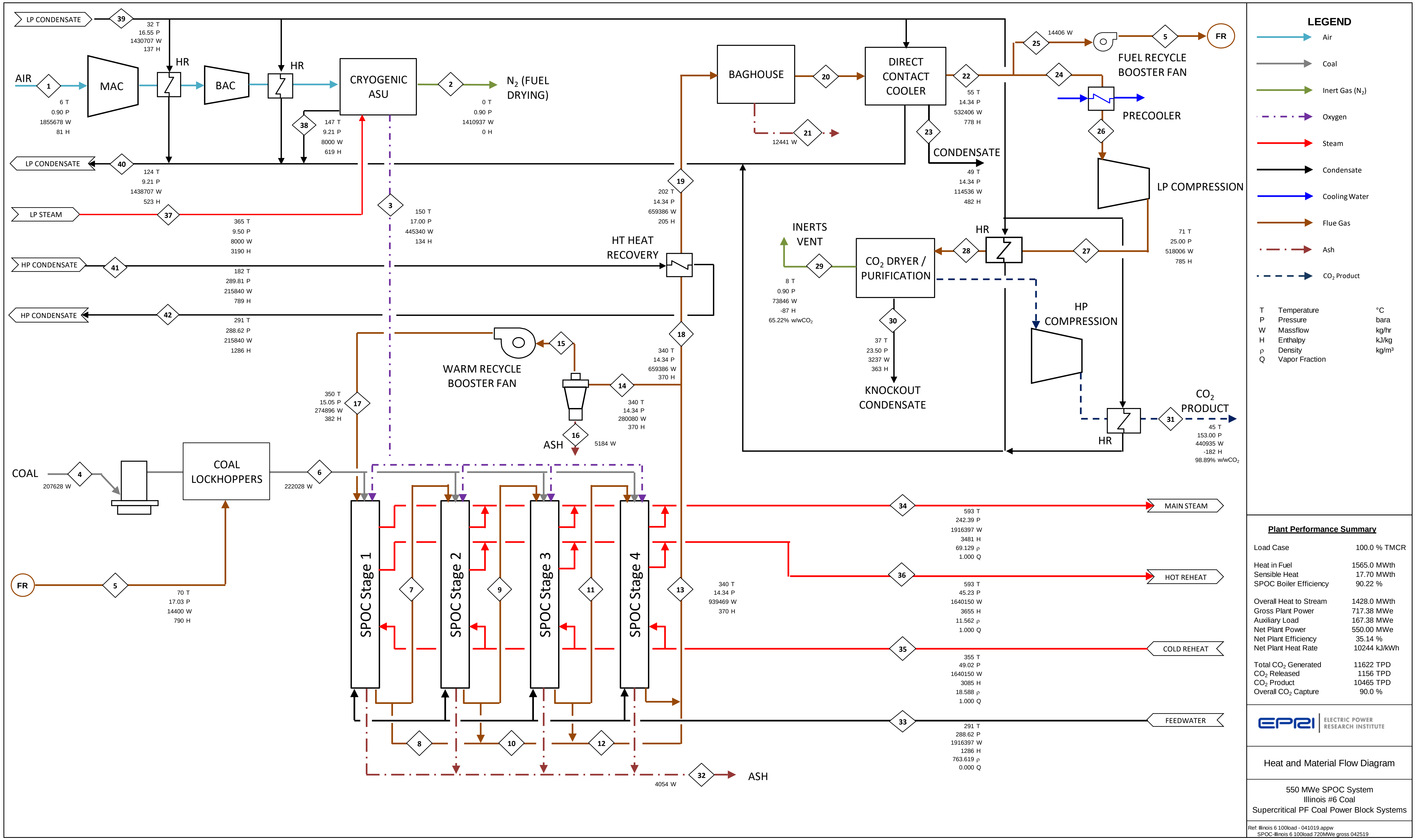



**Figure B-5**
**Check Coal Case Illinois No. 6 100% Load – Boiler Island – SI Units**

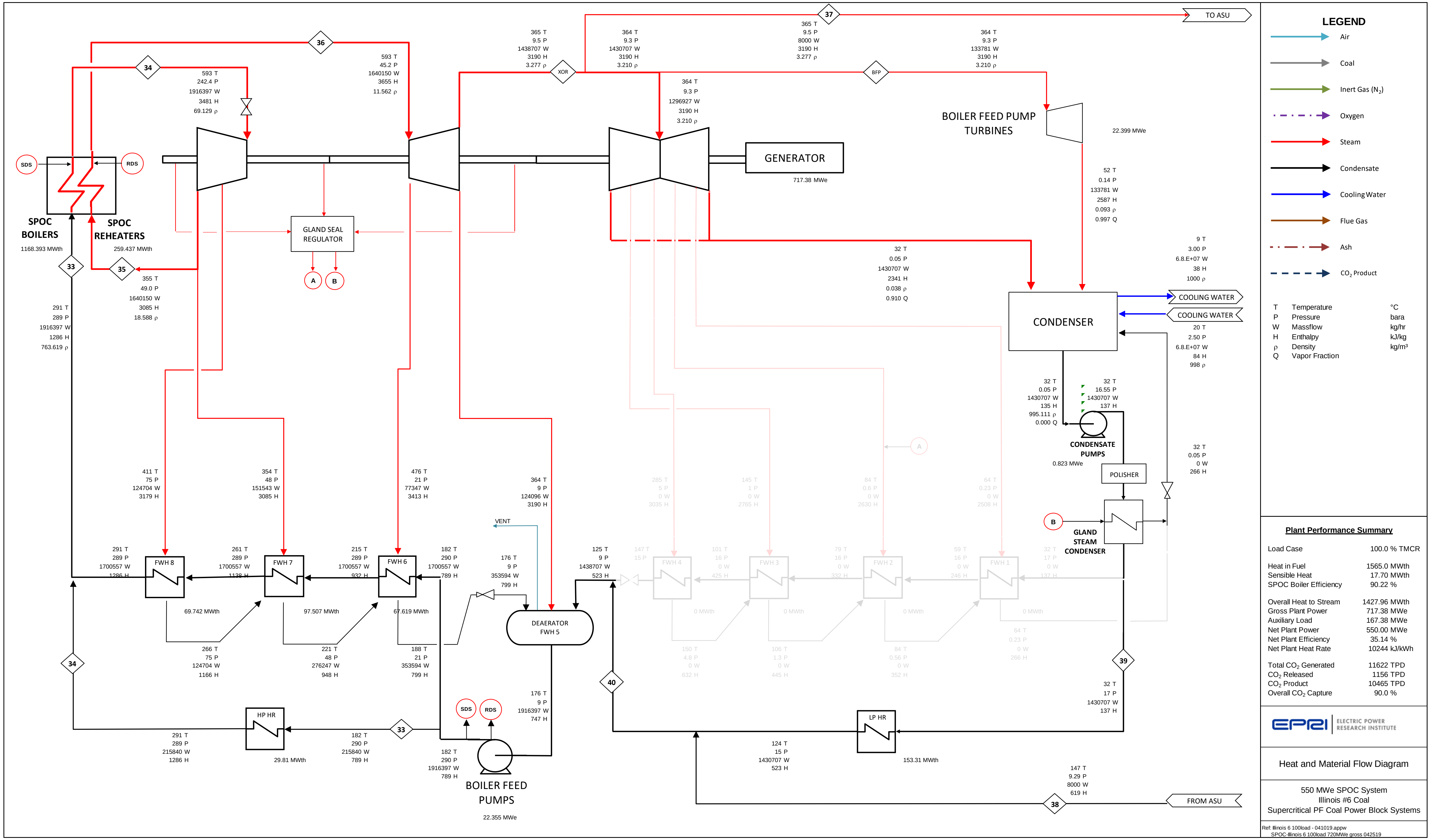



**Figure B-6**
**Check Coal Case Illinois No. 6 100% Load – Turbine Island – SI Units**

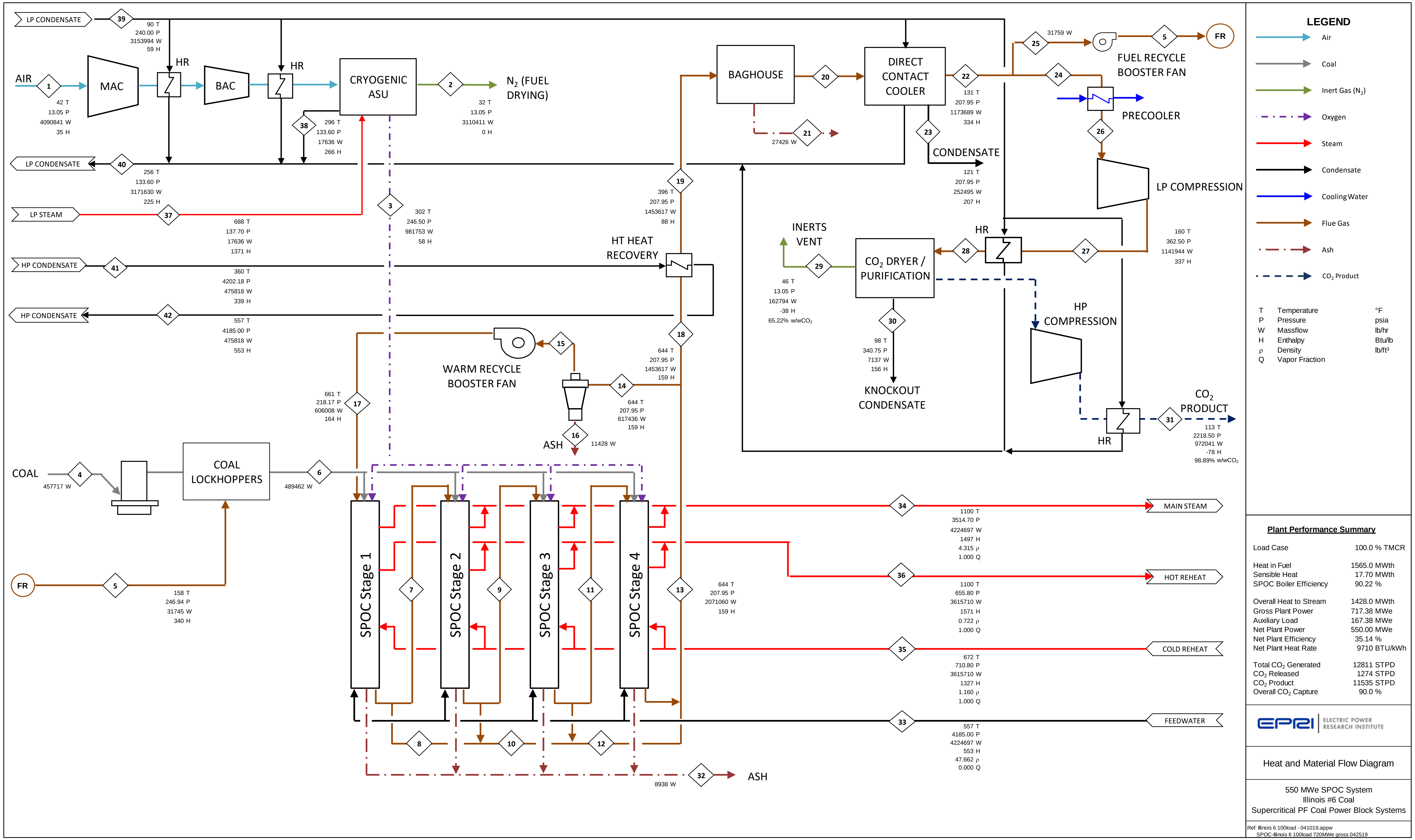
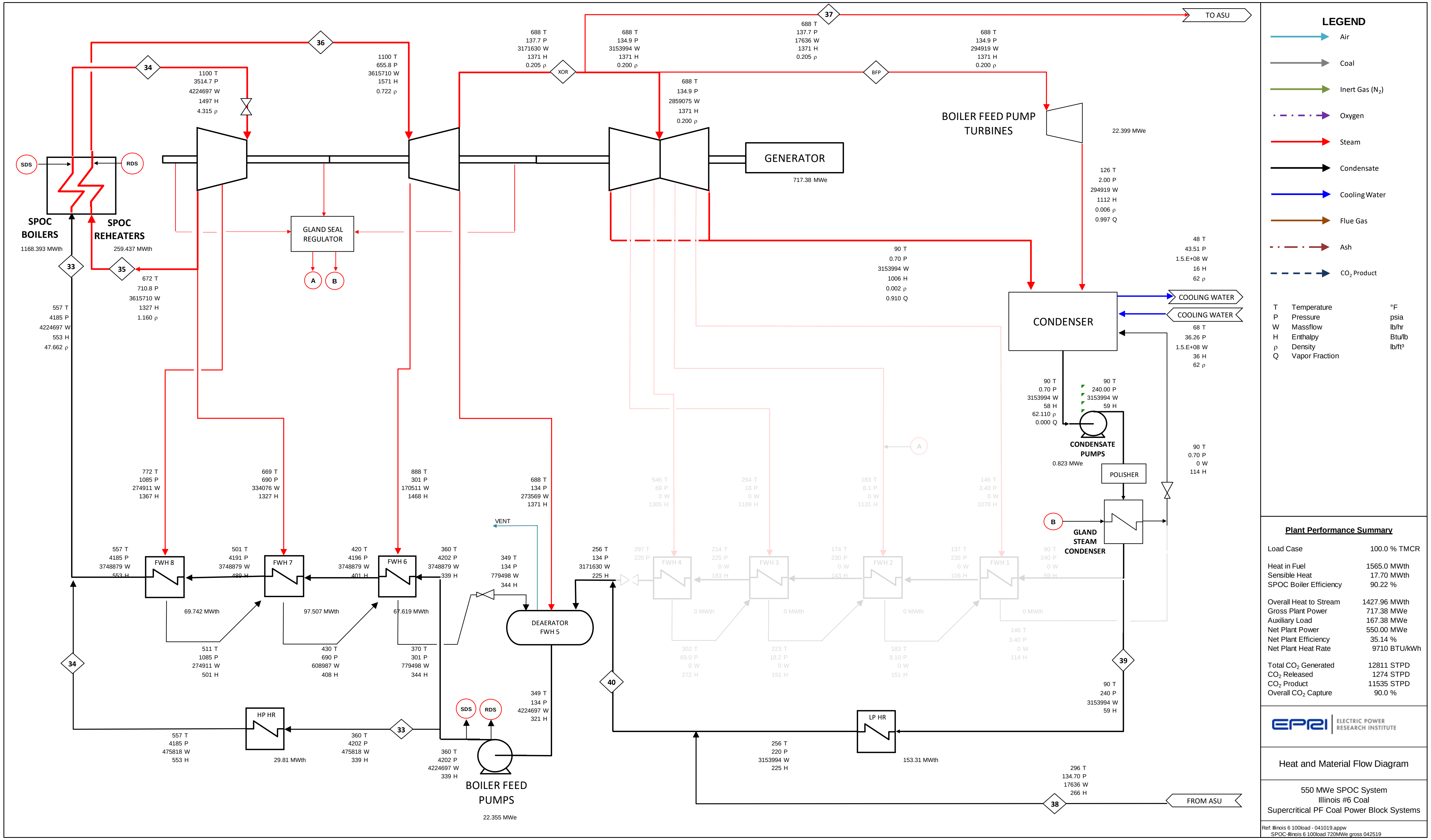



**Figure B-7**
**Check Coal Case Illinois No. 6 100% Load – Boiler Island – English Units**




# Figure B-8
## Check Coal Case Illinois No. 6 100% Load – Turbine Island – English Units

**Table B-3**
**Check Coal Case Illinois No. 6 100% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9165 | 0.9165 | 0.6188 | 0.6188 | 0.6188 | 0.6188 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0111 | 0.0111 | 0.3231 | 0.3231 | 0.3231 | 0.3231 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0134 | 0.0134 | 0.0090 | 0.0090 | 0.0090 | 0.0090 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0162 | 0.0162 | 0.0110 | 0.0110 | 0.0110 | 0.0110 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0007 | 0.0007 | 0.0091 | 0.0091 | 0.0091 | 0.0091 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0414 | 0.0414 | 0.0279 | 0.0279 | 0.0279 | 0.0279 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0007 | 0.0007 | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 64,220 | 50,019 | 13,803 | - | 334 | 334 | 7678 | 4654 | 7614 | 9287 |
| V-L Flowrate (kg/hr) | 1,855,678 | 1,403,164 | 445,340 | 0 | 14,400 | 14,400 | 271,787 | 164,738 | 269,525 | 328,733 |
| Solids Flowrate (kg/hr) | 0 | 7,773 | 0 | 207,628 | 0 | 207,628 | 3474 | 2106 | 4681 | 4954 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 16 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.51 | 1.50 | 1.50 | 1.48 | 1.48 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 278.8 | 789.9 | 311.9 | 370.4 | 370.4 | 370.4 | 370.4 |
| Density (kg/m$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.283 | 749.884 | 10.044 | 10.044 | 10.044 | 10.044 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.152 | 43.152 | 35.396 | 35.396 | 35.396 | 35.396 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 141,572 | 110,267 | 30,428 | - | 736 | 736 | 16,927 | 10,260 | 16,786 | 20,474 |
| V-L Flowrate (lb/hr) | 4,090,841 | 3,093,276 | 981,753 | 0 | 31,745 | 31,745 | 599,153 | 363,164 | 594,168 | 724,692 |
| Solids Flowrate (lb/hr) | 0 | 17,135 | 0 | 457,717 | 0 | 457,717 | 7,659 | 4,642 | 10,318 | 10,920 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 60 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 218.2 | 217.5 | 217.5 | 215.1 | 215.1 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 119.9 | 339.6 | 134.1 | 159.3 | 159.3 | 159.3 | 159.3 |
| Density (lb/ft$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.283 | 749.884 | 10.044 | 10.044 | 10.044 | 10.044 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.6188 | 0.6188 | 0.6188 | 0.6188 | 0.6188 | 0.0000 | 0.6188 | 0.6188 | 0.6188 | 0.6188 |
| $H_2O$ | 0.3231 | 0.3231 | 0.3231 | 0.3231 | 0.3231 | 0.0000 | 0.3231 | 0.3231 | 0.3231 | 0.3231 |
| $N_2$ | 0.0090 | 0.0090 | 0.0090 | 0.0090 | 0.0090 | 0.0000 | 0.0090 | 0.0090 | 0.0090 | 0.0090 |
| $O_2$ | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 |
| $SO_2$ | 0.0091 | 0.0091 | 0.0091 | 0.0091 | 0.0091 | 0.0000 | 0.0091 | 0.0091 | 0.0091 | 0.0091 |
| Ar | 0.0279 | 0.0279 | 0.0279 | 0.0279 | 0.0279 | 0.0000 | 0.0279 | 0.0279 | 0.0279 | 0.0279 |
| HCl | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0010 | 0.0000 | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 7564 | 13,907 | 26,040 | 7763 | 7763 | - | 7763 | 18,277 | 18,277 | 18,277 |
| V-L Flowrate (kg/hr) | 267,728 | 492,264 | 921,726 | 274,790 | 274,790 | - | 274,790 | 646,933 | 646,933 | 646,933 |
| Solids Flowrate (kg/hr) | 5423 | 8266 | 17,743 | 5290 | 106 | 5,184 | 106 | 12,454 | 12,454 | 12.5 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.47 | 1.47 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 370.4 | 370.4 | 370.4 | 370.4 | 370.4 | 322.9 | 381.9 | 370.4 | 204.7 | 204.7 |
| Density (kg/m$^3$) | 10.044 | 10.044 | 10.044 | 10.044 | 9.899 | - | 10.373 | 10.044 | 13.177 | 13.177 |
| V-L Molecular Weight | 35.396 | 35.396 | 35.396 | 35.396 | 35.396 | - | 35.396 | 35.396 | 35.396 | 35.396 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 16,674 | 30,658 | 57,406 | 17,114 | 17,114 | - | 17,114 | 40,291 | 40,291 | 40,291 |
| V-L Flowrate (lb/hr) | 590,206 | 1,085,197 | 2,031,945 | 605,775 | 605,775 | - | 605,775 | 1,426,163 | 1,426,163 | 1,426,163 |
| Solids Flowrate (lb/hr) | 11,955 | 18,222 | 39,115 | 11,661 | 233 | 11,428 | 233 | 27,454 | 27,454 | 27.5 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 661 | 644 | 396 | 396 |
| Pressure (psia) | 212.7 | 212.7 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 159.3 | 159.3 | 159.3 | 159.3 | 159.3 | 138.9 | 164.2 | 159.3 | 88.0 | 88.0 |
| Density (lb/ft$^3$) | 10.044 | 10.044 | 10.044 | 10.044 | 9.899 | - | 10.373 | 10.044 | 13.177 | 13.177 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9165 | 0.0002 | 0.9165 | 0.9165 | 0.9165 | 0.9165 | 0.9165 | 0.6040 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0111 | 0.9713 | 0.0111 | 0.0111 | 0.0111 | 0.0111 | 0.0111 | 0.0000 | 0.8886 |
| $N_2$ | 0.0000 | 0.0134 | 0.0000 | 0.0134 | 0.0134 | 0.0134 | 0.0134 | 0.0134 | 0.0758 | 0.0000 |
| $O_2$ | 0.0000 | 0.0162 | 0.0000 | 0.0162 | 0.0162 | 0.0162 | 0.0162 | 0.0162 | 0.0939 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0007 | 0.0266 | 0.0007 | 0.0007 | 0.0007 | 0.0007 | 0.0007 | 0.0000 | 0.0534 |
| Ar | 0.0000 | 0.0414 | 0.0000 | 0.0414 | 0.0414 | 0.0414 | 0.0414 | 0.0414 | 0.2264 | 0.0000 |
| HCl | 0.0000 | 0.0007 | 0.0015 | 0.0007 | 0.0007 | 0.0007 | 0.0007 | 0.0007 | 0.0000 | 0.0565 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0003 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0012 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 12,338 | 5939 | 12,338 | 334 | 12,004 | 12,004 | 12,004 | 1812 | 150 |
| V-L Flowrate (kg/hr) | - | 532,400 | 114,533 | 532,400 | 14,400 | 518,000 | 518,000 | 518,000 | 73,840 | 3231 |
| Solids Flowrate (kg/hr) | 12,441 | 6.23 | 3.11 | 6.23 | 6.23 | 6.23 | 6.23 | 6.23 | 6.23 | 6.23 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 49 | 55 | 55 | 30 | 71 | 37 | 8 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.37 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 777.6 | 482.0 | 777.6 | 777.6 | 746.7 | 784.7 | 743.5 | -87.3 | 362.8 |
| Density ($kg/m^3$) | - | 24.007 | 595.265 | 24.007 | 24.007 | 25.394 | 41.065 | 45.619 | 2.629 | 218.549 |
| V-L Molecular Weight | - | 43.152 | 19.285 | 43.152 | 43.152 | 43.152 | 43.152 | 43.152 | 40.750 | 21.542 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 27,199 | 13,093 | 27,199 | 736 | 26,463 | 26,463 | 26,463 | 3,995 | 331 |
| V-L Flowrate (lb/hr) | - | 1,173,675 | 252,488 | 1,173,675 | 31,745 | 1,141,930 | 1,141,930 | 1,141,930 | 162,780 | 7,123 |
| Solids Flowrate (lb/hr) | 27,426 | 13.7 | 6.86 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 121 | 131 | 131 | 86 | 160 | 99 | 46 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 198.9 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 334.3 | 207.3 | 334.3 | 334.3 | 321.1 | 337.4 | 319.7 | -37.5 | 156.0 |
| Density ($lb/ft^3$) | - | 24.007 | 595.265 | 24.007 | 24.007 | 25.394 | 41.065 | 45.619 | 2.629 | 218.549 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9866 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0023 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0025 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0086 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 10,042 | - | 106,377 | 106,377 | 91,043 | 91,043 | 444 | 444 | 79,417 | 79,861 |
| V-L Flowrate (kg/hr) | 440,929 | - | 1,916,397 | 1,916,397 | 1,640,150 | 1,640,150 | 8,000 | 8,000 | 1,430,707 | 1,438,707 |
| Solids Flowrate (kg/hr) | 6.23 | 4,054 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 340 | 291 | 593 | 355 | 593 | 365 | 147 | 32 | 124 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 28.86 | 24.24 | 4.90 | 4.52 | 0.95 | 0.92 | 1.66 | 0.92 |
| Enthalpy (kJ/kg) | -181.9 | 323.0 | 1285.9 | 3480.7 | 3085.4 | 3654.9 | 3189.7 | 618.6 | 137.2 | 523.0 |
| Density (kg/m$^3$) | 730.483 | - | 763.619 | 69.129 | 18.588 | 11.562 | 3.277 | 920.459 | 995.796 | 940.053 |
| V-L Molecular Weight | 43.908 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 22,138 | - | 234,507 | 234,507 | 200,703 | 200,703 | 979 | 979 | 175,074 | 176,053 |
| V-L Flowrate (lb/hr) | 972,027 | - | 4,224,697 | 4,224,697 | 3,615,710 | 3,615,710 | 17,636 | 17,636 | 3,153,994 | 3,171,630 |
| Solids Flowrate (lb/hr) | 13.7 | 8,938 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 644 | 557 | 1100 | 672 | 1100 | 688 | 296 | 90 | 256 |
| Pressure (psia) | 2218.5 | 13.1 | 4185.0 | 3514.7 | 710.8 | 655.8 | 137.7 | 133.6 | 240.0 | 133.6 |
| Enthalpy (Btu/lb) | -78.2 | 138.9 | 552.9 | 1496.6 | 1326.6 | 1571.5 | 1371.5 | 266.0 | 59.0 | 224.9 |
| Density (lb/ft$^3$) | 730.483 | - | 763.619 | 69.129 | 18.588 | 11.562 | 3.277 | 920.459 | 995.796 | 940.053 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 11,981 | 11,981 |
| V-L Flowrate (kg/hr) | 215,840 | 215,840 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 182 | 291 |
| Pressure (MPa, abs) | 28.98 | 28.86 |
| Enthalpy (kJ/kg) | 788.7 | 1285.9 |
| Density (kg/m$^3$) | 902.211 | 763.619 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 26,412 | 26,412 |
| V-L Flowrate (lb/hr) | 475,818 | 475,818 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 360 | 557 |
| Pressure (psia) | 4202.2 | 4185.0 |
| Enthalpy (Btu/lb) | 339.1 | 552.9 |
| Density (lb/ft$^3$) | 902.211 | 763.619 |

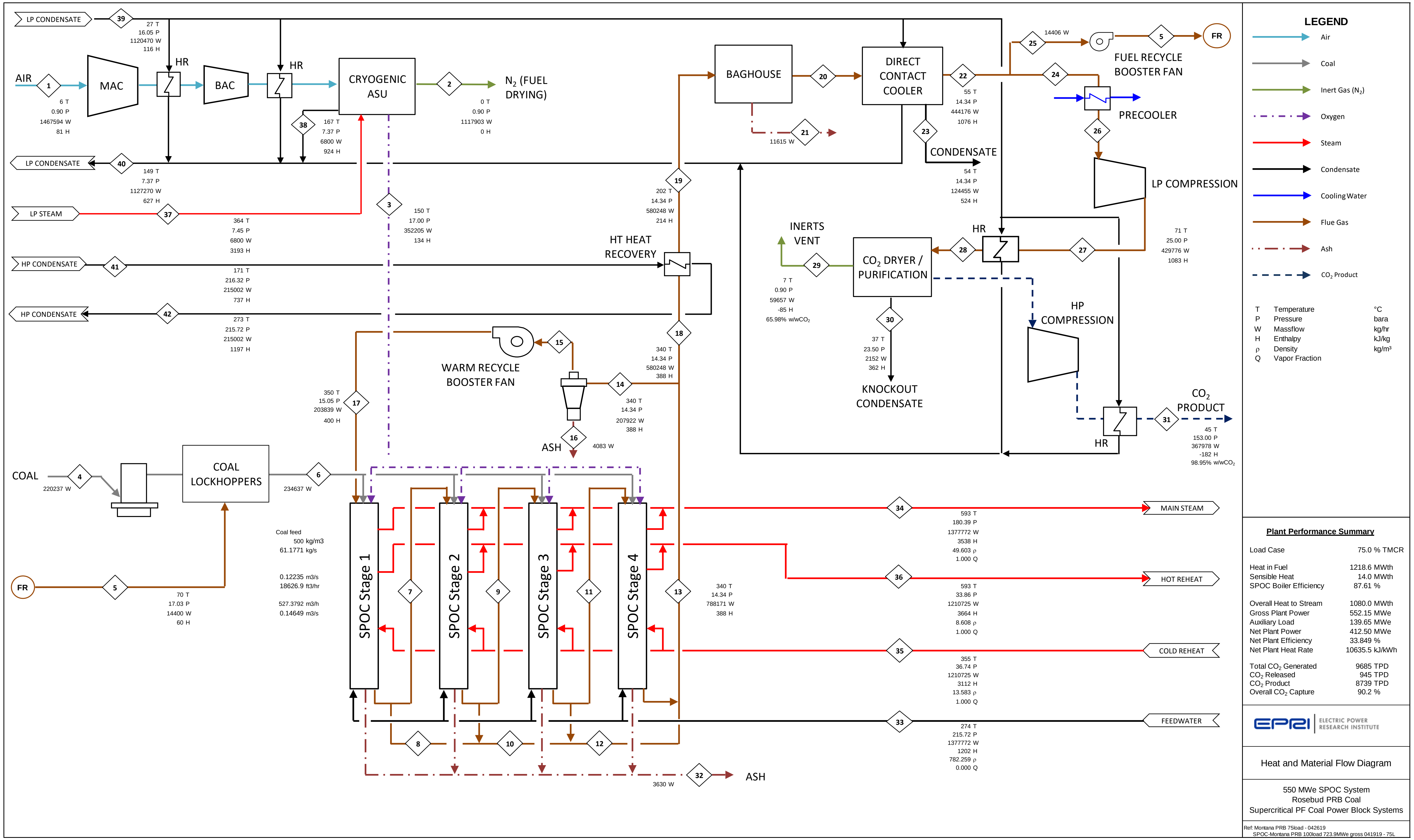



**Figure B-9**
**Part-Load Case Montana PRB 75% Load – Boiler Island – SI Units**

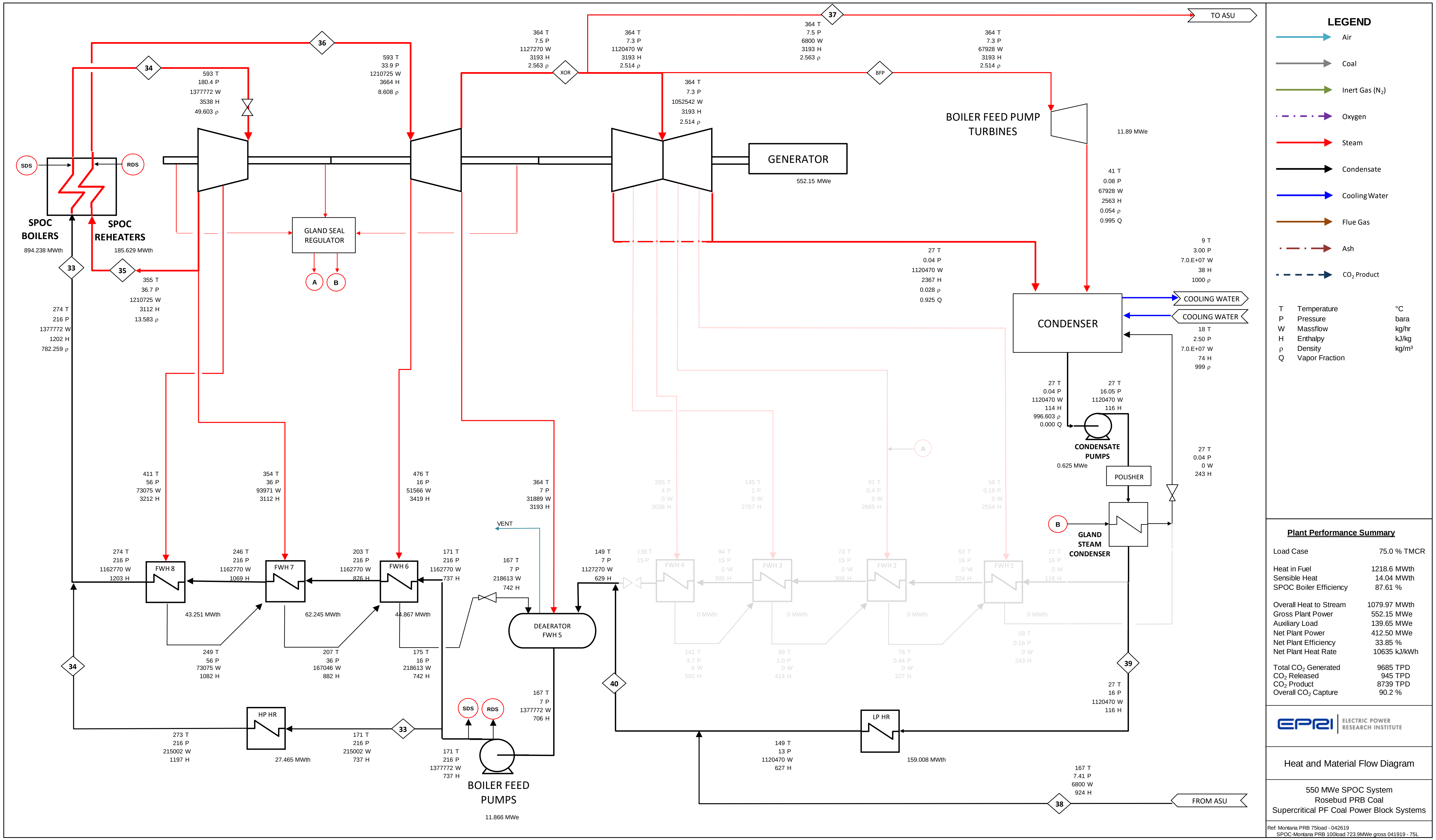



**Figure B-10**
**Part-Load Case Montana PRB 75% Load – Turbine Island – SI Units**

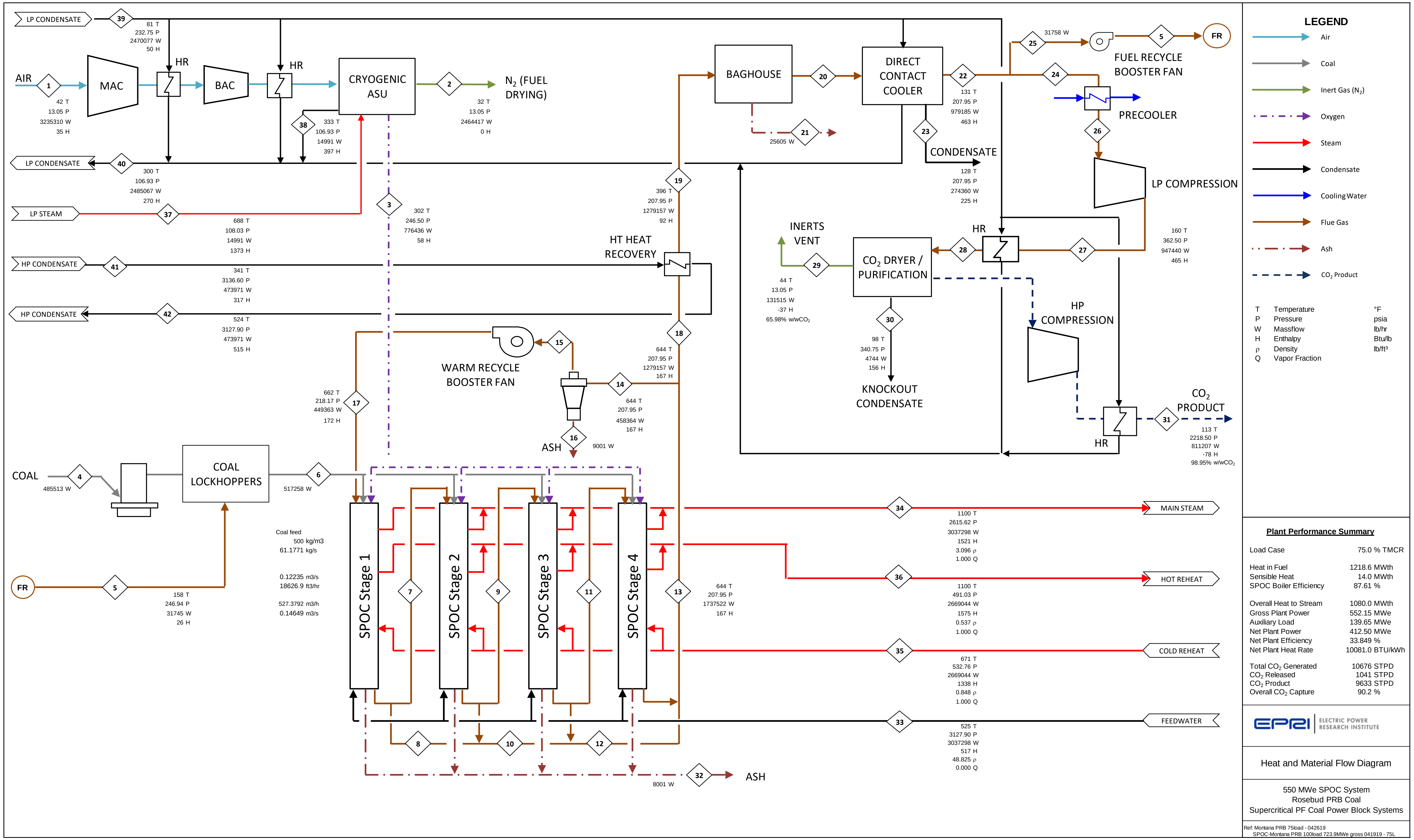



**Figure B-11**
**Part-Load Case Montana PRB 75% Load – Boiler Island – English Units**

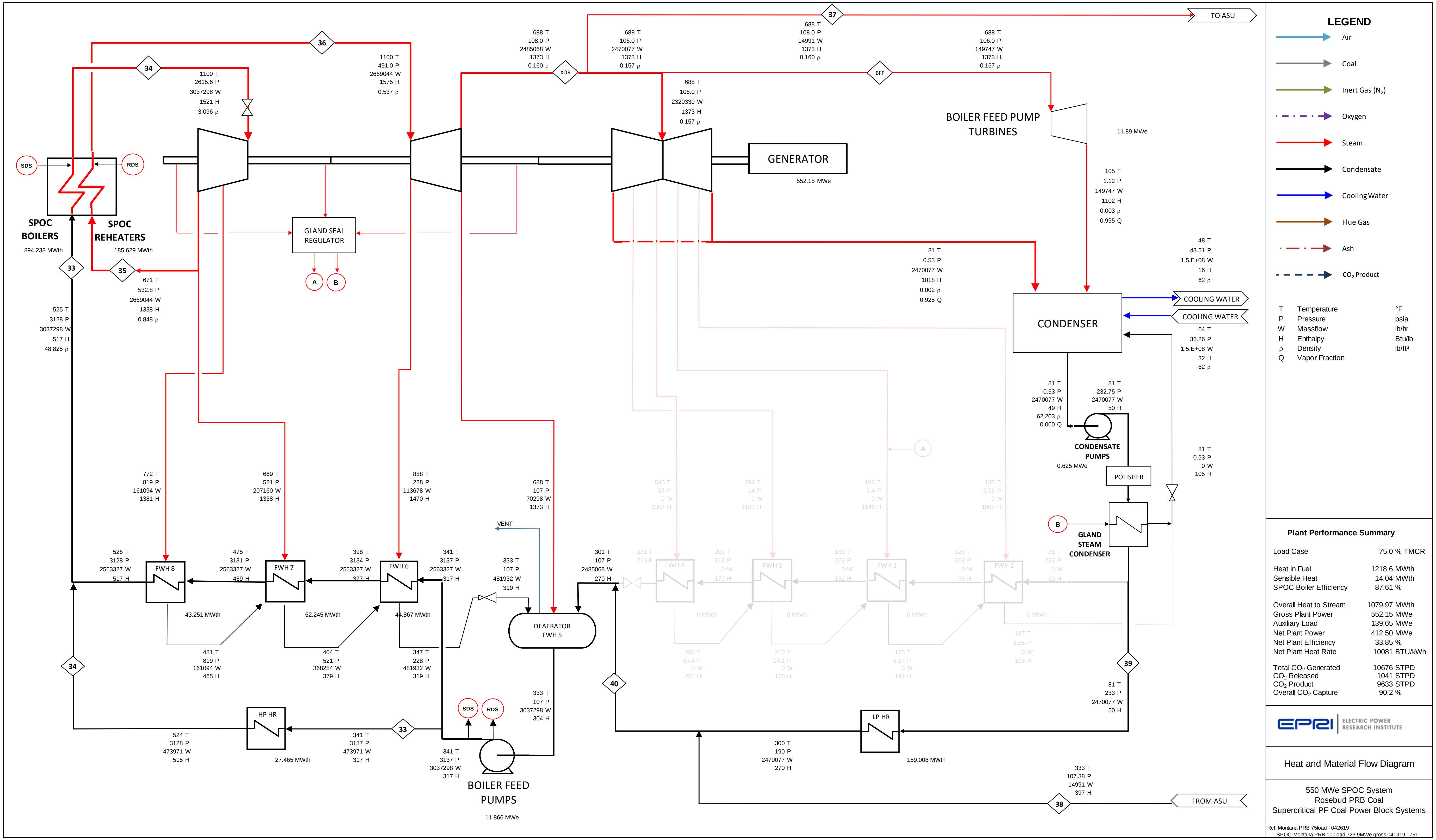


**Figure B-12**
**Part-Load Case Montana PRB 75% Load – Turbine Island – English Units**

**Table B-4**
**Part-Load Case Montana PRB 75% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9213 | 0.9213 | 0.5554 | 0.5554 | 0.5554 | 0.5554 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0110 | 0.0110 | 0.4008 | 0.4008 | 0.4008 | 0.4008 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0110 | 0.0110 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0169 | 0.0169 | 0.0102 | 0.0102 | 0.0102 | 0.0102 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0395 | 0.0395 | 0.0238 | 0.0238 | 0.0238 | 0.0238 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 50,789 | 39,558 | 10,916 | - | 333 | 333 | 6039 | 4341 | 5984 | 8662 |
| V-L Flowrate (kg/hr) | 1,467,594 | 1,109,716 | 352,205 | 0 | 14,400 | 14,400 | 201,251 | 144,661 | 199,413 | 288,654 |
| Solids Flowrate (kg/hr) | 0 | 8187 | 0 | 220,237 | 0 | 220,237 | 2853 | 2051 | 3764 | 4769 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 17 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.48 | 1.47 | 1.47 | 1.46 | 1.46 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 20.7 | 59.8 | 23.1 | 387.9 | 387.9 | 387.9 | 387.9 |
| Density (kg/m$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 752.579 | 9.473 | 9.473 | 9.473 | 9.473 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.189 | 43.189 | 33.325 | 33.325 | 33.325 | 33.325 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 111,965 | 87,206 | 24,064 | - | 735 | 735 | 13,313 | 9570 | 13,191 | 19,095 |
| V-L Flowrate (lb/hr) | 3,235,310 | 2,446,369 | 776,436 | 0 | 31,745 | 31,745 | 443,657 | 318,905 | 439,606 | 636,338 |
| Solids Flowrate (lb/hr) | 0 | 18,048 | 0 | 485,513 | 0 | 485,513 | 6,290 | 4,521 | 8,299 | 10,513 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 62 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 214.0 | 213.6 | 213.6 | 212.2 | 212.2 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 8.9 | 25.7 | 9.9 | 166.8 | 166.8 | 166.8 | 166.8 |
| Density (lb/ft$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 752.579 | 9.473 | 9.473 | 9.473 | 9.473 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.5554 | 0.5554 | 0.5554 | 0.5554 | 0.5554 | 0.0000 | 0.5554 | 0.5554 | 0.5554 | 0.5554 |
| $H_2O$ | 0.4008 | 0.4008 | 0.4008 | 0.4008 | 0.4008 | 0.0000 | 0.4008 | 0.4008 | 0.4008 | 0.4008 |
| $N_2$ | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0000 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.0102 | 0.0102 | 0.0102 | 0.0102 | 0.0102 | 0.0000 | 0.0102 | 0.0102 | 0.0102 | 0.0102 |
| $SO_2$ | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0000 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0238 | 0.0238 | 0.0238 | 0.0238 | 0.0238 | 0.0000 | 0.0238 | 0.0238 | 0.0238 | 0.0238 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 5940 | 12,971 | 23,177 | 6114 | 6114 | - | 6114 | 17,063 | 17,063 | 17,063 |
| V-L Flowrate (kg/hr) | 197,965 | 432,257 | 772,378 | 203,756 | 203,756 | - | 203,756 | 568,622 | 568,622 | 568,622 |
| Solids Flowrate (kg/hr) | 4285 | 7878 | 15,793 | 4166 | 83 | 4083 | 83 | 11,626 | 11,626 | 11.6 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.45 | 1.45 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 387.9 | 387.9 | 387.9 | 387.9 | 387.9 | 322.9 | 400.1 | 387.9 | 214.1 | 214.1 |
| Density ($kg/m^3$) | 9.473 | 9.473 | 9.473 | 9.473 | 9.336 | - | 9.782 | 9.473 | 12.448 | 12.448 |
| V-L Molecular Weight | 33.325 | 33.325 | 33.325 | 33.325 | 33.325 | - | 33.325 | 33.325 | 33.325 | 33.325 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 13,096 | 28,594 | 51,094 | 13,479 | 13,479 | - | 13,479 | 37,615 | 37,615 | 37,615 |
| V-L Flowrate (lb/hr) | 436,415 | 952,911 | 1,702,707 | 449,179 | 449,179 | - | 449,179 | 1,253,526 | 1,253,526 | 1,253,526 |
| Solids Flowrate (lb/hr) | 9447 | 17,366 | 34,815 | 9184 | 184 | 9,001 | 184 | 25,630 | 25,630 | 25.6 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 662 | 644 | 396 | 396 |
| Pressure (psia) | 210.8 | 210.8 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 166.8 | 166.8 | 166.8 | 166.8 | 166.8 | 138.8 | 172.0 | 166.8 | 92.1 | 92.1 |
| Density ($lb/ft^3$) | 9.473 | 9.473 | 9.473 | 9.473 | 9.336 | - | 9.782 | 9.473 | 12.448 | 12.448 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9213 | 0.0002 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.6129 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0110 | 0.9923 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.9741 |
| $N_2$ | 0.0000 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0644 | 0.0000 |
| $O_2$ | 0.0000 | 0.0169 | 0.0000 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.1003 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0002 | 0.0072 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0219 |
| Ar | 0.0000 | 0.0395 | 0.0000 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.2225 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0028 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0010 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 10,284 | 6779 | 10,284 | 333 | 9951 | 9951 | 9951 | 1459 | 112 |
| V-L Flowrate (kg/hr) | - | 444,170 | 124,452 | 444,170 | 14,400 | 429,770 | 429,770 | 429,770 | 59,652 | 2,146 |
| Solids Flowrate (kg/hr) | 11,615 | 5.81 | 2.91 | 5.81 | 5.81 | 5.81 | 5.81 | 5.81 | 5.81 | 5.81 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 54 | 55 | 55 | 30 | 71 | 37 | 7 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.38 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 1075.7 | 523.9 | 1075.7 | 1075.7 | 1044.8 | 1082.5 | 1041.6 | -85.1 | 362.4 |
| Density (kg/$m^3$) | - | 24.032 | 932.547 | 24.032 | 24.032 | 25.500 | 41.145 | 45.681 | 2.622 | 820.375 |
| V-L Molecular Weight | - | 43.189 | 18.360 | 43.189 | 43.189 | 43.189 | 43.189 | 43.189 | 40.872 | 19.095 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 22,672 | 14,943 | 22,672 | 735 | 21,937 | 21,937 | 21,937 | 3217 | 248 |
| V-L Flowrate (lb/hr) | - | 979,172 | 274,354 | 979,172 | 31,745 | 947,428 | 947,428 | 947,428 | 131,502 | 4731 |
| Solids Flowrate (lb/hr) | 25,605 | 12.8 | 6.41 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 128 | 131 | 131 | 86 | 160 | 99 | 44 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 199.4 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 462.5 | 225.3 | 462.5 | 462.5 | 449.2 | 465.5 | 447.8 | -36.6 | 155.8 |
| Density (lb/$ft^3$) | - | 24.032 | 932.547 | 24.032 | 24.032 | 25.500 | 41.145 | 45.681 | 2.622 | 820.375 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9874 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0081 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 8,379 | - | 76,478 | 76,478 | 67,206 | 67,206 | 377 | 377 | 62,196 | 62,573 |
| V-L Flowrate (kg/hr) | 367,972 | - | 1,377,772 | 1,377,772 | 1,210,725 | 1,210,725 | 6,800 | 6,800 | 1,120,470 | 1,127,270 |
| Solids Flowrate (kg/hr) | 5.81 | 3,630 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 950 | 274 | 593 | 355 | 593 | 364 | 167 | 27 | 149 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 21.57 | 18.04 | 3.67 | 3.39 | 0.75 | 0.74 | 1.61 | 0.74 |
| Enthalpy (kJ/kg) | -182.2 | 902.5 | 1201.7 | 3538.2 | 3112.2 | 3664.1 | 3193.1 | 924.5 | 116.3 | 627.2 |
| Density (kg/$m^3$) | 731.673 | - | 782.259 | 49.603 | 13.583 | 8.608 | 2.563 | 35.067 | 997.283 | 918.468 |
| V-L Molecular Weight | 43.916 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 18,471 | - | 168,596 | 168,596 | 148,155 | 148,155 | 832 | 832 | 137,111 | 137,943 |
| V-L Flowrate (lb/hr) | 811,194 | - | 3,037,298 | 3,037,298 | 2,669,044 | 2,669,044 | 14,991 | 14,991 | 2,470,077 | 2,485,067 |
| Solids Flowrate (lb/hr) | 12.8 | 8,001 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 1742 | 525 | 1100 | 671 | 1100 | 688 | 333 | 81 | 300 |
| Pressure (psia) | 2218.5 | 13.1 | 3127.9 | 2615.6 | 532.8 | 491.0 | 108.0 | 106.9 | 232.7 | 106.9 |
| Enthalpy (Btu/lb) | -78.4 | 388.0 | 516.7 | 1521.3 | 1338.1 | 1575.5 | 1372.9 | 397.5 | 50.0 | 269.7 |
| Density (lb/$ft^3$) | 731.673 | - | 782.259 | 49.603 | 13.583 | 8.608 | 2.563 | 35.067 | 997.283 | 918.468 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 11,934 | 11,934 |
| V-L Flowrate (kg/hr) | 215,002 | 215,002 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 171 | 273 |
| Pressure (MPa, abs) | 21.63 | 21.57 |
| Enthalpy (kJ/kg) | 737.0 | 1196.9 |
| Density (kg/$m^3$) | 908.790 | 783.797 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 26,309 | 26,309 |
| V-L Flowrate (lb/hr) | 473,971 | 473,971 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 341 | 524 |
| Pressure (psia) | 3136.6 | 3127.9 |
| Enthalpy (Btu/lb) | 316.9 | 514.6 |
| Density (lb/$ft^3$) | 908.790 | 783.797 |

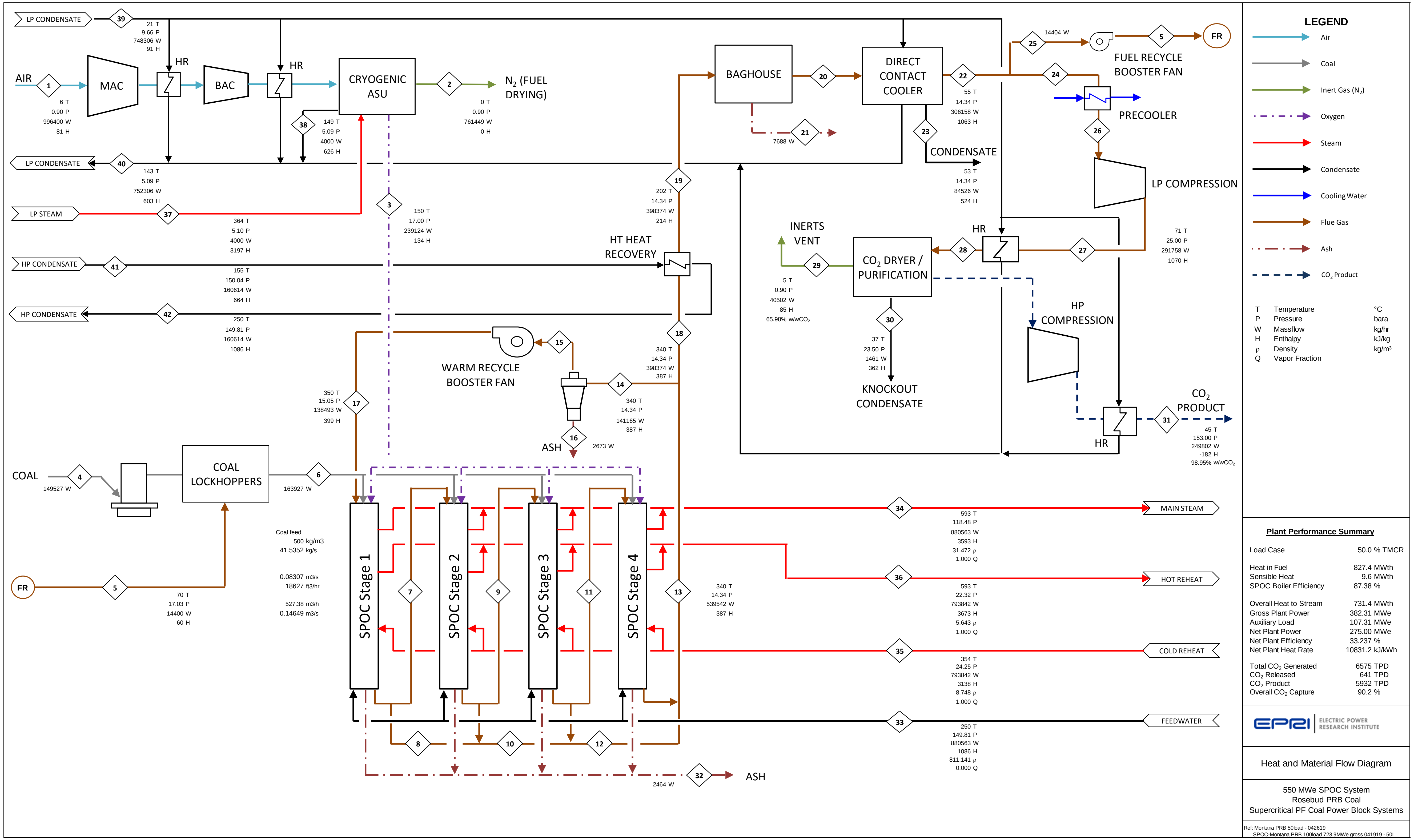



**Figure B-13**
**Part-Load Case Montana PRB 50% Load – Boiler Island – SI Units**

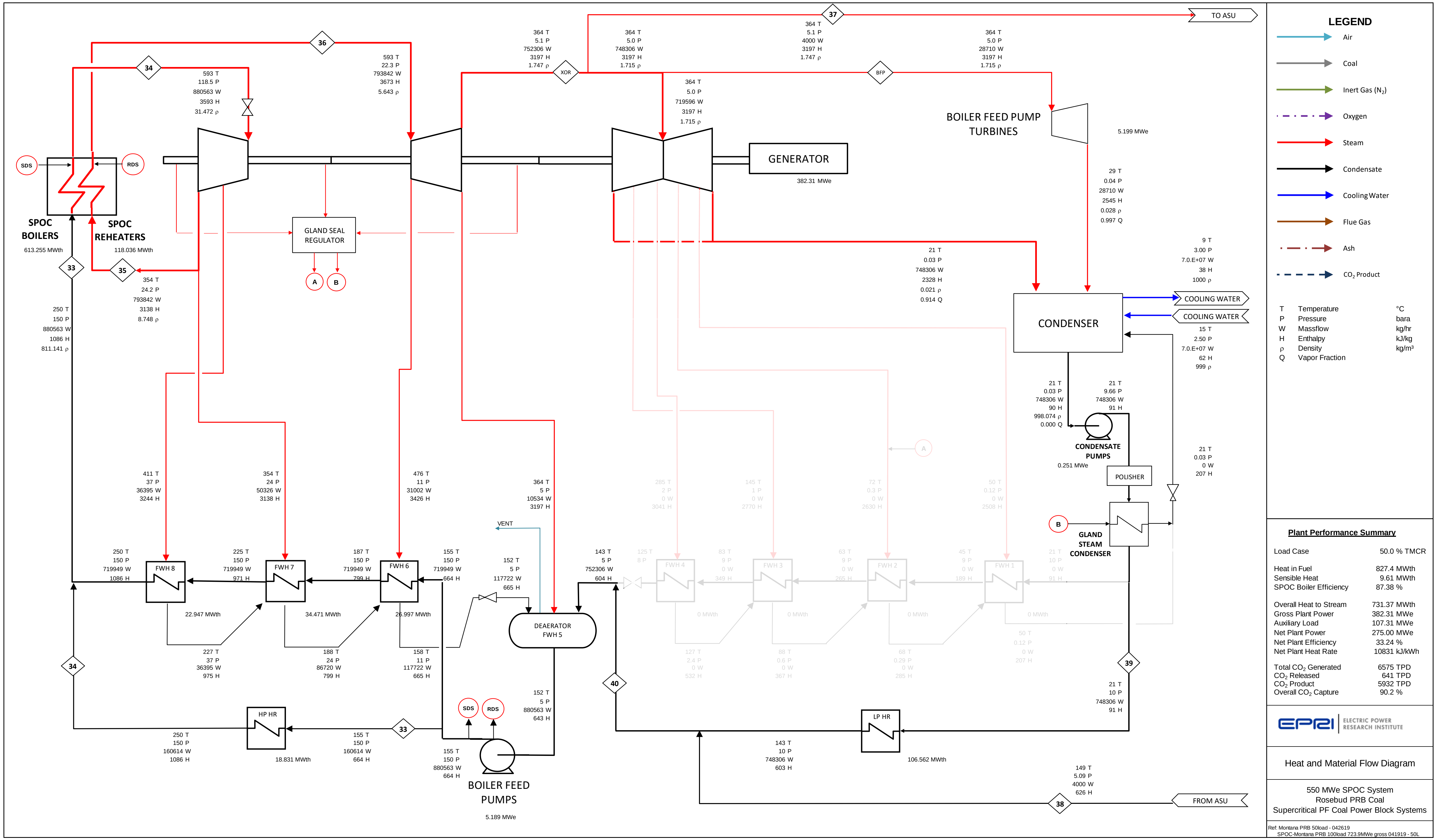



**Figure B-14**
**Part-Load Case Montana PRB 50% Load – Turbine Island – SI Units**

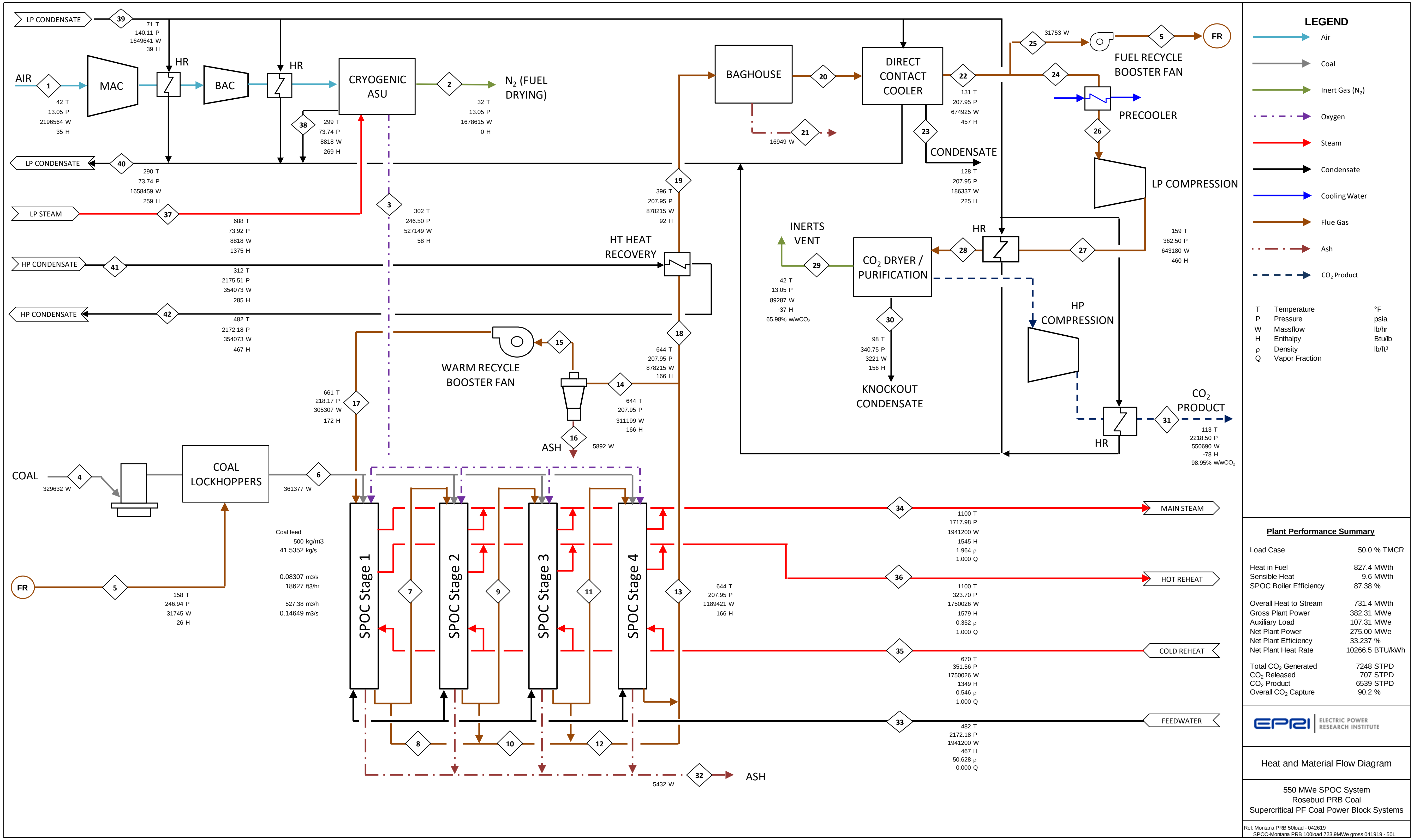



**Figure B-15**
**Part-Load Case Montana PRB 50% Load – Boiler Island – English Units**

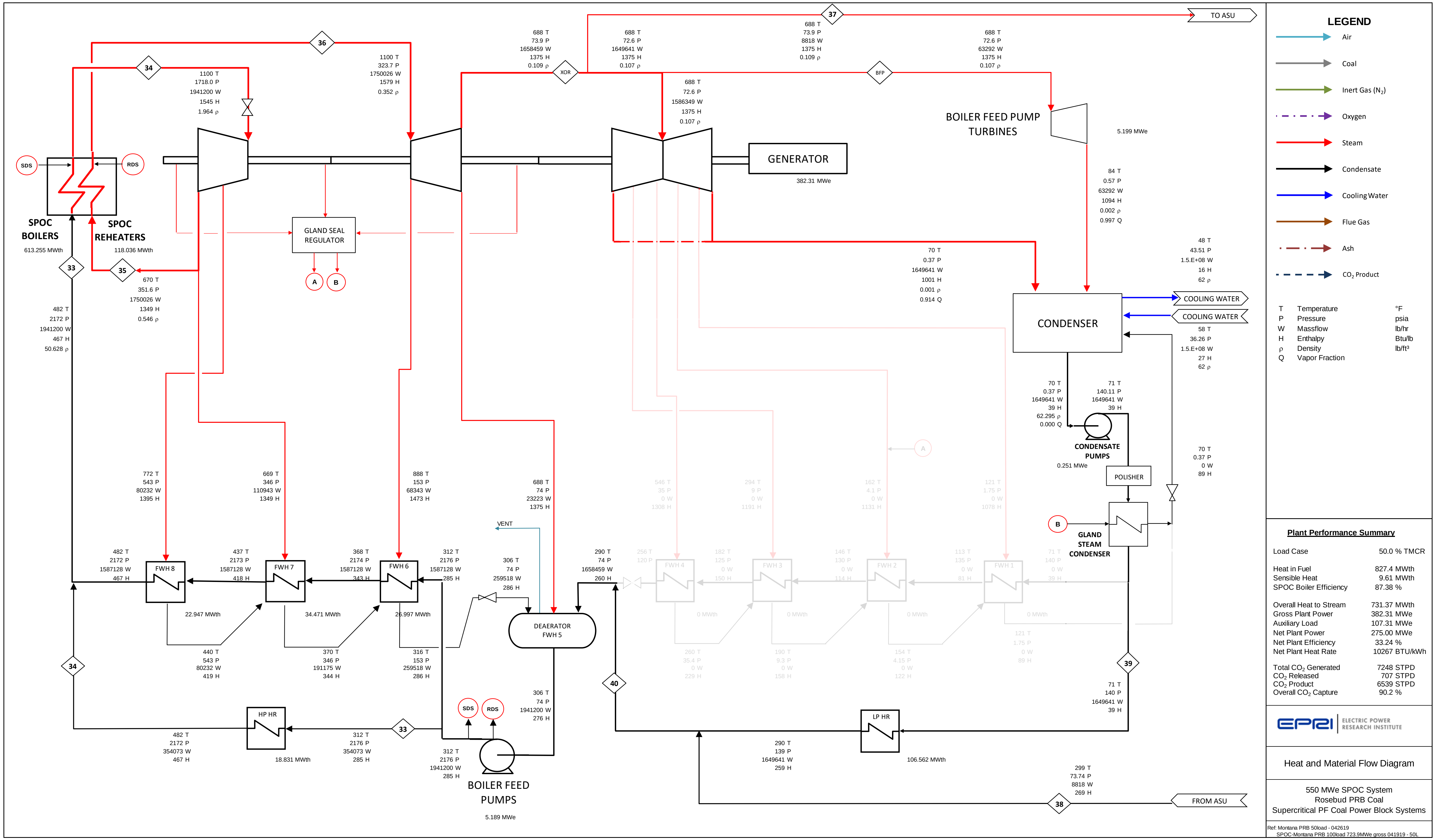



**Figure B-16**
**Part-Load Case Montana PRB 50% Load – Turbine Island – English Units**

**Table B-5**
**Part-Load Case Montana PRB 50% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9213 | 0.9213 | 0.5587 | 0.5587 | 0.5587 | 0.5587 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0110 | 0.0110 | 0.3973 | 0.3973 | 0.3973 | 0.3973 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0110 | 0.0110 | 0.0067 | 0.0067 | 0.0067 | 0.0067 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0169 | 0.0169 | 0.0102 | 0.0102 | 0.0102 | 0.0102 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0395 | 0.0395 | 0.0239 | 0.0239 | 0.0239 | 0.0239 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 34,483 | 26,858 | 7411 | - | 333 | 333 | 4088 | 2977 | 4049 | 5939 |
| V-L Flowrate (kg/hr) | 996,400 | 753,425 | 239,124 | 0 | 14,400 | 14,400 | 136,622 | 99,486 | 135,311 | 198,468 |
| Solids Flowrate (kg/hr) | 0 | 8,025 | 0 | 149,527 | 0 | 149,527 | 1754 | 1277 | 2436 | 3059 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 17 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 20.7 | 59.8 | 24.1 | 387.1 | 387.1 | 387.1 | 387.1 |
| Density ($kg/m^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 732.123 | 9.498 | 9.498 | 9.498 | 9.498 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.189 | 43.189 | 33.416 | 33.416 | 33.416 | 33.416 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 76,017 | 59,207 | 16,338 | - | 735 | 735 | 9013 | 6563 | 8927 | 13,093 |
| V-L Flowrate (lb/hr) | 2,196,564 | 1,660,924 | 527,149 | 0 | 31,745 | 31,745 | 301,183 | 219,318 | 298,292 | 437,522 |
| Solids Flowrate (lb/hr) | 0 | 17,691 | 0 | 329,632 | 0 | 329,632 | 3866 | 2815 | 5370 | 6743 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 63 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 210.8 | 210.6 | 210.6 | 209.9 | 209.9 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 8.9 | 25.7 | 10.4 | 166.4 | 166.4 | 166.4 | 166.4 |
| Density ($lb/ft^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 732.123 | 9.498 | 9.498 | 9.498 | 9.498 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.5587 | 0.5587 | 0.5587 | 0.5587 | 0.5587 | 0.0000 | 0.5587 | 0.5587 | 0.5587 | 0.5587 |
| $H_2O$ | 0.3973 | 0.3973 | 0.3973 | 0.3973 | 0.3973 | 0.0000 | 0.3973 | 0.3973 | 0.3973 | 0.3973 |
| $N_2$ | 0.0067 | 0.0067 | 0.0067 | 0.0067 | 0.0067 | 0.0000 | 0.0067 | 0.0067 | 0.0067 | 0.0067 |
| $O_2$ | 0.0102 | 0.0102 | 0.0102 | 0.0102 | 0.0102 | 0.0000 | 0.0102 | 0.0102 | 0.0102 | 0.0102 |
| $SO_2$ | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0000 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0239 | 0.0239 | 0.0239 | 0.0239 | 0.0239 | 0.0000 | 0.0239 | 0.0239 | 0.0239 | 0.0239 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 4019 | 8893 | 15,834 | 4143 | 4143 | - | 4143 | 11,691 | 11,691 | 11,691 |
| V-L Flowrate (kg/hr) | 134,293 | 297,156 | 529,119 | 138,438 | 138,438 | - | 138,438 | 390,678 | 390,678 | 390,678 |
| Solids Flowrate (kg/hr) | 2825 | 5135 | 10,423 | 2727 | 55 | 2673 | 55 | 7696 | 7696 | 7.7 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.44 | 1.44 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 387.1 | 387.1 | 387.1 | 387.1 | 387.1 | 322.9 | 399.3 | 387.1 | 213.7 | 213.7 |
| Density (kg/m$^3$) | 9.498 | 9.498 | 9.498 | 9.498 | 9.361 | - | 9.807 | 9.498 | 12.480 | 12.480 |
| V-L Molecular Weight | 33.416 | 33.416 | 33.416 | 33.416 | 33.416 | - | 33.416 | 33.416 | 33.416 | 33.416 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 8859 | 19,604 | 34,906 | 9133 | 9133 | - | 9,133 | 25,773 | 25,773 | 25,773 |
| V-L Flowrate (lb/hr) | 296,049 | 655,080 | 1,166,443 | 305,187 | 305,187 | - | 305,187 | 861,249 | 861,249 | 861,249 |
| Solids Flowrate (lb/hr) | 6227 | 11,319 | 22,978 | 6012 | 120 | 5892 | 120 | 16,966 | 16,966 | 17.0 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 661 | 644 | 396 | 396 |
| Pressure (psia) | 209.3 | 209.3 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 166.4 | 166.4 | 166.4 | 166.4 | 166.4 | 138.8 | 171.7 | 166.4 | 91.9 | 91.9 |
| Density (lb/ft$^3$) | 9.498 | 9.498 | 9.498 | 9.498 | 9.361 | - | 9.807 | 9.498 | 12.480 | 12.480 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9213 | 0.0002 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.6128 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0110 | 0.9922 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.9740 |
| $N_2$ | 0.0000 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0644 | 0.0000 |
| $O_2$ | 0.0000 | 0.0169 | 0.0000 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.1003 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0002 | 0.0073 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0219 |
| Ar | 0.0000 | 0.0395 | 0.0000 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.2225 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0028 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0010 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 7089 | 4603 | 7089 | 333 | 6755 | 6755 | 6755 | 991 | 76 |
| V-L Flowrate (kg/hr) | - | 306,154 | 84,524 | 306,154 | 14,400 | 291,754 | 291,754 | 291,754 | 40,498 | 1,457 |
| Solids Flowrate (kg/hr) | 7688 | 3.85 | 1.92 | 3.85 | 3.85 | 3.85 | 3.85 | 3.85 | 3.85 | 3.85 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 53 | 55 | 55 | 30 | 71 | 37 | 5 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.38 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 1063.1 | 523.7 | 1063.1 | 1063.1 | 1032.1 | 1069.6 | 1028.9 | -85.2 | 362.4 |
| Density (kg/m$^3$) | - | 24.032 | 931.856 | 24.032 | 24.032 | 25.593 | 41.190 | 45.681 | 2.622 | 820.049 |
| V-L Molecular Weight | - | 43.189 | 18.365 | 43.189 | 43.189 | 43.189 | 43.189 | 43.189 | 40.872 | 19.096 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 15,627 | 10,146 | 15,627 | 735 | 14,892 | 14,892 | 14,892 | 2184 | 168 |
| V-L Flowrate (lb/hr) | - | 674,917 | 186,333 | 674,917 | 31,745 | 643,172 | 643,172 | 643,172 | 89,279 | 3,212 |
| Solids Flowrate (lb/hr) | 16,949 | 8.5 | 4.24 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 128 | 131 | 131 | 86 | 159 | 99 | 42 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 200.1 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 457.1 | 225.2 | 457.1 | 457.1 | 443.8 | 459.9 | 442.4 | -36.6 | 155.8 |
| Density (lb/ft$^3$) | - | 24.032 | 931.856 | 24.032 | 24.032 | 25.593 | 41.190 | 45.681 | 2.622 | 820.049 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9874 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0081 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 5,688 | - | 48,879 | 48,879 | 44,065 | 44,065 | 222 | 222 | 41,537 | 41,760 |
| V-L Flowrate (kg/hr) | 249,799 | - | 880,563 | 880,563 | 793,842 | 793,842 | 4,000 | 4,000 | 748,306 | 752,306 |
| Solids Flowrate (kg/hr) | 3.85 | 2,464 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 950 | 250 | 593 | 354 | 593 | 364 | 149 | 21 | 143 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 14.98 | 11.85 | 2.42 | 2.23 | 0.51 | 0.51 | 0.97 | 0.51 |
| Enthalpy (kJ/kg) | -182.2 | 902.5 | 1086.0 | 3593.2 | 3138.2 | 3673.5 | 3197.3 | 626.2 | 90.8 | 603.4 |
| Density (kg/m$^3$) | 731.673 | - | 811.141 | 31.472 | 8.748 | 5.643 | 1.747 | 918.523 | 998.496 | 923.404 |
| V-L Molecular Weight | 43.916 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 12,539 | - | 107,753 | 107,753 | 97,142 | 97,142 | 489 | 489 | 91,569 | 92,059 |
| V-L Flowrate (lb/hr) | 550,681 | - | 1,941,200 | 1,941,200 | 1,750,026 | 1,750,026 | 8,818 | 8,818 | 1,649,641 | 1,658,459 |
| Solids Flowrate (lb/hr) | 8.5 | 5,432 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 1742 | 482 | 1100 | 670 | 1100 | 688 | 299 | 71 | 290 |
| Pressure (psia) | 2218.5 | 13.1 | 2172.2 | 1718.0 | 351.6 | 323.7 | 73.9 | 73.7 | 140.1 | 73.7 |
| Enthalpy (Btu/lb) | -78.4 | 388.0 | 466.9 | 1544.9 | 1349.3 | 1579.5 | 1374.8 | 269.2 | 39.0 | 259.5 |
| Density (lb/ft$^3$) | 731.673 | - | 811.141 | 31.472 | 8.748 | 5.643 | 1.747 | 918.523 | 998.496 | 923.404 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 8,915 | 8,915 |
| V-L Flowrate (kg/hr) | 160,614 | 160,614 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 155 | 250 |
| Pressure (MPa, abs) | 15.00 | 14.98 |
| Enthalpy (kJ/kg) | 663.9 | 1086.0 |
| Density (kg/m$^3$) | 920.370 | 811.146 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 19,654 | 19,654 |
| V-L Flowrate (lb/hr) | 354,073 | 354,073 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 312 | 482 |
| Pressure (psia) | 2175.5 | 2172.2 |
| Enthalpy (Btu/lb) | 285.5 | 466.9 |
| Density (lb/ft$^3$) | 920.370 | 811.146 |

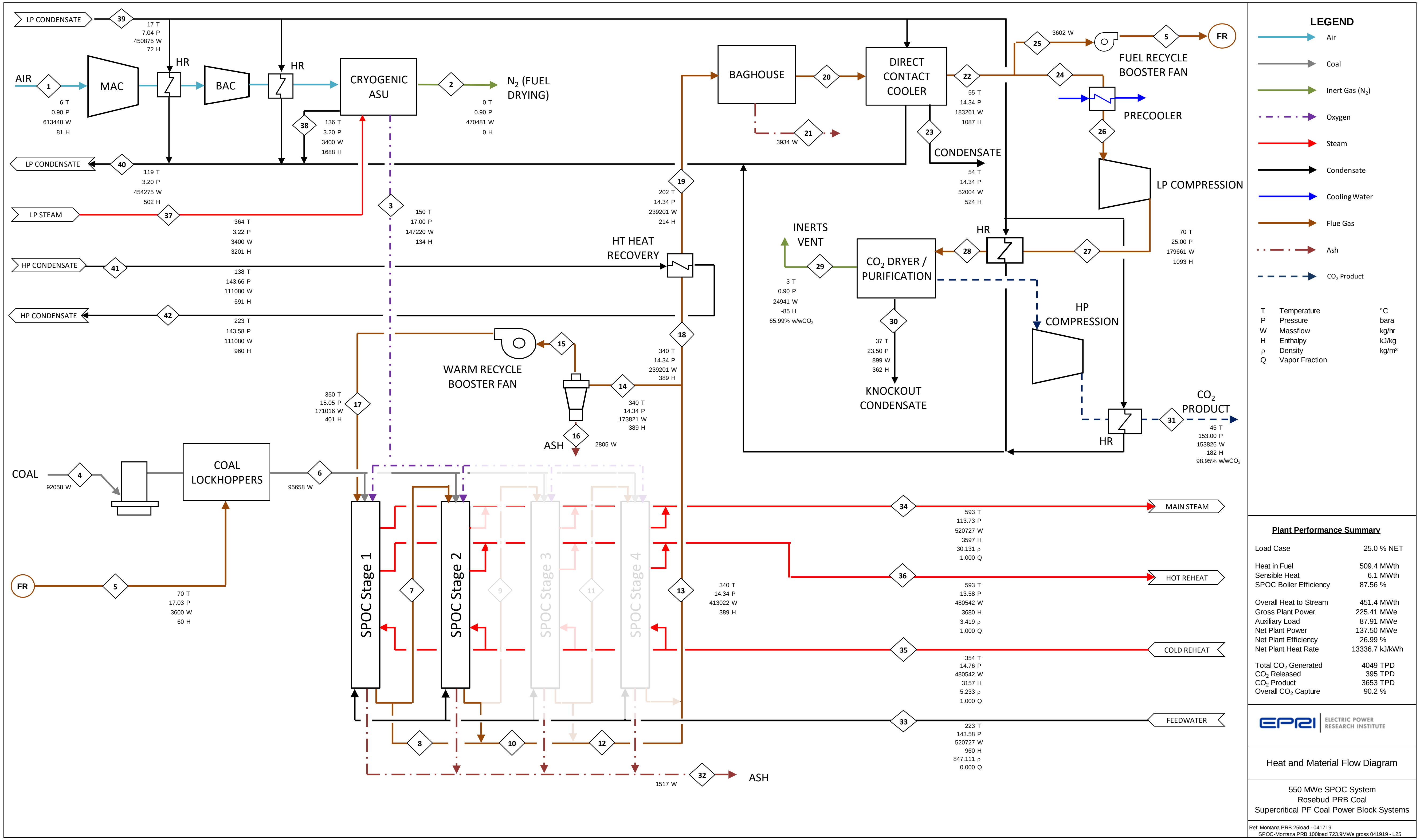



**Figure B-17**
**Part-Load Case Montana PRB 25% Load – Boiler Island – SI Units**

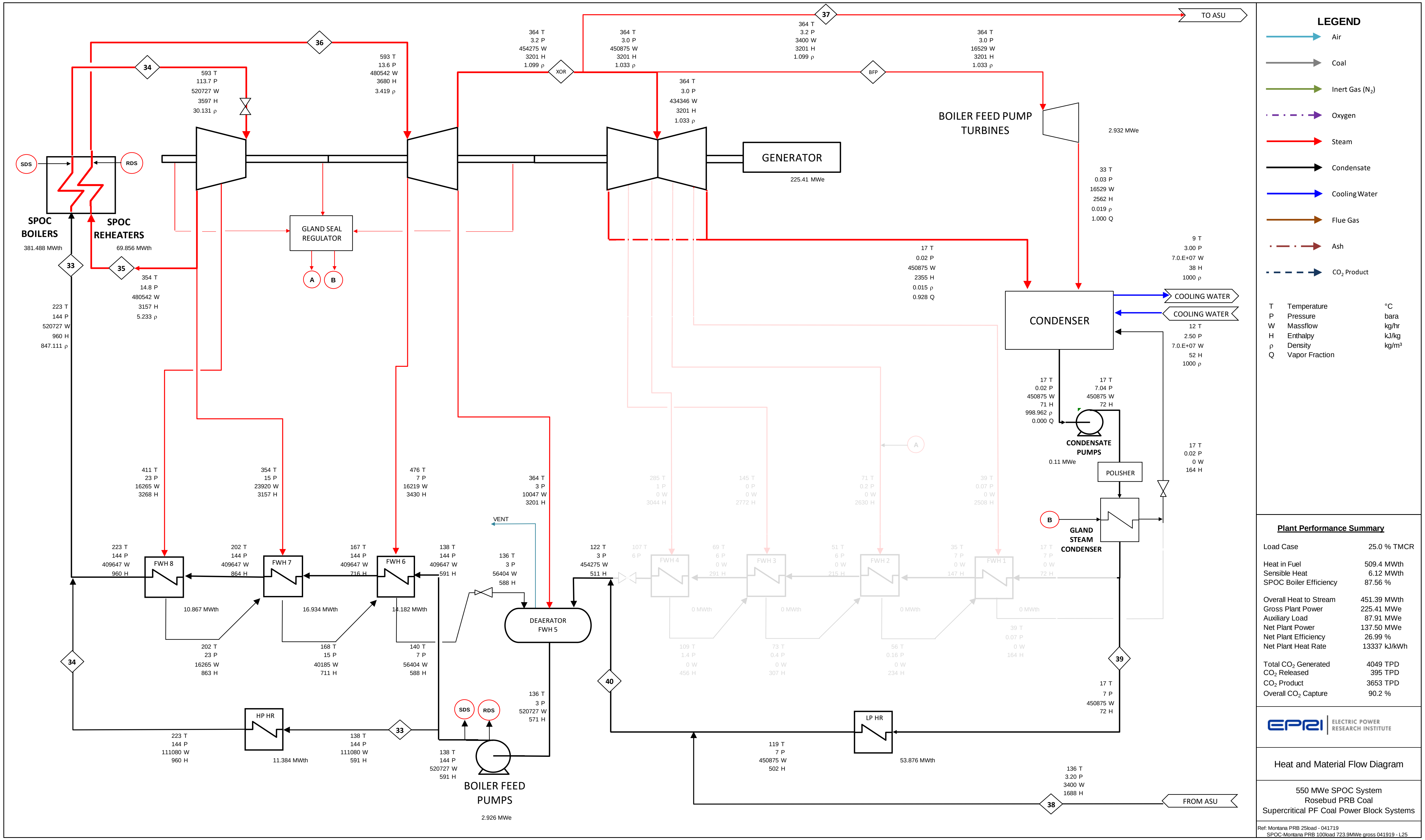



**Figure B-18**
**Part-Load Case Montana PRB 25% Load – Turbine Island – SI Units**

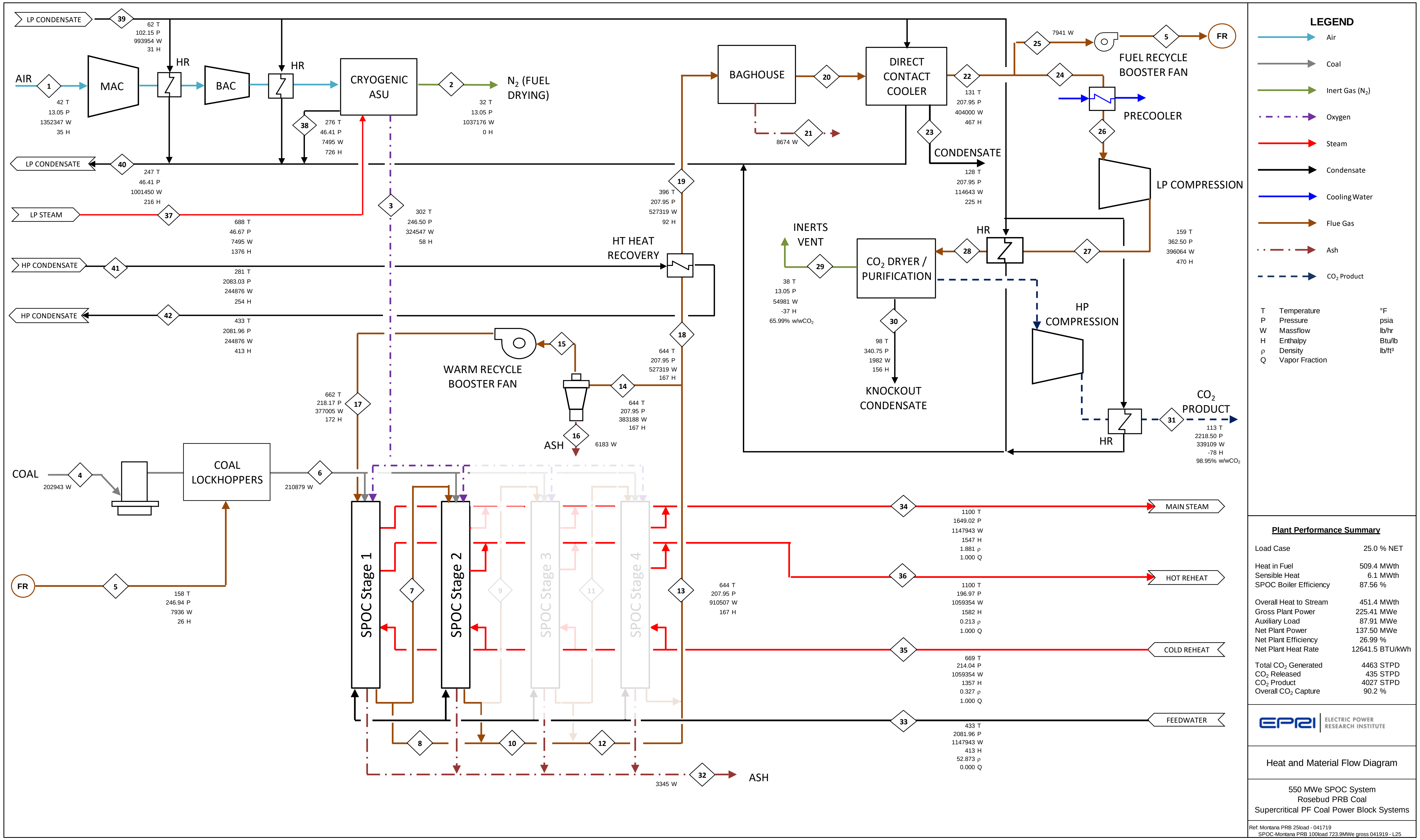



**Figure B-19**
**Part-Load Case Montana PRB 25% Load – Boiler Island – English Units**

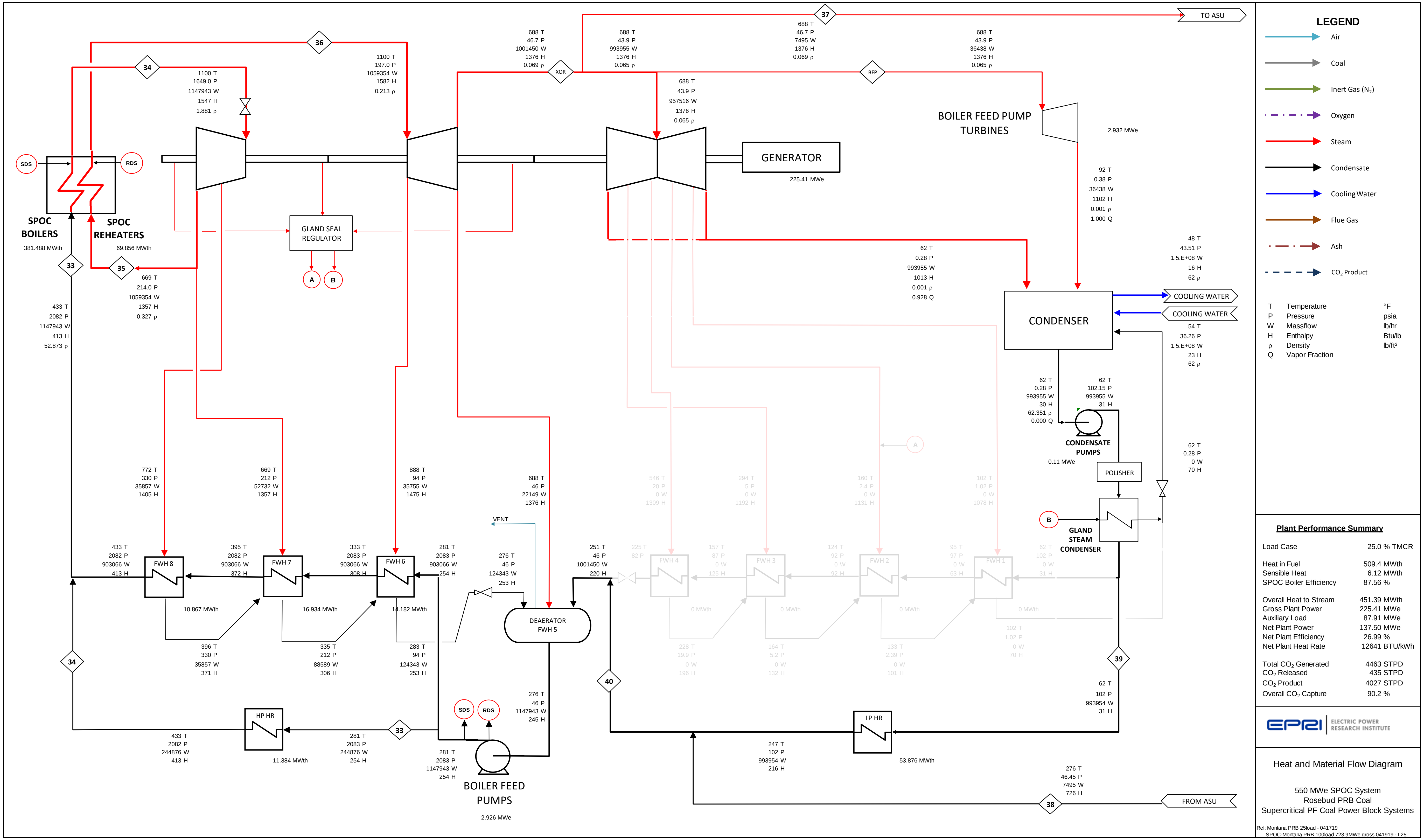



**Figure B-20**
**Part-Load Case Montana PRB 25% Load – Turbine Island – English Units**

**Table B-6**
**Part-Load Case Montana PRB 25% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9213 | 0.9213 | 0.5543 | 0.5543 | 0.5518 | 0.5526 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0110 | 0.0110 | 0.4020 | 0.4020 | 0.4047 | 0.4039 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0110 | 0.0110 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0169 | 0.0169 | 0.0101 | 0.0101 | 0.0101 | 0.0101 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0395 | 0.0395 | 0.0237 | 0.0237 | 0.0236 | 0.0237 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 21,230 | 16,535 | 4563 | - | 83 | 83 | 5068 | 3654 | 0 | 12,219 |
| V-L Flowrate (kg/hr) | 613,448 | 463,857 | 147,220 | 0 | 3,600 | 3,600 | 168,728 | 121,662 | 0 | 406,221 |
| Solids Flowrate (kg/hr) | 0 | 6624 | 0 | 92,058 | 0 | 92,058 | 2188 | 1578 | 0 | 6800 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 16 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.50 | 1.50 | 1.50 | 1.49 | 1.49 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 20.7 | 59.8 | 22.2 | 388.6 | 388.6 | 388.6 | 388.6 |
| Density (kg/m$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 770.920 | 9.452 | 9.452 | 9.452 | 9.452 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.189 | 43.189 | 33.294 | 33.294 | 33.226 | 33.246 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 46,801 | 36,452 | 10,059 | - | 184 | 184 | 11,172 | 8056 | 0 | 26,936 |
| V-L Flowrate (lb/hr) | 1,352,347 | 1,022,573 | 324,547 | 0 | 7,936 | 7,936 | 371,961 | 268,204 | 1 | 895,515 |
| Solids Flowrate (lb/hr) | 0 | 14,604 | 0 | 202,943 | 0 | 202,943 | 4824 | 3478 | 0 | 14,991 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 61 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 217.8 | 217.5 | 217.5 | 216.5 | 216.5 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 8.9 | 25.7 | 9.5 | 167.1 | 167.1 | 167.1 | 167.1 |
| Density (lb/ft$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 770.920 | 9.452 | 9.452 | 9.452 | 9.452 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.6344 | 0.5526 | 0.5526 | 0.5526 | 0.5526 | 0.0000 | 0.5526 | 0.5526 | 0.5526 | 0.5526 |
| $H_2O$ | 0.3157 | 0.4039 | 0.4039 | 0.4039 | 0.4039 | 0.0000 | 0.4039 | 0.4039 | 0.4039 | 0.4039 |
| $N_2$ | 0.0075 | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0000 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.0116 | 0.0101 | 0.0101 | 0.0101 | 0.0101 | 0.0000 | 0.0101 | 0.0101 | 0.0101 | 0.0101 |
| $SO_2$ | 0.0035 | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0000 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0272 | 0.0237 | 0.0237 | 0.0237 | 0.0237 | 0.0000 | 0.0237 | 0.0237 | 0.0237 | 0.0237 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 0 | 12,219 | 12,219 | 5142 | 5142 | - | 5142 | 7076 | 7076 | 7076 |
| V-L Flowrate (kg/hr) | 0 | 406,222 | 406,222 | 170,959 | 170,959 | - | 170,959 | 235,263 | 235,263 | 235,263 |
| Solids Flowrate (kg/hr) | 0 | 6800 | 6800 | 2,862 | 57 | 2805 | 57 | 3938 | 3938 | 3.9 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.49 | 1.49 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 388.6 | 388.6 | 388.6 | 388.6 | 388.6 | 322.9 | 400.8 | 388.6 | 214.5 | 214.5 |
| Density ($kg/m^3$) | 9.452 | 9.452 | 9.452 | 9.452 | 9.315 | - | 9.759 | 9.452 | 12.421 | 12.421 |
| V-L Molecular Weight | 35.501 | 33.246 | 33.246 | 33.246 | 33.246 | - | 33.246 | 33.246 | 33.246 | 33.246 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 0 | 26,936 | 26,936 | 11,336 | 11,336 | - | 11,336 | 15,600 | 15,600 | 15,600 |
| V-L Flowrate (lb/hr) | 0 | 895,515 | 895,515 | 376,879 | 376,879 | - | 376,879 | 518,637 | 518,637 | 518,637 |
| Solids Flowrate (lb/hr) | 0 | 14,991 | 14,991 | 6309 | 126 | 6,183 | 126 | 8682 | 8682 | 8.7 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 662 | 644 | 396 | 396 |
| Pressure (psia) | 215.5 | 215.5 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 167.1 | 167.1 | 167.1 | 167.1 | 167.1 | 138.8 | 172.3 | 167.1 | 92.2 | 92.2 |
| Density ($lb/ft^3$) | 9.452 | 9.452 | 9.452 | 9.452 | 9.315 | - | 9.759 | 9.452 | 12.421 | 12.421 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9213 | 0.0002 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.6128 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0110 | 0.9924 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.9740 |
| $N_2$ | 0.0000 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0644 | 0.0000 |
| $O_2$ | 0.0000 | 0.0169 | 0.0000 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.1003 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0002 | 0.0071 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0219 |
| Ar | 0.0000 | 0.0395 | 0.0000 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.2225 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0028 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0010 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 4243 | 2833 | 4243 | 83 | 4160 | 4160 | 4160 | 610 | 47 |
| V-L Flowrate (kg/hr) | - | 183,259 | 52,003 | 183,259 | 3,600 | 179,659 | 179,659 | 179,659 | 24,939 | 897 |
| Solids Flowrate (kg/hr) | 3,934 | 1.97 | 0.98 | 1.97 | 1.97 | 1.97 | 1.97 | 1.97 | 1.97 | 1.97 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 54 | 55 | 55 | 30 | 70 | 37 | 3 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.38 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 1086.8 | 524.1 | 1086.8 | 1086.8 | 1055.8 | 1093.1 | 1052.6 | -85.2 | 362.4 |
| Density ($kg/m^3$) | - | 24.032 | 932.898 | 24.032 | 24.032 | 25.642 | 41.214 | 45.681 | 2.623 | 819.855 |
| V-L Molecular Weight | - | 43.189 | 18.355 | 43.189 | 43.189 | 43.189 | 43.189 | 43.189 | 40.872 | 19.096 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 9,354 | 6,246 | 9,354 | 184 | 9,170 | 9,170 | 9,170 | 1,345 | 104 |
| V-L Flowrate (lb/hr) | - | 403,996 | 114,641 | 403,996 | 7936 | 396,059 | 396,059 | 396,059 | 54,977 | 1978 |
| Solids Flowrate (lb/hr) | 8,674 | 4.3 | 2.17 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 128 | 131 | 131 | 86 | 159 | 99 | 38 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 200.5 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 467.3 | 225.3 | 467.3 | 467.3 | 453.9 | 470.0 | 452.6 | -36.6 | 155.8 |
| Density ($lb/ft^3$) | - | 24.032 | 932.898 | 24.032 | 24.032 | 25.642 | 41.214 | 45.681 | 2.623 | 819.855 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9874 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0081 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 3,503 | - | 28,905 | 28,905 | 26,674 | 26,674 | 189 | 189 | 25,027 | 25,216 |
| V-L Flowrate (kg/hr) | 153,824 | - | 520,727 | 520,727 | 480,542 | 480,542 | 3,400 | 3,400 | 450,875 | 454,275 |
| Solids Flowrate (kg/hr) | 1.97 | 1,517 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 950 | 223 | 593 | 354 | 593 | 364 | 136 | 17 | 119 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 14.36 | 11.37 | 1.48 | 1.36 | 0.32 | 0.32 | 0.70 | 0.32 |
| Enthalpy (kJ/kg) | -182.2 | 902.5 | 959.9 | 3597.3 | 3157.1 | 3680.5 | 3200.8 | 1688.3 | 71.5 | 501.7 |
| Density (kg/m$^3$) | 731.673 | - | 847.111 | 30.131 | 5.233 | 3.419 | 1.099 | 3.380 | 999.278 | 943.762 |
| V-L Molecular Weight | 43.916 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 7,722 | - | 63,721 | 63,721 | 58,803 | 58,803 | 416 | 416 | 55,173 | 55,589 |
| V-L Flowrate (lb/hr) | 339,104 | - | 1,147,943 | 1,147,943 | 1,059,354 | 1,059,354 | 7,495 | 7,495 | 993,954 | 1,001,450 |
| Solids Flowrate (lb/hr) | 4.3 | 3,345 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 1742 | 433 | 1100 | 669 | 1100 | 688 | 276 | 62 | 247 |
| Pressure (psia) | 2218.5 | 13.1 | 2082.0 | 1649.0 | 214.0 | 197.0 | 46.7 | 46.4 | 102.1 | 46.4 |
| Enthalpy (Btu/lb) | -78.4 | 388.0 | 412.7 | 1546.7 | 1357.5 | 1582.5 | 1376.2 | 725.9 | 30.8 | 215.7 |
| Density (lb/ft$^3$) | 731.673 | - | 847.111 | 30.131 | 5.233 | 3.419 | 1.099 | 3.380 | 999.278 | 943.762 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 6,166 | 6,166 |
| V-L Flowrate (kg/hr) | 111,080 | 111,080 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 138 | 223 |
| Pressure (MPa, abs) | 14.37 | 14.36 |
| Enthalpy (kJ/kg) | 590.9 | 959.9 |
| Density (kg/m$^3$) | 935.220 | 847.112 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 13,593 | 13,593 |
| V-L Flowrate (lb/hr) | 244,876 | 244,876 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 281 | 433 |
| Pressure (psia) | 2083.0 | 2082.0 |
| Enthalpy (Btu/lb) | 254.1 | 412.7 |
| Density (lb/ft$^3$) | 935.220 | 847.112 |

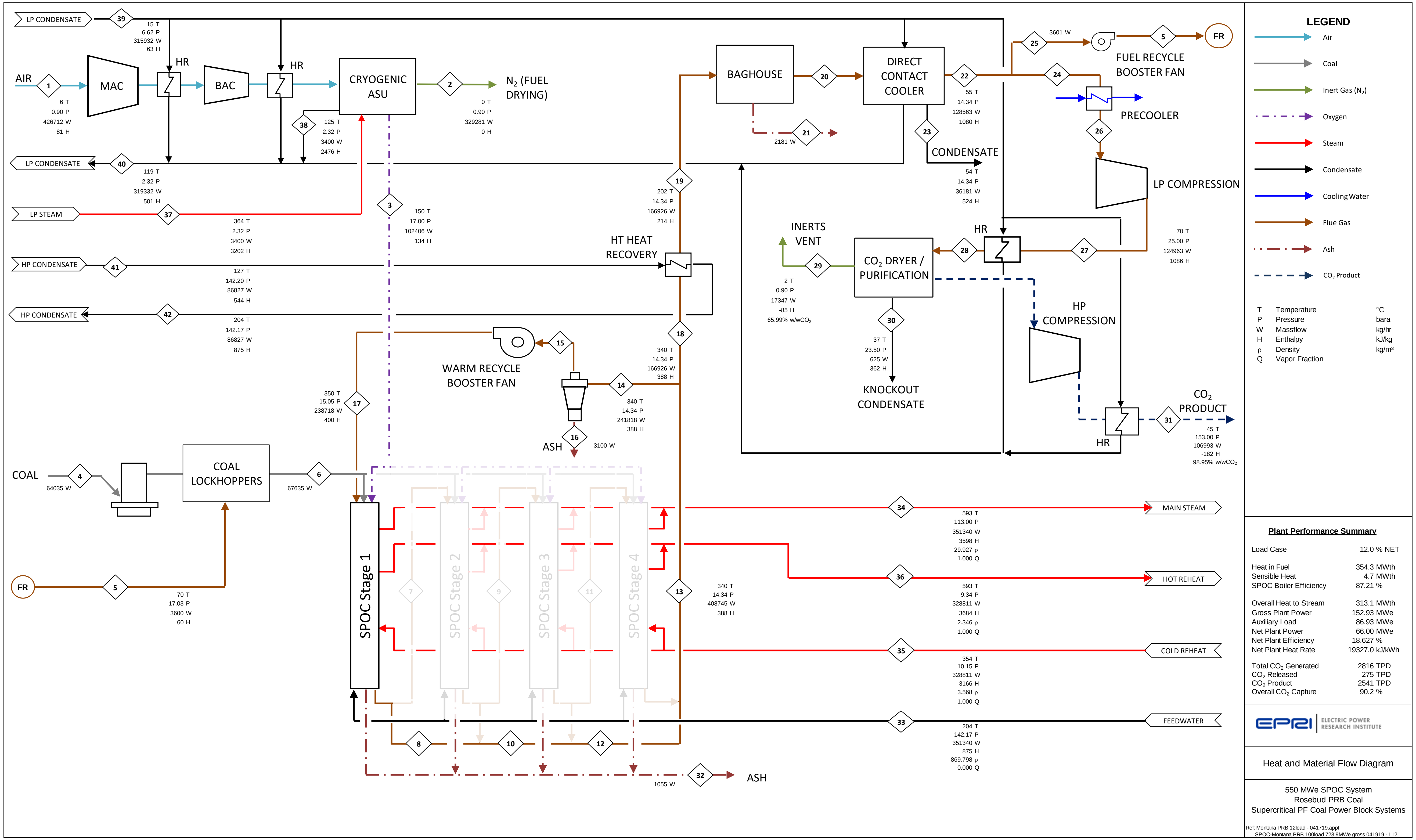



**Figure B-21**
**Part-Load Case Montana PRB 12% Load – Boiler Island – SI Units**

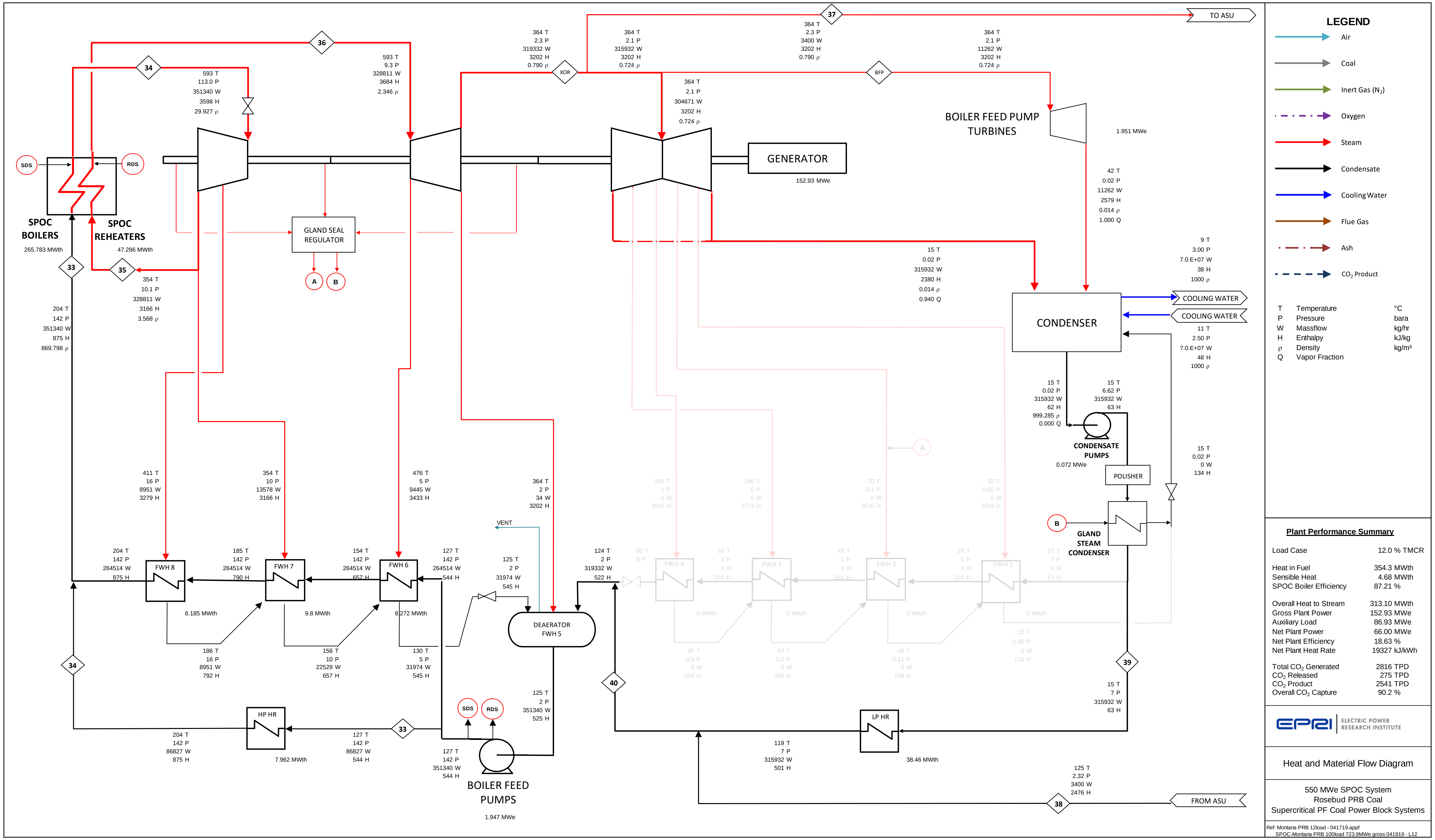



**Figure B-22**
**Part-Load Case Montana PRB 12% Load – Turbine Island – SI Units**

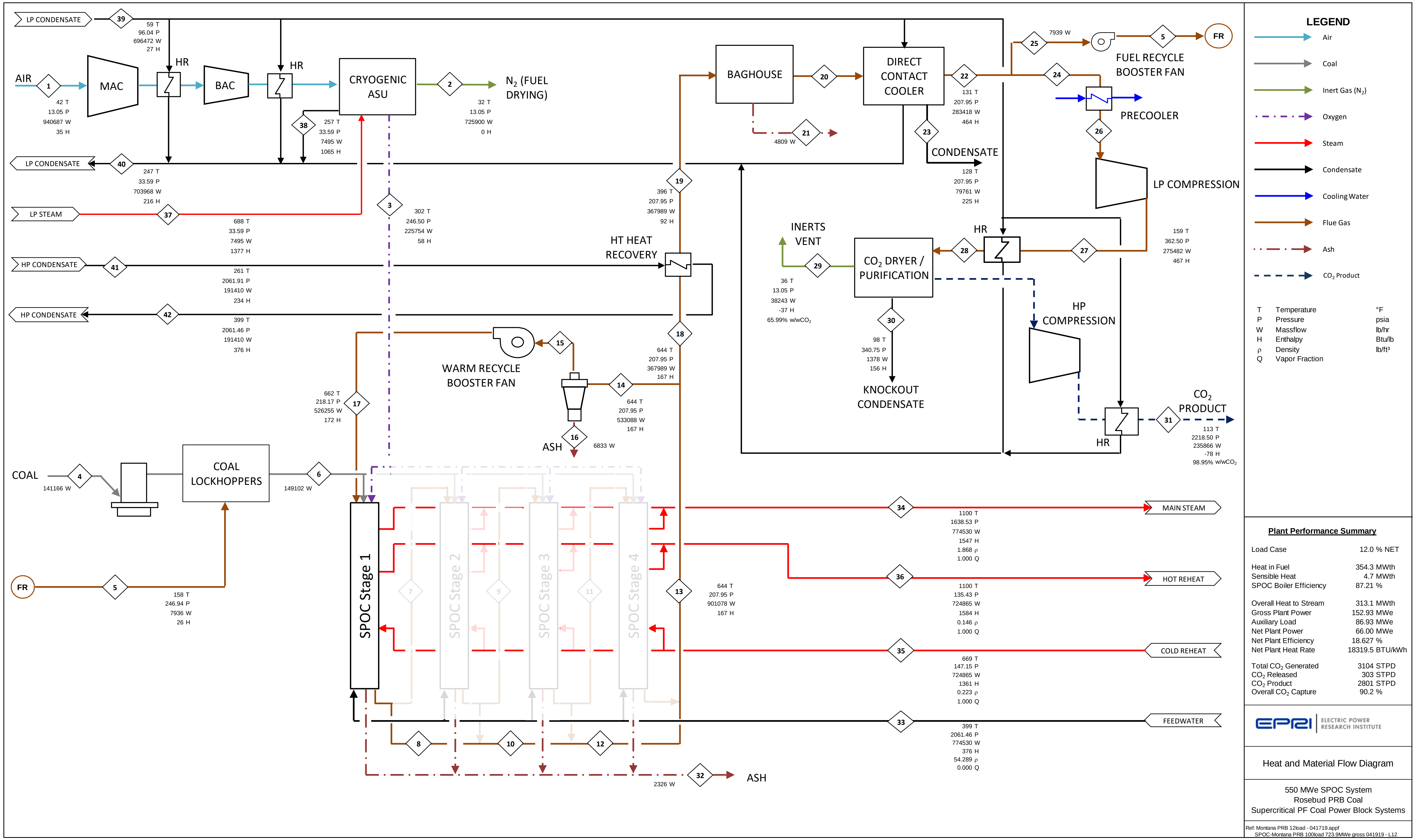



**Figure B-23**
**Part-Load Case Montana PRB 12% Load – Boiler Island – English Units**

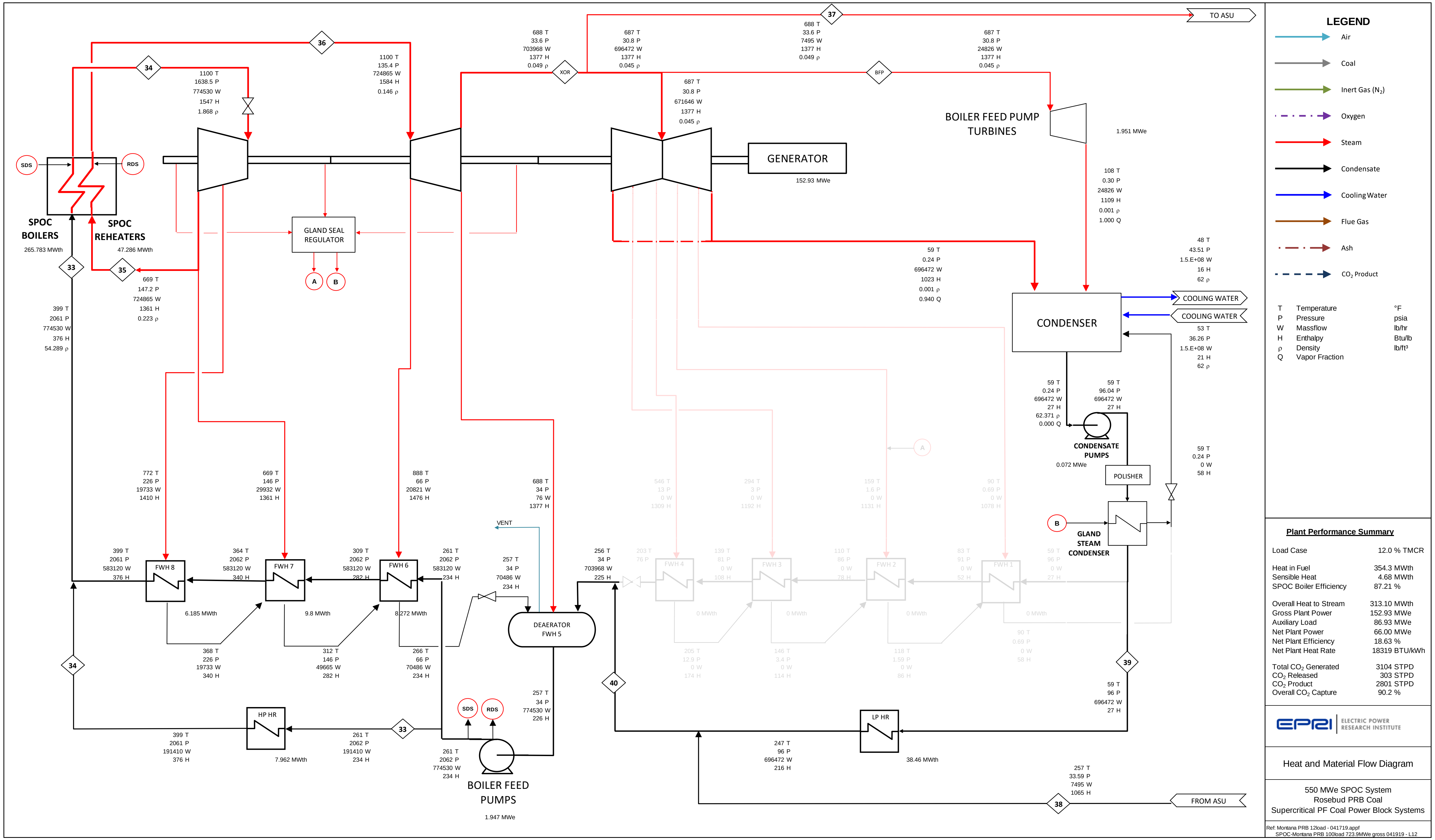



**Figure B-24**
**Part-Load Case Montana PRB 12% Load – Turbine Island – English Units**

**Table B-7**
**Part-Load Case Montana PRB 12% Load Stream Data**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0003 | 0.0004 | 0.0000 | 0.0000 | 0.9213 | 0.9213 | 0.5544 | 0.5544 | 0.6344 | 0.5544 |
| $H_2O$ | 0.0062 | 0.0000 | 0.0000 | 0.0000 | 0.0110 | 0.0110 | 0.4019 | 0.4019 | 0.3157 | 0.4019 |
| $N_2$ | 0.7761 | 0.9951 | 0.0050 | 0.0000 | 0.0110 | 0.0110 | 0.0066 | 0.0066 | 0.0075 | 0.0066 |
| $O_2$ | 0.2082 | 0.0027 | 0.9590 | 0.0000 | 0.0169 | 0.0169 | 0.0101 | 0.0101 | 0.0116 | 0.0101 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 | 0.0030 | 0.0030 | 0.0035 | 0.0030 |
| Ar | 0.0092 | 0.0019 | 0.0360 | 0.0000 | 0.0395 | 0.0395 | 0.0238 | 0.0238 | 0.0272 | 0.0238 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| NO/$NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0002 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 14,767 | 11,502 | 3174 | - | 83 | 83 | 0 | 12,115 | 0 | 12,115 |
| V-L Flowrate (kg/hr) | 426,712 | 322,657 | 102,406 | 0 | 3600 | 3600 | 0 | 403,398 | 0 | 403,398 |
| Solids Flowrate (kg/hr) | 0 | 6,624 | 0 | 64,035 | 0 | 64,035 | 0 | 5,347 | 0 | 5,347 |
| | | | | | | | | | | |
| Temperature (°C) | 6 | 0 | 150 | 15 | 70 | 17 | 340 | 340 | 340 | 340 |
| Pressure (MPa, abs) | 0.09 | 0.09 | 1.70 | 0.09 | 1.70 | 1.45 | 1.45 | 1.45 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 81.1 | -0.2 | 134.0 | 20.7 | 59.8 | 22.8 | 388.1 | 388.1 | 388.1 | 388.1 |
| Density (kg/m$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 758.872 | 9.466 | 9.466 | 9.466 | 9.466 |
| V-L Molecular Weight | 28.896 | 28.053 | 32.265 | - | 43.189 | 43.189 | 33.298 | 33.298 | 35.501 | 33.298 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 32,554 | 25,356 | 6,997 | - | 184 | 184 | 0 | 26,707 | 0 | 26,707 |
| V-L Flowrate (lb/hr) | 940,687 | 711,297 | 225,754 | 0 | 7936 | 7936 | 1 | 889,291 | 0 | 889,292 |
| Solids Flowrate (lb/hr) | 0 | 14,604 | 0 | 141,166 | 0 | 141,166 | 0 | 11,786 | 0 | 11,786 |
| | | | | | | | | | | |
| Temperature (°F) | 42 | 32 | 302 | 59 | 158 | 62 | 644 | 644 | 644 | 644 |
| Pressure (psia) | 13.1 | 13.1 | 246.5 | 13.1 | 246.9 | 210.4 | 209.9 | 209.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 34.9 | -0.1 | 57.6 | 8.9 | 25.7 | 9.8 | 166.9 | 166.9 | 166.9 | 166.9 |
| Density (lb/ft$^3$) | 1.123 | 1.112 | 15.610 | 800.000 | 27.305 | 758.872 | 9.466 | 9.466 | 9.466 | 9.466 |

| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.6344 | 0.5544 | 0.5544 | 0.5544 | 0.5544 | 0.0000 | 0.5544 | 0.5544 | 0.5544 | 0.5544 |
| $H_2O$ | 0.3157 | 0.4019 | 0.4019 | 0.4019 | 0.4019 | 0.0000 | 0.4019 | 0.4019 | 0.4019 | 0.4019 |
| $N_2$ | 0.0075 | 0.0066 | 0.0066 | 0.0066 | 0.0066 | 0.0000 | 0.0066 | 0.0066 | 0.0066 | 0.0066 |
| $O_2$ | 0.0116 | 0.0101 | 0.0101 | 0.0101 | 0.0101 | 0.0000 | 0.0101 | 0.0101 | 0.0101 | 0.0101 |
| $SO_2$ | 0.0035 | 0.0030 | 0.0030 | 0.0030 | 0.0030 | 0.0000 | 0.0030 | 0.0030 | 0.0030 | 0.0030 |
| Ar | 0.0272 | 0.0238 | 0.0238 | 0.0238 | 0.0238 | 0.0000 | 0.0238 | 0.0238 | 0.0238 | 0.0238 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| TOTAL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 0 | 12,115 | 12,115 | 7167 | 7167 | - | 7167 | 4948 | 4948 | 4948 |
| V-L Flowrate (kg/hr) | 0 | 403,398 | 403,398 | 238,655 | 238,655 | - | 238,655 | 164,743 | 164,743 | 164,743 |
| Solids Flowrate (kg/hr) | 0 | 5347 | 5347 | 3163 | 63 | 3100 | 63 | 2183 | 2183 | 2.2 |
| | | | | | | | | | | |
| Temperature (°C) | 340 | 340 | 340 | 340 | 340 | 340 | 350 | 340 | 202 | 202 |
| Pressure (MPa, abs) | 1.43 | 1.43 | 1.43 | 1.43 | 1.41 | 1.41 | 1.50 | 1.43 | 1.43 | 1.43 |
| Enthalpy (kJ/kg) | 388.1 | 388.1 | 388.1 | 388.1 | 388.1 | 322.9 | 400.4 | 388.1 | 214.3 | 214.3 |
| Density ($kg/m^3$) | 9.466 | 9.466 | 9.466 | 9.466 | 9.329 | - | 9.774 | 9.466 | 12.439 | 12.439 |
| V-L Molecular Weight | 35.501 | 33.298 | 33.298 | 33.298 | 33.298 | - | 33.298 | 33.298 | 33.298 | 33.298 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 0 | 26,707 | 26,707 | 15,800 | 15,800 | - | 15,800 | 10,907 | 10,907 | 10,907 |
| V-L Flowrate (lb/hr) | 0 | 889,292 | 889,292 | 526,115 | 526,115 | - | 526,115 | 363,175 | 363,175 | 363,175 |
| Solids Flowrate (lb/hr) | 0 | 11,786 | 11,786 | 6,973 | 139 | 6,833 | 139 | 4,813 | 4,813 | 4.8 |
| | | | | | | | | | | |
| Temperature (°F) | 644 | 644 | 644 | 644 | 644 | 644 | 662 | 644 | 396 | 396 |
| Pressure (psia) | 207.9 | 207.9 | 207.9 | 207.9 | 204.9 | 204.9 | 218.2 | 207.9 | 207.9 | 207.9 |
| Enthalpy (Btu/lb) | 166.9 | 166.9 | 166.9 | 166.9 | 166.9 | 138.8 | 172.1 | 166.9 | 92.1 | 92.1 |
| Density ($lb/ft^3$) | 9.466 | 9.466 | 9.466 | 9.466 | 9.329 | - | 9.774 | 9.466 | 12.439 | 12.439 |

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.0000 | 0.9213 | 0.0002 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.9213 | 0.6128 | 0.0002 |
| $H_2O$ | 0.0000 | 0.0110 | 0.9923 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0000 | 0.9741 |
| $N_2$ | 0.0000 | 0.0110 | 0.0000 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0110 | 0.0644 | 0.0000 |
| $O_2$ | 0.0000 | 0.0169 | 0.0000 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.0169 | 0.1003 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0002 | 0.0072 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0000 | 0.0219 |
| Ar | 0.0000 | 0.0395 | 0.0000 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.0395 | 0.2225 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0028 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0010 |
| TOTAL | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | - | 2977 | 1971 | 2977 | 83 | 2893 | 2893 | 2893 | 424 | 33 |
| V-L Flowrate (kg/hr) | - | 128,562 | 36,180 | 128,562 | 3,600 | 124,962 | 124,962 | 124,962 | 17,346 | 624 |
| Solids Flowrate (kg/hr) | 2,181 | 1.09 | 0.55 | 1.09 | 1.09 | 1.09 | 1.09 | 1.09 | 1.09 | 1.09 |
| | | | | | | | | | | |
| Temperature (°C) | 202 | 55 | 54 | 55 | 55 | 30 | 70 | 37 | 2 | 37 |
| Pressure (MPa, abs) | 0.09 | 1.43 | 1.43 | 1.43 | 1.43 | 1.38 | 2.50 | 2.40 | 0.09 | 2.35 |
| Enthalpy (kJ/kg) | 191.9 | 1079.6 | 524.0 | 1079.6 | 1079.6 | 1048.6 | 1085.9 | 1045.4 | -85.2 | 362.4 |
| Density (kg/m$^3$) | - | 24.032 | 932.913 | 24.032 | 24.032 | 25.658 | 41.222 | 45.680 | 2.623 | 821.044 |
| V-L Molecular Weight | - | 43.189 | 18.358 | 43.189 | 43.189 | 43.189 | 43.189 | 43.189 | 40.872 | 19.096 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | - | 6562 | 4345 | 6562 | 184 | 6378 | 6378 | 6378 | 936 | 72 |
| V-L Flowrate (lb/hr) | - | 283,416 | 79,760 | 283,416 | 7,936 | 275,479 | 275,479 | 275,479 | 38,240 | 1,376 |
| Solids Flowrate (lb/hr) | 4,809 | 2.4 | 1.20 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 |
| | | | | | | | | | | |
| Temperature (°F) | 396 | 131 | 128 | 131 | 131 | 86 | 159 | 99 | 36 | 98 |
| Pressure (psia) | 13.1 | 207.9 | 207.9 | 207.9 | 207.9 | 200.6 | 362.5 | 348.0 | 13.1 | 340.8 |
| Enthalpy (Btu/lb) | 82.5 | 464.2 | 225.3 | 464.2 | 464.2 | 450.8 | 466.9 | 449.5 | -36.6 | 155.8 |
| Density (lb/ft$^3$) | - | 24.032 | 932.913 | 24.032 | 24.032 | 25.658 | 41.222 | 45.680 | 2.623 | 821.044 |

| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| V-L Mole Fraction | | | | | | | | | | |
| $CO_2$ | 0.9874 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $H_2O$ | 0.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| $N_2$ | 0.0019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $O_2$ | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ar | 0.0081 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | | | | | | | | | | |
| V-L Flowrate ($kg_{mol}$/hr) | 2,436 | - | 19,502 | 19,502 | 18,252 | 18,252 | 189 | 189 | 17,537 | 17,726 |
| V-L Flowrate (kg/hr) | 106,992 | - | 351,340 | 351,340 | 328,811 | 328,811 | 3,400 | 3,400 | 315,932 | 319,332 |
| Solids Flowrate (kg/hr) | 1.09 | 1,055 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°C) | 45 | 950 | 204 | 593 | 354 | 593 | 364 | 125 | 15 | 119 |
| Pressure (MPa, abs) | 15.30 | 0.09 | 14.22 | 11.30 | 1.01 | 0.93 | 0.23 | 0.23 | 0.66 | 0.23 |
| Enthalpy (kJ/kg) | -182.2 | 902.5 | 874.6 | 3597.9 | 3166.2 | 3683.9 | 3202.4 | 2476.4 | 63.0 | 501.2 |
| Density (kg/m$^3$) | 731.673 | - | 869.798 | 29.927 | 3.568 | 2.346 | 0.790 | 1.452 | 999.586 | 943.790 |
| V-L Molecular Weight | 43.916 | - | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 | 18.015 |
| | | | | | | | | | | |
| V-L Flowrate ($lb_{mol}$/hr) | 5,371 | - | 42,993 | 42,993 | 40,236 | 40,236 | 416 | 416 | 38,660 | 39,076 |
| V-L Flowrate (lb/hr) | 235,864 | - | 774,530 | 774,530 | 724,865 | 724,865 | 7,495 | 7,495 | 696,472 | 703,968 |
| Solids Flowrate (lb/hr) | 2.4 | 2,326 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | |
| Temperature (°F) | 113 | 1742 | 399 | 1100 | 669 | 1100 | 688 | 257 | 59 | 247 |
| Pressure (psia) | 2218.5 | 13.1 | 2061.5 | 1638.5 | 147.2 | 135.4 | 33.6 | 33.6 | 96.0 | 33.6 |
| Enthalpy (Btu/lb) | -78.4 | 388.0 | 376.0 | 1547.0 | 1361.3 | 1583.9 | 1376.9 | 1064.8 | 27.1 | 215.5 |
| Density (lb/ft$^3$) | 731.673 | - | 869.798 | 29.927 | 3.568 | 2.346 | 0.790 | 1.452 | 999.586 | 943.790 |

| | 41 | 42 |
|---|---|---|
| V-L Mole Fraction | | |
| $CO_2$ | 0.0000 | 0.0000 |
| $H_2O$ | 1.0000 | 1.0000 |
| $N_2$ | 0.0000 | 0.0000 |
| $O_2$ | 0.0000 | 0.0000 |
| $SO_2$ | 0.0000 | 0.0000 |
| Ar | 0.0000 | 0.0000 |
| HCl | 0.0000 | 0.0000 |
| $SO_3$ | 0.0000 | 0.0000 |
| $NO/NO_2$ | 0.0000 | 0.0000 |
| TOTAL | 1.0000 | 1.0000 |
| | | |
| V-L Flowrate ($kg_{mol}$/hr) | 4,820 | 4,820 |
| V-L Flowrate (kg/hr) | 86,827 | 86,827 |
| Solids Flowrate (kg/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°C) | 127 | 204 |
| Pressure (MPa, abs) | 14.22 | 14.22 |
| Enthalpy (kJ/kg) | 544.4 | 874.6 |
| Density (kg/$m^3$) | 944.318 | 869.799 |
| V-L Molecular Weight | 18.015 | 18.015 |
| | | |
| V-L Flowrate ($lb_{mol}$/hr) | 10,625 | 10,625 |
| V-L Flowrate (lb/hr) | 191,410 | 191,410 |
| Solids Flowrate (lb/hr) | 0.00 | 0.00 |
| | | |
| Temperature (°F) | 261 | 399 |
| Pressure (psia) | 2061.9 | 2061.5 |
| Enthalpy (Btu/lb) | 234.1 | 376.0 |
| Density (lb/$ft^3$) | 944.318 | 869.799 |

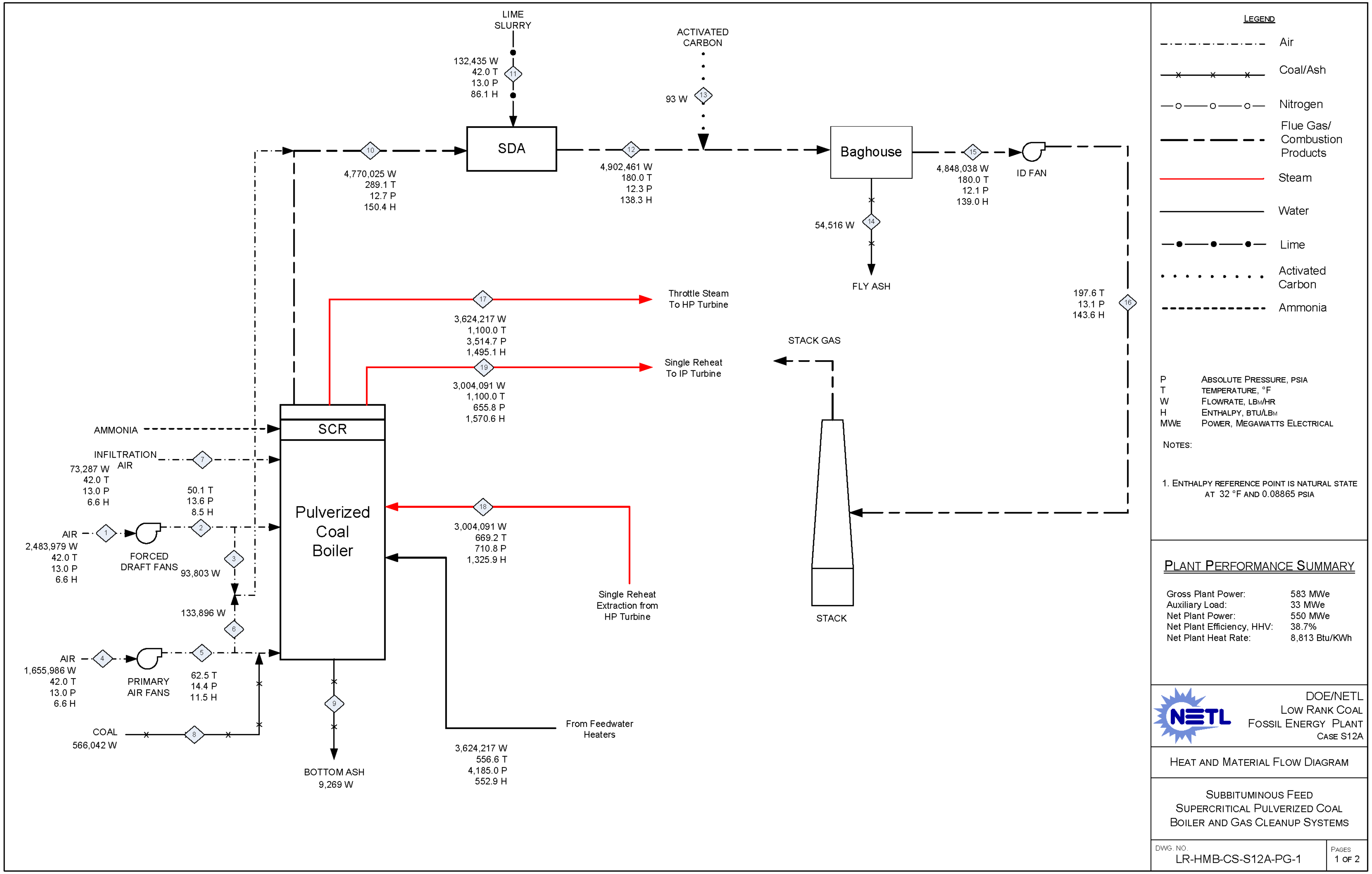



**Figure B-25**
**NETL Baseline Case S12A, Montana PRB Fuel, Boiler Island, 100% Load**

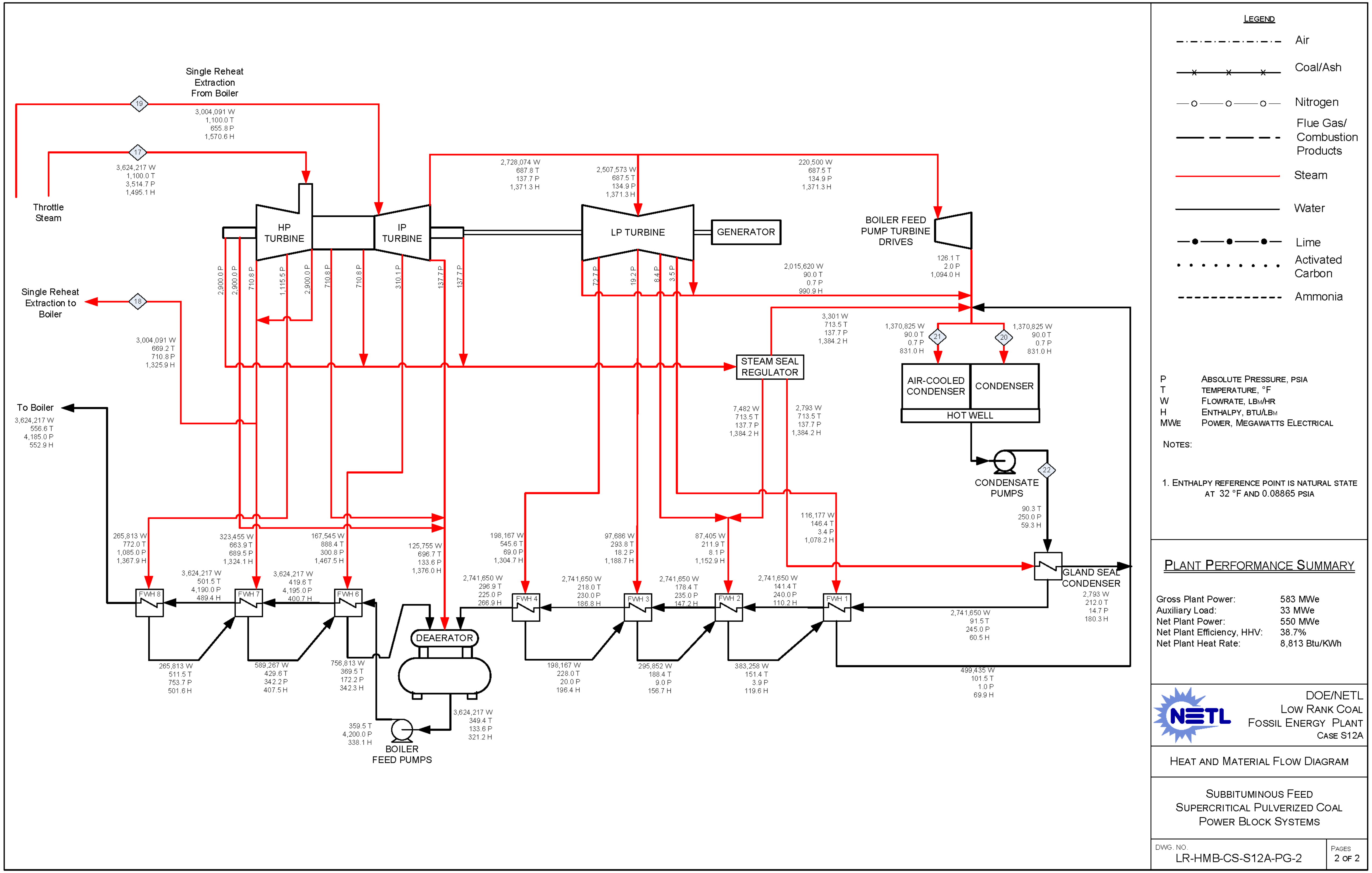



**Figure B-26**
**NETL Baseline Case S12A, Montana PRB Fuel, Turbine Island, 100% Load**

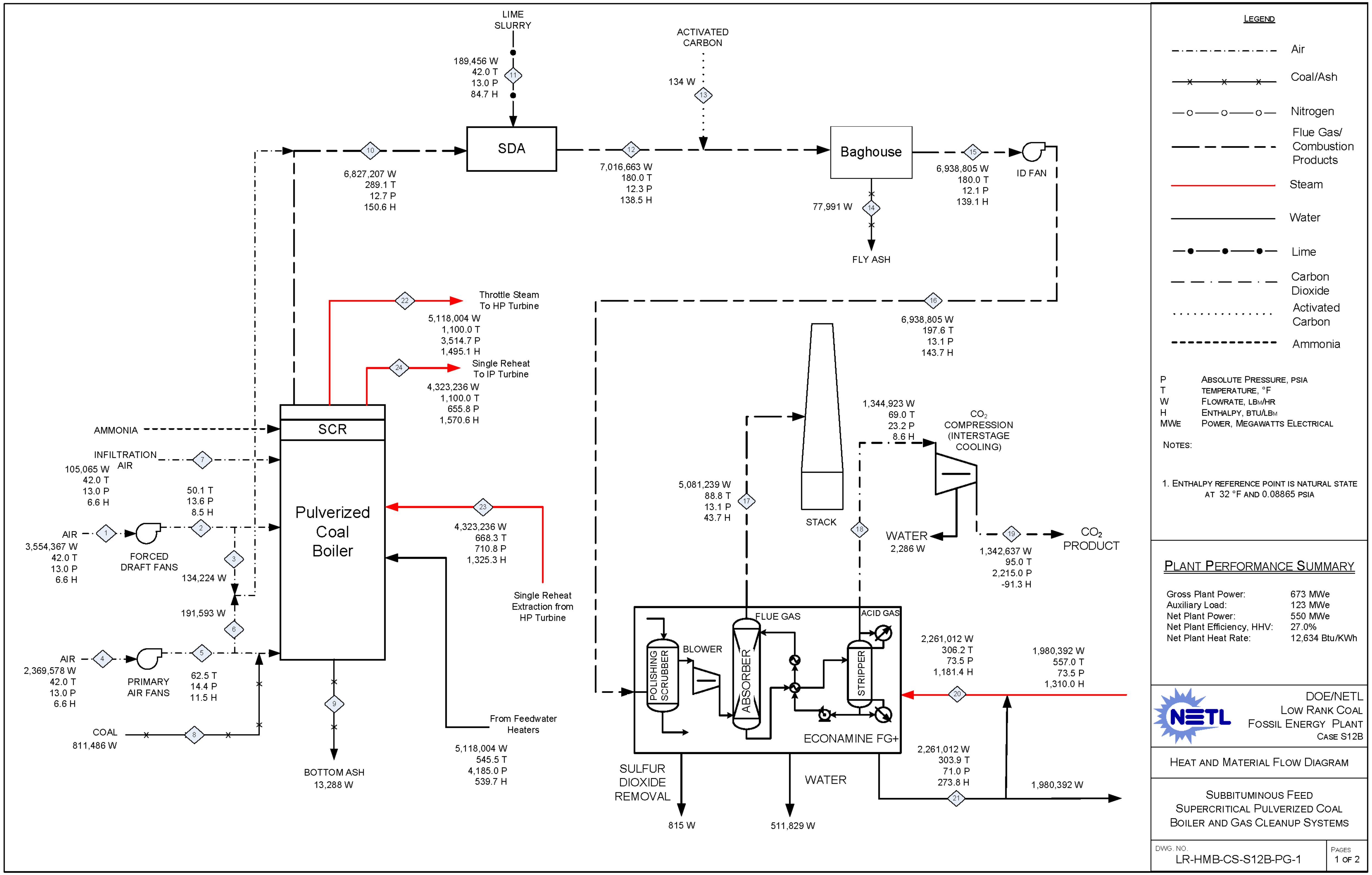



**Figure B-27**
**NETL Baseline Case S12B, Montana PRB Fuel, Boiler Island, 100% Load**

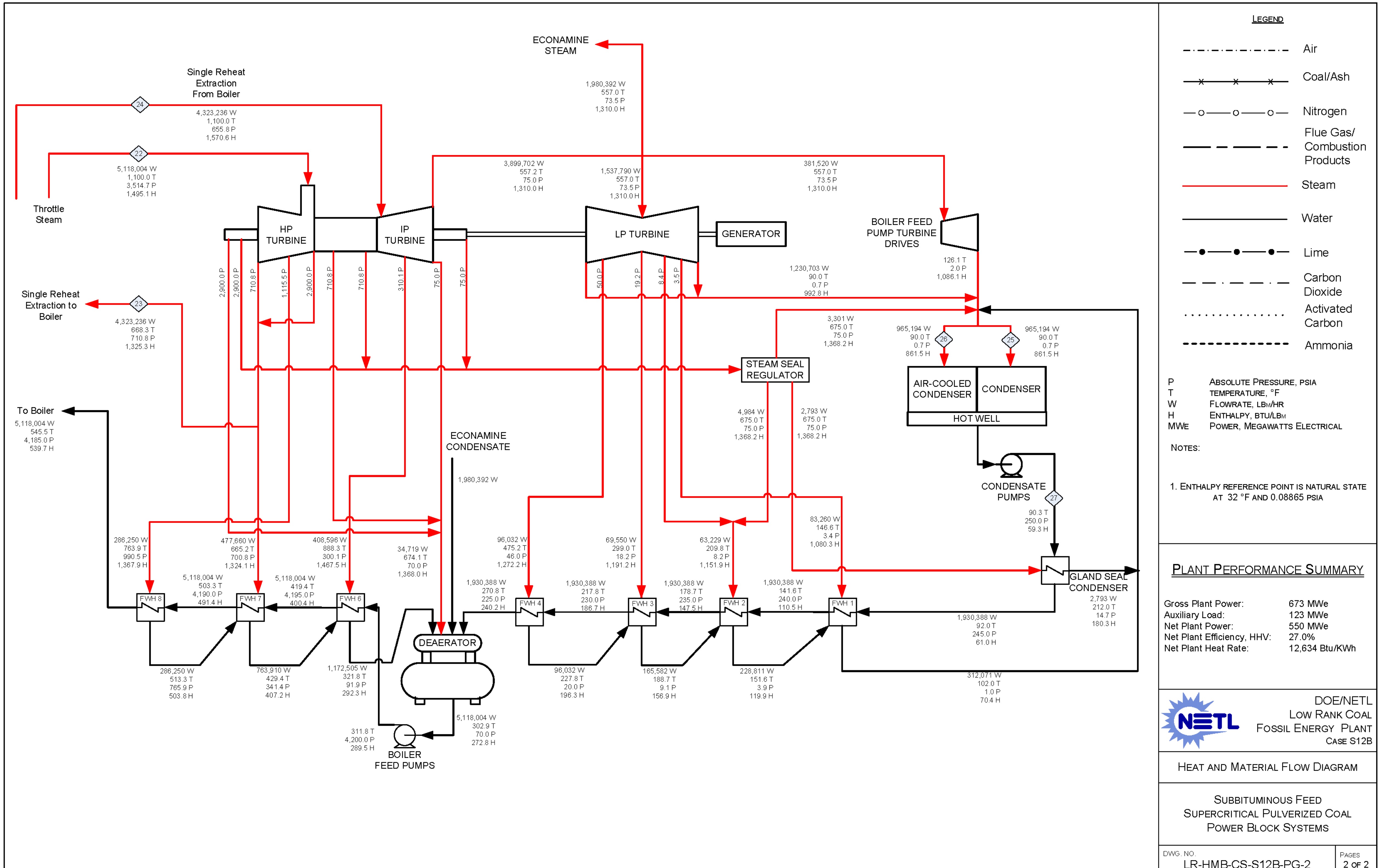



**Figure B-28**
**NETL Baseline Case S12B, Montana PRB Fuel, Turbine Island, 100% Load**

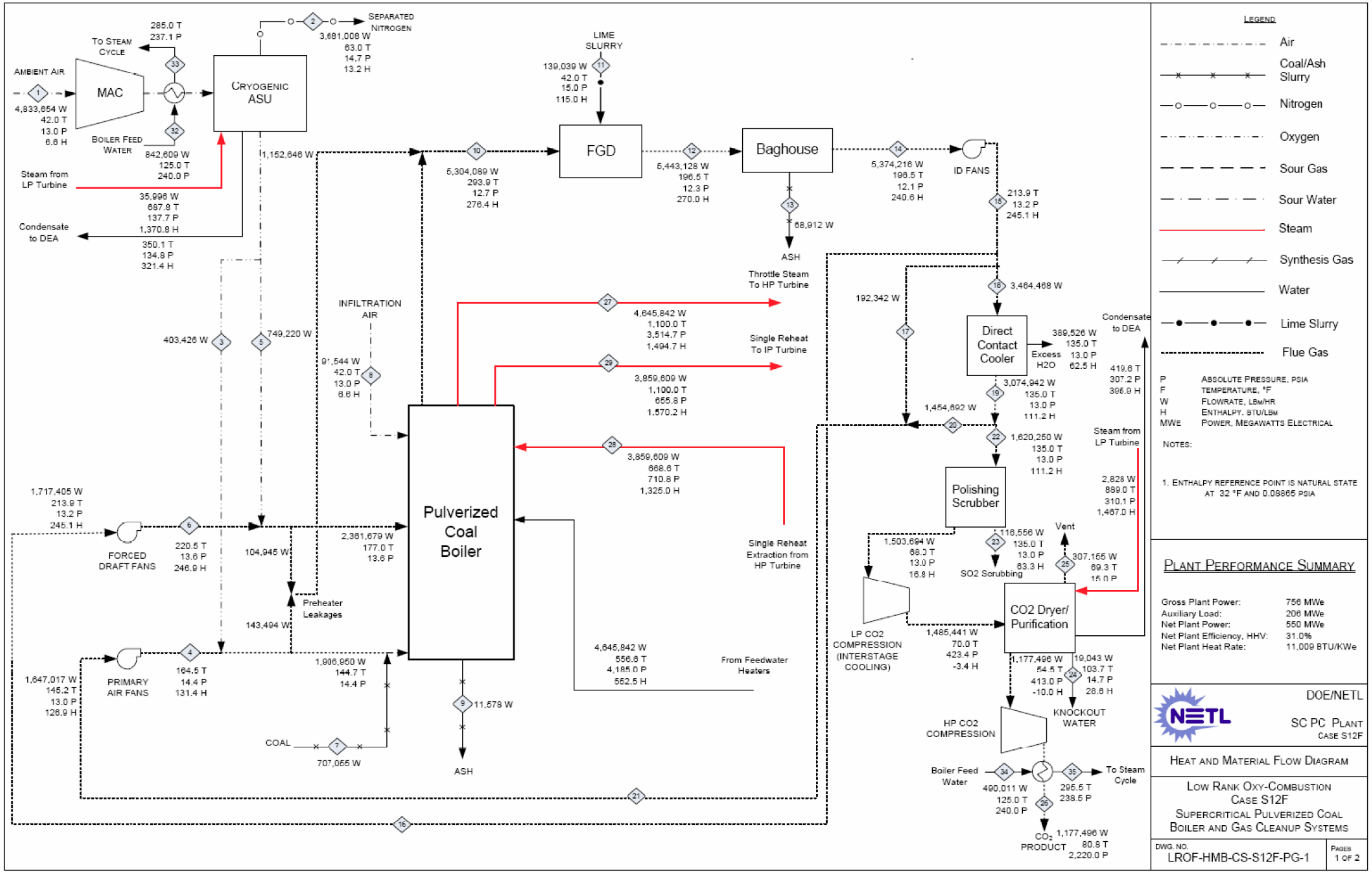



**Figure B-29**
**NETL Baseline Case S12F, Montana PRB Fuel, Boiler Island, 100% Load**

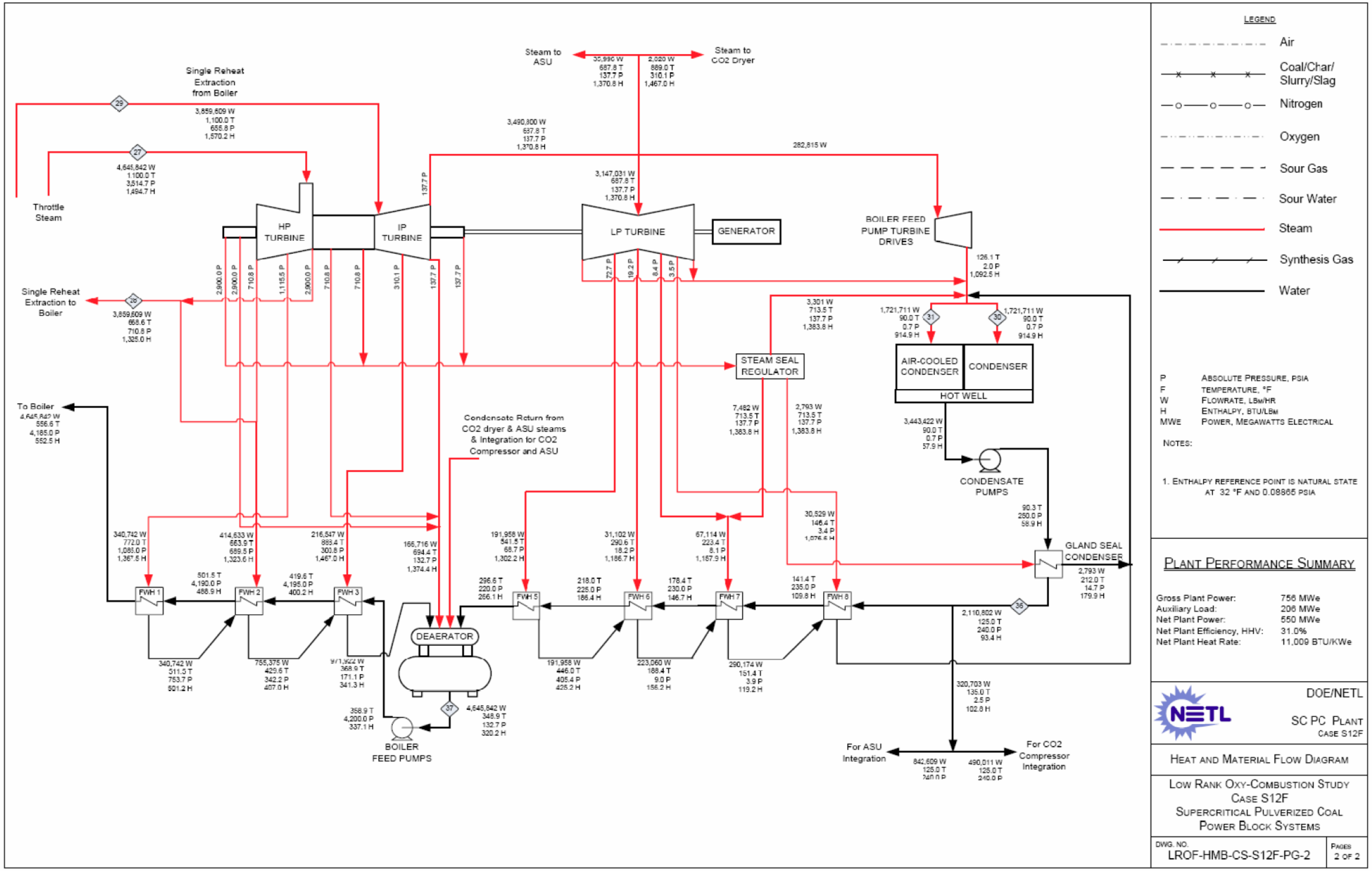



**Figure B-30**
**NETL Baseline Case S12F, Montana PRB Fuel, Turbine Island, 100% Load**