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Performance and flexibility improvements of Staged Pressurized Oxy-Combustion

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Abstract

Staged Pressurized Oxy-Combustion (SPOC) is a low-carbon coal combustion power technology being developed by Washington University in St. Louis (WUSTL). Oxy-combustion plants enable straightforward capture of carbon dioxide (CO_2) by removing most of the nitrogen in the combustion air prior to use, thereby burning fuel in near-pure oxygen instead of air, producing a flue gas containing primarily CO_2 and water. CO_2 capture at amounts > 90% is possible, often using cryogenic air separation. Oxy-combustion typically relies on flue gas recycle (FGR) to reduce the peak temperature and radiation that would otherwise occur in a fuel/oxygen only flame. SPOC reduces the peak temperatures of combustion by utilizing two or more pressurized boiler modules connected in series to produce fuel staging; hence, only a portion of the fuel is combusted in any given furnace module. This means that the thermal energy released at each stage can be captured and removed from the gases prior to subsequent stages, when more fuel is introduced. This allows the SPOC process to operate with minimal FGR, avoiding the associated efficiency losses and additional costs. Also, the process operates at an elevated gas-side pressure, reducing boiler size, enhancing heat transfer to achieve a compact boiler configuration as compared to an atmospheric-pressure boiler design, and allowing for recovery of the latent heat of the water from the flue gas at a temperature useful to the steam cycle. The resultant net efficiency of the system is over 3 percentage points greater than traditional atmospheric-pressure oxy-combustion, and 7 percentage points greater than the post combustion variant, representing a step-change improvement over first-generation capture technologies.

To further develop the concept, WUSTL and the Electric Power Research Institute, Inc., organized a project with American Air Liquide, Inc., Doosan Babcock Limited, and the U.S. Department of Energy to investigate a practicable and workable boiler design. The team has identified the potential for enhanced process flexibility for controlling power generation over a wider load range than is normally available to conventional coal-fired power plants due to the staged nature of the heat release. With increasing intermittent renewable generator contribution, on-demand generators need to be highly flexible to participate in the future energy market, requiring extensive operation at reduced load.

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Conventional coal-fired steam generators typically face challenges in maintaining temperature control of the reheat steam and main steam at reduced loads. This results in inefficient operation, both in terms of the boiler efficiency and steam turbine heat rate. The results of this project show the SPOC process is capable of exceptional turndown, both on a stage basis and with the ability to bypass entire stages. Oxygen-supply flexibility was also investigated, as this is also a key consideration for the overall flexibility of the SPOC process given the operating constraints of conventional air separation units.

A boiler design concept assessment was conducted and was focused on delivering compact and constructible design. The assessment checked appropriate tube operating metal temperatures at full load and at lower operating loads, balanced against the needs of efficient coal combustion, and the resultant slagging and ash environments. Combustion testing in the 100-kWth pressurized combustion test rig at WUSTL was carried out to validate the combustion, heat flux profiles and burnout at multiple loads. Combustion parameters investigated were flame stability, fuel burnout, ash composition, radiative heat flux, and temperature profiles. The results of these tests formed the basis of a full-scale boiler design that will encompass improvements in both efficiency and flexibility over conventional oxy-combustion processes. The air separation unit flexibility was investigated, and associated cost implications were addressed. Detailed economic assessment results for a 550 MWe net power block are also provided, allowing for a comparison against the baseline NETL oxy-combustion and post combustion capture cases.

Keywords: Oxy-combustion; Carbon Capture; SPOC; Staging; Flexibility;

1. Introduction

Oxy-combustion technology is a carbon dioxide (CO_2) capture strategy that combusts fuel using near-pure oxygen rather than using air directly. The resultant flue gas consists of mainly CO_2 and water and can therefore be delivered for CO_2 sequestration or utilization with minimal post processing. Directly burning fuel with oxygen can result in very high flame temperatures, resulting in unmanageable heat fluxes for boiler tubes. To limit these temperatures, conventional oxy-combustion systems use flue gas recycle (FGR) from the boiler exit as a diluent, thereby lowering the heat flux. However, delivering FGR back to the combustion zone requires additional auxiliary power consumption, reducing the plant efficiency.

An oxy-combustion technology being developed by Washington University in St. Louis (WUSTL) called staged pressurized oxy-combustion (SPOC) offers higher overall power plant efficiency than is achievable with first-generation atmospheric oxy-combustion. The levels of FGR needed is substantially reduced by separating the overall fuel burn into multiple stages. Each individual stage is more easily managed due to the smaller size and lower fuel firing rate. Additionally, the SPOC system is pressurized, making the flue gas volume smaller than with conventional atmospheric oxy-combustion. This means the plant can have a smaller overall footprint, more effective gas-side heat transfer, and lower downstream CO_2 compression power requirements. Another benefit of pressurization is the ability to recover thermal energy from moisture latent heat. This energy is usually lost in the stack gas in conventional thermal plants or to the cooling system for the case of atmospheric oxy-combustion systems. The partial pressure of the moisture in the SPOC process allows the condensation of this moisture to occur at temperatures that are beneficial to the steam cycle, e.g., to carry out feedwater heating duties.

With support from the U.S. Department of Energy (DOE), the Electric Power Research Institute, Inc. (EPRI), WUSTL, American Air Liquide Inc. (AAL), and Doosan Babcock Limited (DBL) investigated the potential for SPOC, both as an efficient low-carbon electricity generating technology and for enhanced flexibility capability, given the system ability to adjust firing systems on a per-stage basis. The SPOC concept was reviewed by DBL, a boiler plant original equipment manufacturer (OEM), to determine what would be required to deliver a feasible working system within acceptable design criteria that would deliver 550 MWe of net output power to allow direct comparison with defined National Energy Technology Laboratory (NETL) baseline cases [2,3], shown in Table 1. The steam cycle used for the SPOC has identical steam and reheat conditions. The only salient difference between the steam turbine system for these cases and the SPOC steam system is the degree of heat recovery that is possible with SPOC due to sensible and latent heat recovery at the back end of the process.

Table 1. NETL baseline cases

Baseline Case	Fuel	CO_2 Capture	Steam Cycle Conditions (Pressure/Temperature)
S12A Air-Fired Supercritical Pulverized Coal (PC)	Powder River Basin (PRB)	0%	241barg/593°C/593°C
S12B Air-Fired Supercritical PC with Post-Combustion Capture	PRB	90%	241barg/593°C/593°C
S12F Oxy-combustion Supercritical PC	PRB	90%	241barg/593°C/593°C

The combustion system needed at this scale was assessed by WUSTL using computational fluid dynamics (CFD) modeling tools, allowing operating temperatures and heat flux profiles to be evaluated. The resultant thermal absorption data were then used for the boiler design, ensuring that the water / steam tubes are operating within acceptable metal temperatures at every point throughout the combustion zone. Combustion testing was carried out in the WUSTL 100-kWth test facility, where temperature profiles, flame stability, burnout characteristics, and performance at low excess oxygen levels were investigated. Radiative heat flux levels obtained from these tests are used to validate the CFD models to ensure that the predictions at the 550-MWe scale are as accurate as possible.

Nomenclature

AAL	American Air Liquide Inc.
ASU	Air Separation Unit
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DBL	Doosan Babcock Limited
DCC	Direct-Contact Cooler
DOE	United States Department of Energy
EPRI	Electric Power Research Institute, Inc.
FGR	Flue Gas Recycle
GCV	Gross Calorific Value (fuel energy inc. moisture)
kWth	Kilowatt thermal (energy)
MWe	Megawatt electric (power)
MWh	Megawatt-hour (energy)
NCV	Net Calorific Value (fuel energy exc. moisture)
NETL	National Energy Technology Laboratory
OEM	Original Equipment Manufacturer
PC	Pulverized Coal
PRB	Powder River Basin (coal type)
SPOC	Staged Pressurized Oxy-Combustion
WUSTL	Washington University in St. Louis

Disclaimer

2. Combustion Testing

To demonstrate the SPOC boiler design concepts and validate the models, a 100-kWth pressurized combustion facility was designed and constructed. This facility is designed to accommodate a wide variety of gas inlet conditions (e.g., air-fuel equivalence ratio 1~3, oxygen concentration 21~99%) to identify the optimal operating conditions for SPOC process. This 160 m^2 research facility located in Washington University in St. Louis contains a 20 ft long furnace for studies of pressurized combustion or gasification of coal or other fuels, at pressures up to 20 bar [4]. A schematic of the system is shown in Figure 1.

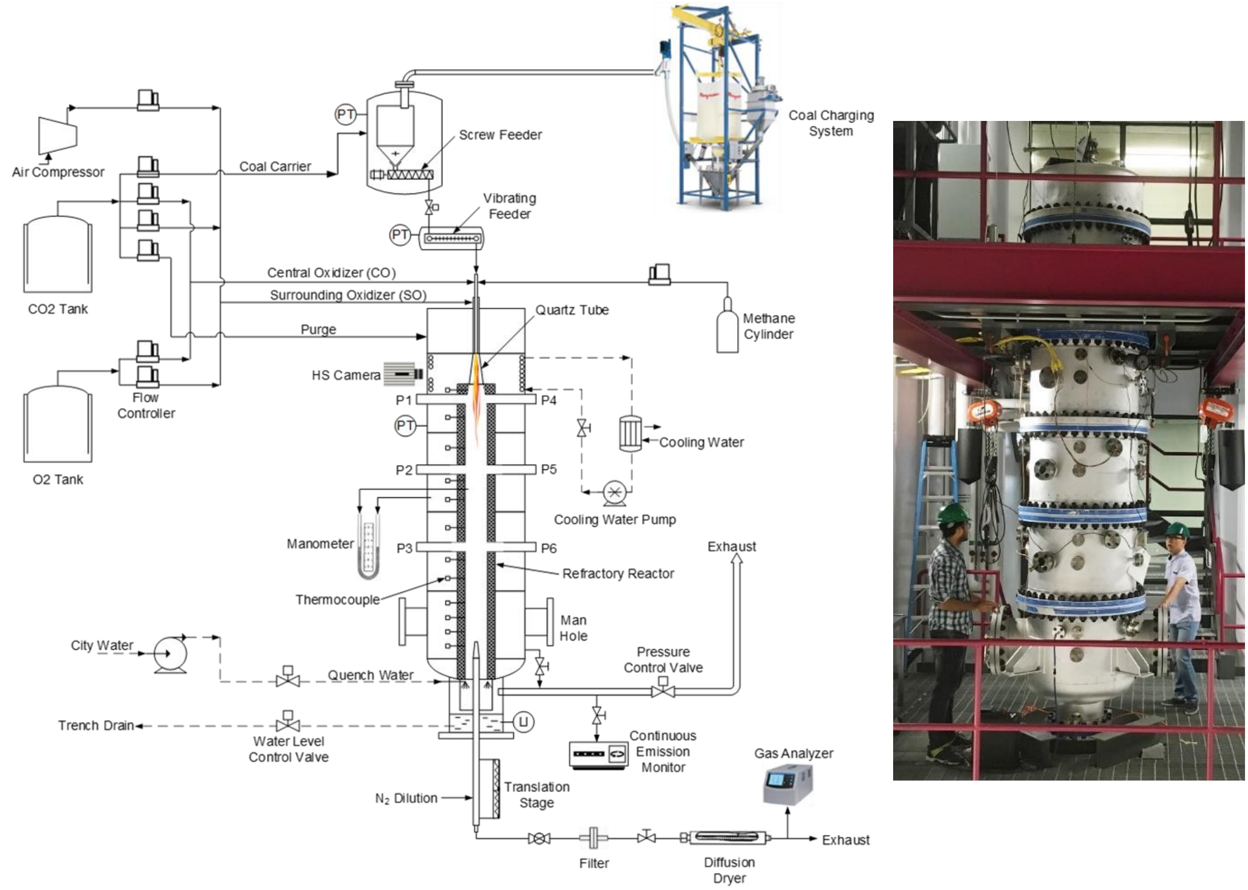
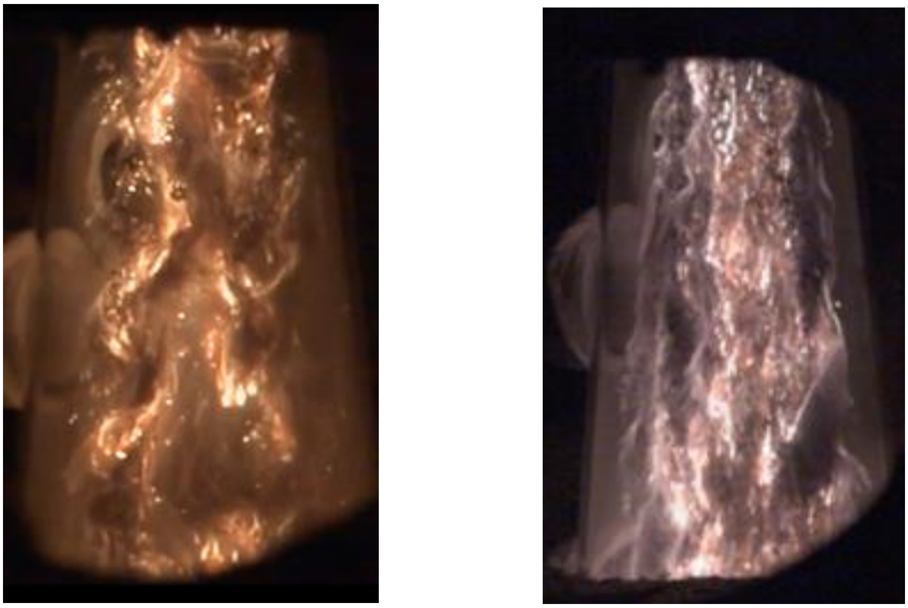


Figure 1. Schematic of the 100 kWth SPOC Pilot Testing Facility

This facility includes bulk liquid storage and gas delivery systems for O_2 and CO_2 for pressurized oxy-combustion research. The reactor is made of refractory with an internal diameter of 5.5 inches, and it is placed at the center of the pressure vessel with a conical-shaped quartz tube at the top section of the reactor allowing visual monitoring and optical diagnostics. There are several optical ports on the pressure vessel's side wall, which can be used for high-speed flame videography and heat flux measurement as well. Through high-speed videography, detailed information on the flame structure can be readily observed, including the flow field, particle motion, and particle transformation (i.e. particle ignition, volatile release and combustion, and char combustion).

Both narrow-angle heat flux and ellipsoidal heat flux measurements were taken using an internally developed line of sight radiometer and a Medtherm Schmidt-Boelter heat flux sensor, respectively. Type K thermocouples are installed along the length of the reactor to remotely monitor the temperature distribution along the reactor wall. A laser diagnostic system is mounted on a multi-axis translation stage, which allows for two-dimensional scanning of the flame through the quartz tube. Figure 2 shows examples of down-fired coal flames seen from the quartz tube.



(a) **(b)**

Figure 2. Photographs of 100% Coal Combustion in the SPOC Test Facility: a) 20 kWth and b) 80 kWth.

Sampling for particles and gas components is carried out using two types of pressurized sampling probe: a water-cooled sampling probe inserted through the base of the pressure vessel, and a two-stage dilution sampling probe inserted into the reactor through the side ports of the pressure vessel. A concise summary of the diagnosing capabilities is given in Table 2.

Table 2. Measurement capabilities of the SPOC facility.

Measurement	**Device**
Wall heat flux (both convective and radiative at port locations)	Medtherm Schmidt-Boelter heat flux sensor
Flue gas composition	Flue gas sampler, HORIBA Multi-gas analyzer
Centerline profiles of gas composition (i.e., CO_2, O_2, CO, H_2O, NOx, SO_2)	Pressurized gas & particle sampler, HORIBA Multi-gas analyzer
Centerline particle size distribution	Pressurized gas & particle sampler, DEKATI Electrical Low-Pressure Impactor (ELPI)
Centerline temperature	Thermocouple
Visual observation of flames	HS camera and HD webcam
Flue gas CO and soot concentration	Flue gas sampler, Horiba Multi-gas analyzer, Optical Particle Sizer (OPS)
Ash carbon concentration	Flue gas sampler, Cyclone, Thermogravimetric Analyzer

Initially, gaseous combustion was tested at 15 bara with a wide range of operating conditions. It was found that, even though a down-fired methane flame has a high sooting tendency at elevated pressure, this could be eliminated by choosing an optimal operating condition. A 40 kWth methane flame with an oxidizer-fuel equivalence ratio of 2.2 and 30% v/v overall oxygen fractions in oxidizer streams is identified as the best operating condition for heating up the system.

Following this, transitions from air-fired mode to oxy-fired mode and from methane flame to coal flame were tested at 15 bara with smooth transitions demonstrated. Full load (100 kWth) and half load (50 kWth) were then tested successfully with a coal flame achieved without any methane support. Stable and complete combustion at these conditions was verified as no soot and CO emission were detected at the exit of the reactor even when the oxygen fraction at the outlet is as low as 3% v/v. Particle samples at the exit of the reactor also indicate no unburnt carbon content, as shown in Table 3.

Table 3. Test Conditions for Determining Carbon Burnout.

15 bara (271.5 psia), 3% vol 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), 1% vol 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%

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, however 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 3. 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 the 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 %.

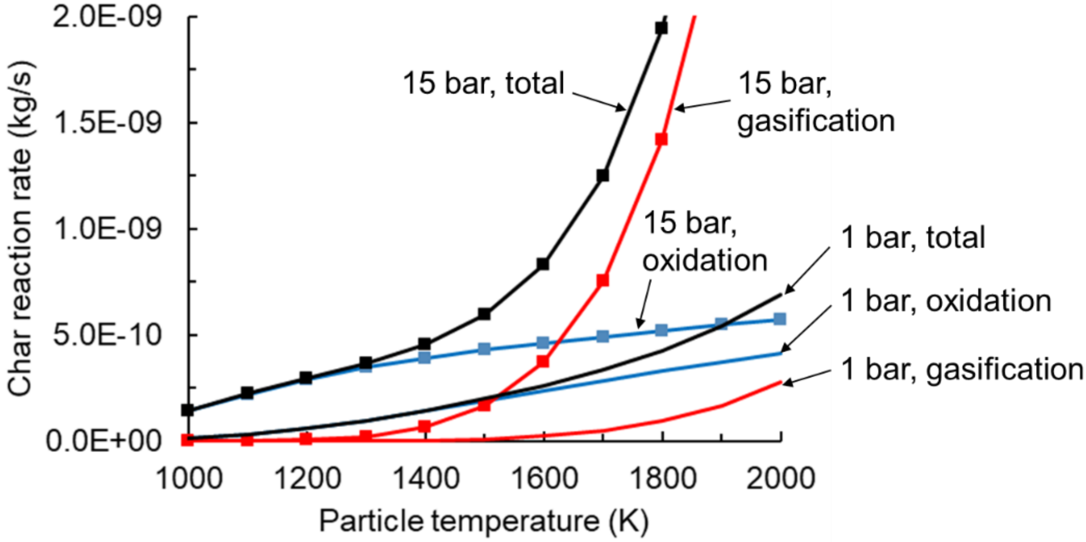


Figure 3 Calculated Oxidation and Gasification Reaction Rates for a Char Particle at Different Temperatures and Pressures.

Downstream of the reactor, the flue gas was quenched using a direct contact water spray, leading to low NOx and SOx levels at the outlet due to absorption in the cooling water. It should be noted that NOx generation during combustion is also limited due to the absence of nitrogen and the controlled flame temperature, both which limit the thermal NOx formation mechanism. At the end of the test campaign the total thermal input was pushed to 125 kWth (100 kWth coal and 25 kWth methane) without any operational problems.

3. Steam Generator Design

WUSTL had carried out previous work on the steam generator for the SPOC process that was based on a downshot combustion design with high-temperature radiant tube surfaces, similar to that found in gasification systems with concentric tubes located near the bottom for flue gas cooling. This heating surface arrangement was assessed by DBL, with the highest risk items identified being:

- Complexity of design for heating surfaces, headers, and supports. Concentric heating surface contained within each SPOC pressure vessel presents several significant mechanical design challenges.
- Potential for excessive ash slagging and fouling resulting in impaired process performance and availability. Concentric heating surface design is not conducive to typical online cleaning methods

The concept design was adjusted to address the key risk items, resulting in a two vessel per stage approach (Figure 4). The first vessel is a combustion module that is comprised of a completely open pass with evaporative membrane tube walls installed at the perimeter. This unit is designed to be tall enough to ensure that the flue gas is cooled sufficiently below the ash initial deformation temperature prior to allowing the gas to change direction and be passed to the next vessel. This ensures that the ash generated in the combustion forms solid particles before exiting, ensuring that downstream systems are not exposed to sticky ash particles that can attach to internal surfaces and form large, performance impacting deposits.

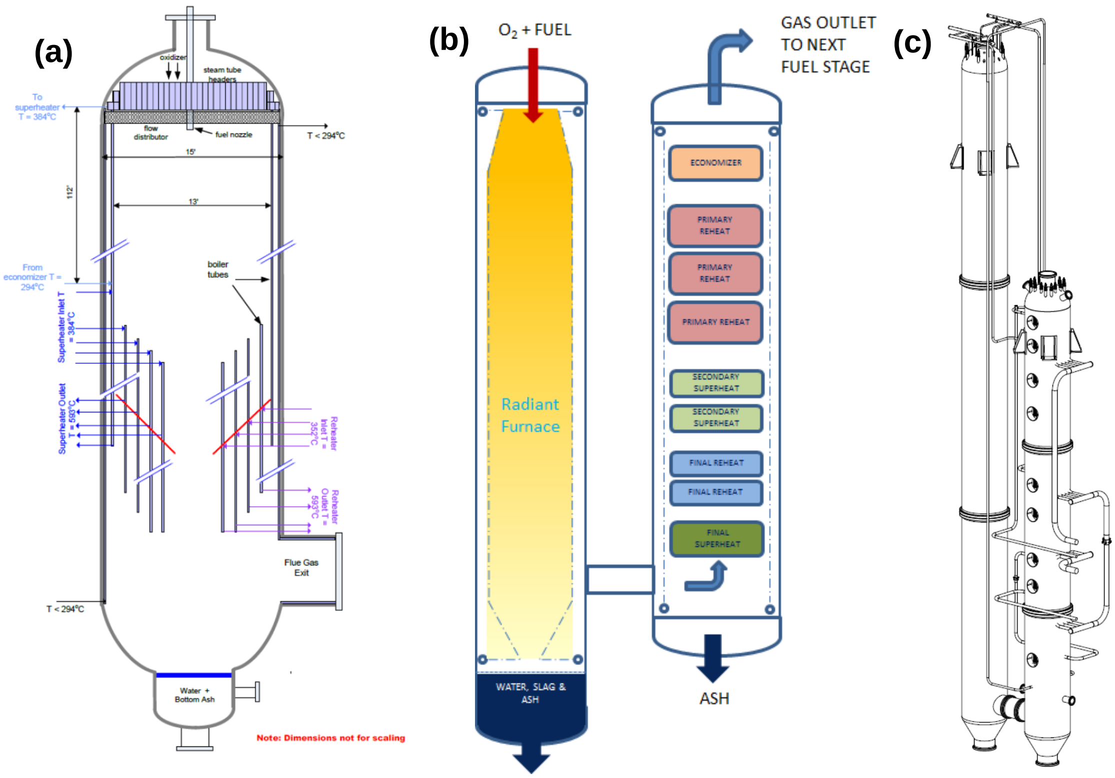


Figure 4. (a) Original configuration, (b) new two-pass concept for a single SPOC stage, and (c) isometric vessel arrangement

This revised concept design addressed the key risk items identified by DBL, although it was noted that there remains a degree of uncertainty due to the small scale of performance testing, a lack of boiler surface during these tests, and the reliance on CFD modeling for performance assessment. Manufacturability was a key consideration for this design with modules being shippable, thereby limiting site-based construction that would otherwise significantly increase the cost. The pressure vessels were therefore limited to an outside diameter of 4.2 m. DBL determined that the inner combustor membrane tube perimeter would need to be restricted to 3.86 m to allow for the pressure vessel wall thickness and a cavity annulus to accommodate piping connections and cooling gas to ensure the pressure vessel is not substantially heated. Using this sizing limitation, WUSTL assessed the heat flux generated in the combustion module using CFD modeling for a four-stage, 550-MWe scale SPOC unit. The design of the combustion module considered a maximum heat flux of 450 kW/m^2 using 13CrMo44/ ASME SA213 T12 tubing material.

Following a transition duct connected at the bottom of the combustor module, the convective module has been configured to be an up-flow arrangement, allowing the outlet to connect to the next SPOC stage. Internally, this stage consists of a square cross section heat exchanger cavity bounded by membrane wall tubes. This arrangement allows banks of tubes to be installed with conventional geometries, ensuring each steam-side flow path is as even as possible, minimizing the risk of flow imbalance between tube elements. The square membrane enclosure surface also facilitates sufficient space between the circular pressure vessel and the membrane walls to accommodate pressure-part components such as stub headers, lowering the need for numerous pressure vessel penetrations thereby reducing cost.

The optimized arrangement was developed to be in series on the gas side using hot FGR from the exit of Stage 4 to ensure that the Stage 1 design is identical to the subsequent stages. Consequently, the steam/water circuit is split equally across all the stages (i.e., identical superheater, reheater, and economizer tube banks). It should be noted that hot FGR can be a challenging scenario, given that the flue gas will contain a substantial fly ash component, making the mechanical design of the blower necessary to withstand erosion, or to have a high-temperature particulate removal device for the FGR stream. The design exercise determined that two pressure vessels are needed for a single SPOC stage with four total SPOC stages required for the 550-MWe SPOC power plant, as shown in Figure 5.

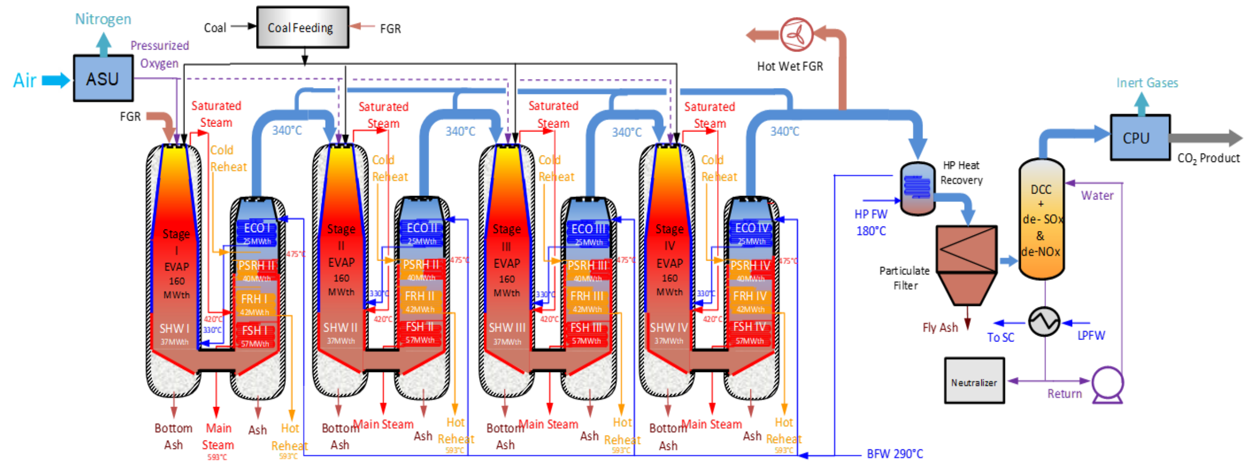


Figure 5. 4-Stage, 2-Pass SPOC Arrangement

4. Rankine Cycle System Integration

A heat recovery heat exchanger is installed prior to the dust removal module to capture relatively high temperature heat from the flue gas. This heat is available at a high enough temperature to be suitable for heat recovery to high pressure feedwater. The feedwater leaving the deaerator in the steam cycle is at a low enough temperature to cool the flue gases towards a targeted 200°C, with further cooling reaching the moisture dew point. Following dust removal, the flue gas is further cooled in a direct contact cooler (DCC) that is anticipated to also remove a significant amount of sulfur and nitrogen oxides due to the elevated pressure conditions (as observed during testing). The latent heat absorbed in the DCC is recovered in the DCC cooler heat exchanger that is cooled by low pressure feedwater. This energy can be added to the heat recovery from the air separation unit (ASU) and the compression plant to allow 100% bypassing of the low-pressure feedwater heaters and partial bypassing of the high-pressure feedwater heaters.

Subsequently, in a full SPOC design, there would not be any requirement for low-pressure feedwater heaters, reducing capital costs. The increased heat recovery delivers a 6% reduction in main steam flow for the same gross power output. The overall performance of the SPOC plant sized to deliver 550MWe net power export to allow comparison with the NETL baseline cases is shown in Table 4.

Table 4. Overall Performance 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	198.3	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	32.4	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 (1489)	583,371 (1286)	527,564 (1163)
CO_2 Captured, kg/hr (klb/hr)	0 (0)	607,619 (1340)	530,219 (1169)	475,287 (1048)
CO_2 Emitted, kg/hr (klb/hr)	472,497 (1042)	67,657 (149)	53,152 (117	52,177 (115)
CO_2 Emission Intensity, kg/MW-hr (lb/MW-hr)	859 (1894)	123 (271)	97 (213)	95 (209)

SPOC offers unique opportunities to deliver a high degree of turndown due to the potential ability to bypass stages, thereby delivering reduced output while the remaining operational stages are firing at full load. Additionally, the firing rate of all stages can be reduced, delivering an even steam generation between all stages. Testing at WUSTL has successfully demonstrated 50% turndown with successful burnout achieved at the targeted excess oxygen level of 3% oxygen at the stage outlet. Hence, a combination of burner turndown and stage bypassing could potentially facilitate 100% load down to below 12% on a four-stage SPOC system. Achieving flexibility in the air separation unit to deliver such low load operation is not possible with standard plant configurations as compressors can't turndown effectively. Adding more (smaller) compressors delivers the ability to operate at lower oxygen production rates efficiently. This increases the capital costs of the system, reflected in the 'Flexible SPOC' in the economic analysis.

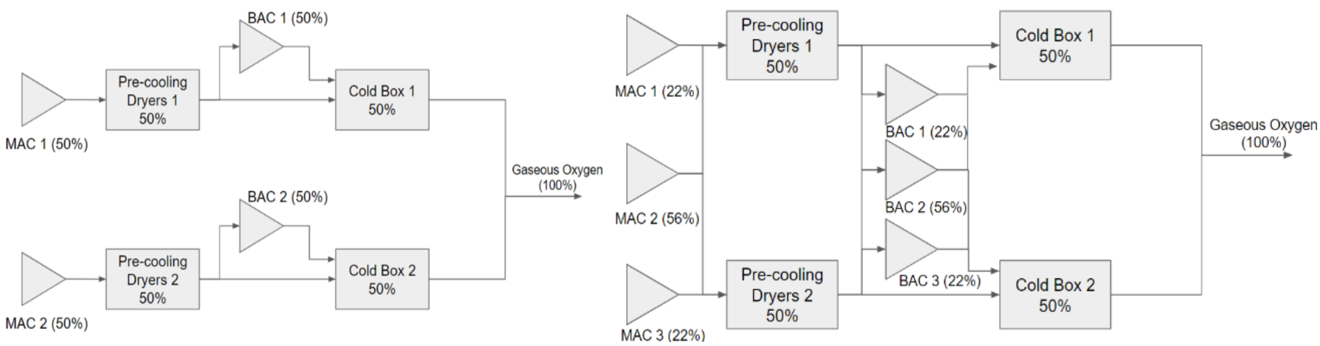


Figure 5. Baseline ASU Arrangement and Enhanced Flexibility Arrangement

5. Economic Analysis

The basis of the economic assessment was a generic plant site in Montana, 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 fuel used for the SPOC case was the Montana Rosebud PRB is identical to that used in the corresponding NETL Baseline cases, expected to cost $1.21/GJ HHV to be delivered to the Montana site. Capital costs are reported in January 2019 dollars (base-year dollars) to put them on a consistent 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.

Recommended Practice 18R-97 of the AACE describes a Cost Estimate Classification System as applied in EPC for the process industries [5]. 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. The estimates developed 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, this does 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. It should be noted that the cost estimates in this study did not include the impact of modular boiler design on the capital cost. Being able to manufacture modular boilers in factories and limiting site-based construction can potentially lead to significant cost reductions. Process contingencies applied to the appropriate subsystem levels were derived from the base-case studies performed by NETL. The all-in union construction craft labor rate for the Montana site was assumed to be $62.87/hour. The craft labour 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).

5.1. First-Year Power Cost

A simplified method provided in the DOE Financial Model User’s Guide [6] was used to calculate the first-year power cost. 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

5.2. Levelized cost of electricity (LCOE)

The DOE Financial Model User’s Guide 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.

5.3. Costs of CO_2 Captured and 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 the 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}).

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 [7] 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. The CO_2 leaves the pipeline at a pressure of 82.7 bara (1200 psia) in a supercritical state. For the Montana plant location used for this study, the T&S value specified by DOE is $10/tonne-$CO_2$. The overall cost results for the NETL baseline cases and both the baseline SPOC and flexible SPOC cases is shown in Table 5.

Table 5. Overall Cost Comparison of SPOC Baseline and Flexible Cases with NETL Baseline 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
% CO_2 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 Cost, (PRB) $/MMBtu	1.15	1.15	1.15	1.15	1.15
Capital Costs					
Total Plant Cost, $/kW	2,406	4,243	4,084	3,634	3,691
Total Overnight Cost, $/kW	2,936	5,174	4,967	4,425	4,494
Total As Spent Capital Cost, $/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

6. Conclusions

The SPOC concept has undergone significant evolution throughout the execution of this project, following a 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.

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.

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. With the added ability to bypass stages, the overall ultra-low load operation is feasible subject to steam turbine limitations. 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 greatly improved the low-load performance.

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 than 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 effectively amplifies the specific cost of capture.

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