ANALYSIS OF CARBON CAPTURE RETROFITS FOR CEMENT PLANTS

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This report was reviewed by technical experts at the PCA to ensure that information presented is based on sound and credible science and considered technically adequate, competently performed, properly documented, and in compliance with established quality requirements. As a step beyond standard internal quality assurance and quality control procedures, the U.S. Department of Energy Office of Fossil Energy and Carbon Management/NETL is committed to rigorous peer review of key work products to meet the quality standards of the research community. The following individuals at PCA are acknowledged, along with several of their expert industry members, for their technical expertise and for their efforts in reviewing the development methods and results of this analysis:

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ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
AACE	AACE International (formerly Association for the Advancement of Cost Engineering)
ACFM	Actual cubic feet per minute
Ar	Argon
Aspen	Aspen Plus®
abs	Absolute
acfm	Actual cubic feet per minute
atm	Atmosphere
B&W	Black and white
BEC	Bare erected cost
BOP	Balance of plant
Btu	British thermal unit
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CCF	Capital charge factor
CH_4	Methane
CH_4S	Methanethiol
cm	Centimeter
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COA	Cost of CO_2 avoided
COC	Cost of CO_2 capture
CS	Carbon steel
CTG	Combustion turbine generator
CWT	Cold water temperature
DCS	Distributed control system
DOE	Department of Energy
Eng'g CM H.O & Fee	Engineering construction management home office and fees
EPC	Engineering/procurement/construction
EPCC	Engineering, procurement, and construction cost
EPRI	Electric Power Research Institute
FGD	Flue gas desulfurization
ft	Foot
ft^3	Cubic foot
gal	Gallon
GHG	Greenhouse gas
GJ	Gigajoule
gpm	Gallons per minute
h, hr	Hour
H_2	Hydrogen
H_2O	Water
HCN	Hydrogen cyanide
HHV	Higher heating value
HWT	Hot water temperature
HVAC	Heating, ventilation, and air conditioning
HX	Heat exchanger
Hz	Hertz
I&C	Instrumentation and control
In WG	Inches water gauge
kg	Kilogram
kg_{mol}	Kilogram mole
kJ	Kilojoule
kV	Kilovolt
kW, kWe	Kilowatt electric
kWt	Kilowatt thermal
lb	Pound
lb_{mol}	Pound mole
lbm	Pound mass
LHV	Lower heating value
LP	Lower pressure
lpm	Liters per minute
m	Meter
M	Million
m^3	Cubic meter
min	Minute
MMBtu	Million British thermal units
mol%	Mole percent
MPa	Megapascal
MVA	Megavolt ampere
MWe	Megawatt electric
MWh	Megawatt-hour
N/A	Not applicable/available
N_2	Nitrogen
NaOH	Sodium hydroxide

NETL	National Energy Technology Laboratory
NG	Natural gas
NH_3	Ammonia
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
O-H	Overhead
PCA	Portland Cement Association
ph	Phase
PH/PC	Pre-heater/Pre-calciner
PM	Particulate matter
ppm_v	Parts per million, by volume
psi	Pound per square inch
psia	Pound per square inch absolute
psig	Pound per square inch gauge
QGESS	Quality Guidelines for Energy System Studies
R&D	Research and development
RO	Reverse osmosis
scfm	Standard cubic feet per minute
SCR	Selective catalytic reduction
SDA	Spray dry absorber
SO_2	Sulfur dioxide
SOx	Oxides of sulfur
SS	Stainless steel
T&S	Transport and storage
TAG®	Technical Assessment Guide
TASC	Total as-spent cost
TEG	Triethylene glycol
TOC	Total overnight cost
tonne	Metric ton (1,000 kg)
TPC	Total plant cost
tph	Tonnes per hour
U.S.	United States
USGS	United States Geological Survey
V	Volt
V-L	Vapor-liquid
wt%	Weight percent

EXECUTIVE SUMMARY

The objective of this study is to provide an estimate of the cost to capture carbon dioxide (CO_2) in retrofit applications at cement plants. In the United States (U.S.), cement production contributed about 69 million (M) tonnes of CO_2 emissions in 2020, representing approximately 1.5 percent of total domestic CO_2 emissions based on reporting to the Environmental Protection Agency. [1] [2] The cement plant configurations considered in this study are summarized in Exhibit ES-1. The base cement plants in this study were not evaluated other than characterization of their kiln off-gas[1] stream and high-level quantification of heat integration potential at the existing plant. In each case, the base cement plant produces 1.5 M tonnes per year of finished cement, assuming 91.4 percent clinker content. [3]

Exhibit ES-1. Case summary description

Case Number	CM99-B	CM95-B[A]	CM95-B1[A]	CM95-B2	CM95-B3[A]	CM95-B4[A]	CM95-B5	CM95-B6	CM95-B7	CM95-B8
Capture Rate	99 Percent	95 Percent								
Kiln Type	Pre-heater/Pre-calciner				Wet Process		Pre-heater/Pre-calciner			
Kiln Off-Gas CO_2 Concentration, mol %	31	31	25	30	17	13	31		25	
Kiln Fuel Type	Coal/Coke		NG	Oil	Coal/ Coke	NG	Coal/Coke		NG	
Heat Integration Potential, %	N/A	N/A	N/A	N/A	N/A	N/A	10	30	10	30

[A]Sensitivity cases regarding SOx and NOx concentrations are shown for these cases in Section 5.2, with SOx levels at 100, 300, and 500 ppm_v and NOx levels at 500, 1,000, and 1,500 ppm_v

The base cases evaluated consider capture directly from the kiln off-gas. However, kiln off-gas can also be used to preheat raw meal solids and can be treated for pollutants before exhaust from such pre-processing unit operations. These steps, along with additional air ingress that inevitably occurs as part of these operations, result in lower CO_2 concentrations, higher humidity, higher flow rates, and a lower temperature for the cement plant exhaust stream entering the CO_2 capture island. Raw meal solids preheating and false air ingress were not evaluated in the cases shown in Exhibit ES-1, therefor the lower flow rates and higher CO_2 concentrations of the base cases do not consider such false air ingress and are expected to be optimistic. To address the variation in flow rates and CO_2 concentration caused by kiln off-gas use in the pre-processing steps, additional cases are presented in Section 7.

[1] Fuel burning to provide kiln heat is one of two CO_2 emissions sources, with the second resulting from the calcination of calcium carbonate to form calcium oxide/calcium silicate species during the cement manufacturing process. The two emissions sources are co-mingled from the kiln and treated at the cement plant to meet emissions requirements. The co-mingled emissions stream leaving the kiln is referred to as "kiln off-gas" in this report.

For each case, the capital and operation and maintenance (O&M) costs for retrofitting and operating CO_2 capture equipment were calculated. The amine-based solvent capture systems modeled capture the CO_2 from the kiln off-gas, as well as the CO_2 generated by the supplemental natural gas (NG) boiler, which is added to meet the heating needs of the solvent regeneration system. Capital costs were estimated by applying a retrofit factor to the greenfield total plant cost (TPC). The figure of merit is the cost of CO_2 capture (COC) in U.S. dollars per tonne, as calculated in Equation ES-1. In this study, costs are presented in November 2022 real dollars, except in Appendix G: Results in December 2018 Dollars, which is provided for retrospective comparison to other reports published by NETL.

$$COC\left(\frac{\$}{tonne\ CO_2}\right) = \frac{TOC * CCF + FOM + VOM + PF + PP}{tonnes\ CO_2\ captured\ per\ year}$$

Equation ES-1: Cost of CO_2 Capture

Where:

- TOC – Total overnight costs of equipment added for the application of CO_2 capture, inclusive of retrofit difficulty (details provided in Section 2)
- CCF – Capital charge factor, based on financial assumptions detailed in Section 2.2
- FOM – Annual fixed O&M costs
- VOM – Annual variable O&M costs
- PF – Purchased fuel
- PP – Purchased power

The CO_2 capture retrofit system includes Shell's CANSOLV® CO_2 capture system, compression, associated intercooling, and glycol dehydration required to prepare the CO_2 product for pipeline transport. Balance of plant equipment, including the NG-fired boiler, is also included in the analysis. Exhibit ES-2 provides the resulting COC for each base case considered in this study, highlighting the capital, variable and fixed O&M, and purchased power/NG fuel cost components for each case, excluding costs associated with CO_2 transport and storage (T&S). Details regarding the estimation of capital, operating, and maintenance costs, as well as added T&S costs, are provided within the body of the report.

Exhibit ES-2 shows the tradeoff between performance improvements realized by utilizing excess heat available from sources within the existing cement plant, and the additional cost required to realize that benefit. This analysis includes a 10 percent retrofit cost increase for the heat integration, when compared to the analogous non-heat integration case. Heat integration is considered as a potential offset to capture system heating demands (i.e., as a percentage reduction). Recovery and reuse of excess heat from the base cement plant can provide economic benefits—primarily by reducing the need to purchase supplemental NG for CO_2 solvent regeneration—but any process improvement must be great enough to overcome the cost increases (i.e., capital and O&M) necessary to realize those benefits. With heat integration potential of 10 percent (i.e., CM95-B5 and CM95-B7) and 30 percent (i.e., CM95-B6 and CM95-B8), that benefit wasn't significant enough to offset the increase in capital and operating costs, and a COC increase was observed based on the assumptions in this report. Benefits of heat integration potential may be realized when NG prices are higher, as demonstrated in the sensitivity to NG price (Section 5.11.4), where crossover points exist between heat integration cases and their respective non-heat integration cases.

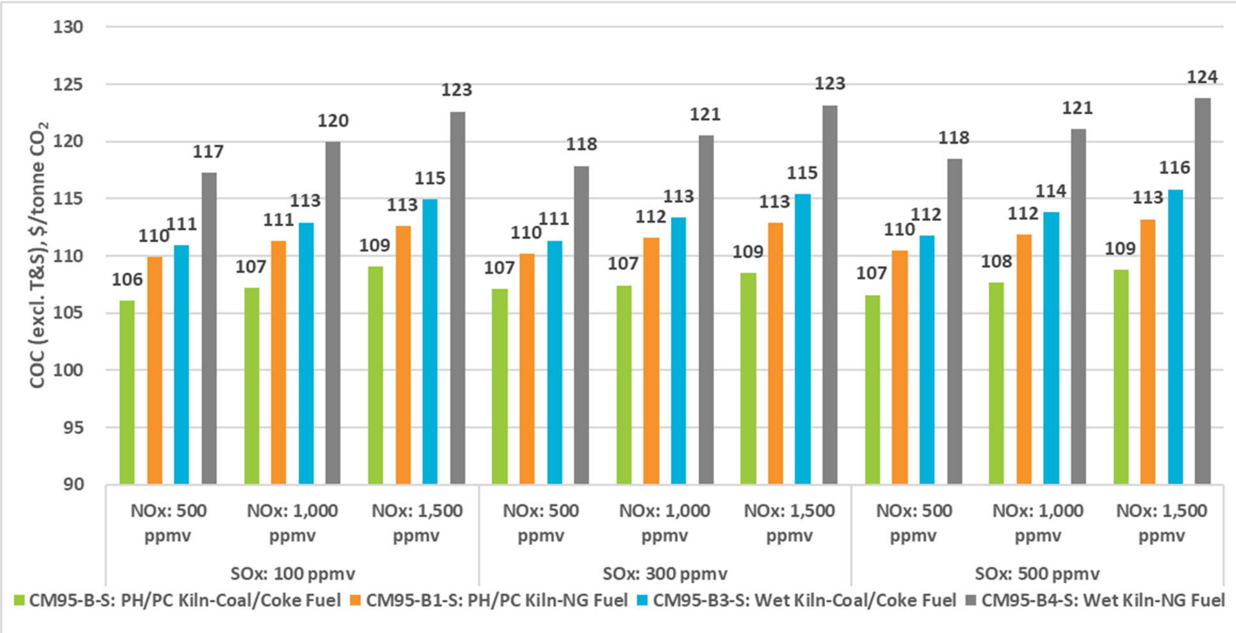
Exhibit ES-2. Base case COC summary (excl. T&S)

Note: All values expressed in November 2022 U.S. dollars per tonne CO_2

Four of the base cases—CM95-B, CM95-B1, CM95-B3, and CM94-B4—were further evaluated to explore the cost implications of deeper levels of gas pre-treatment to remove oxides of nitrogen (NOx) and oxides of sulfur (SOx) from the kiln off-gas stream prior to CO_2 capture, purification, and compression. The kiln off-gas was assumed to have NOx/SOx concentrations of 500–1,500 ppm_v/100–500 ppm_v, respectively, for each of the configurations shown in Exhibit ES-3. The kiln off-gas for each configuration was treated such that pre-scrubber inlet (i.e., after flue gas desulfurization [FGD] scrubbing and selective catalytic reduction [SCR]) SOx levels were 37 ppm_v, and NOx levels were 2 ppm_v.

The results of these additional case analyses showed a 7.4–18.8 percent increase in COC over the respective base case (i.e., analogous cases without SOx/NOx removal). The capital cost increase associated with addition of FGD and SCR was 8.4–13.7 percent relative to their respective base cases, suggesting that additional capital costs provide the most impact to the COC for cases with more advanced SOx and NOx control. SCR systems, including the cost of ammonia, are also relatively expensive to operate in cement plants, further contributing to increasing COC with NOx abatement. Exhibit ES-3 provides a summary of the COC for the sensitivity cases considering the implications of advanced SOx and NOx control.

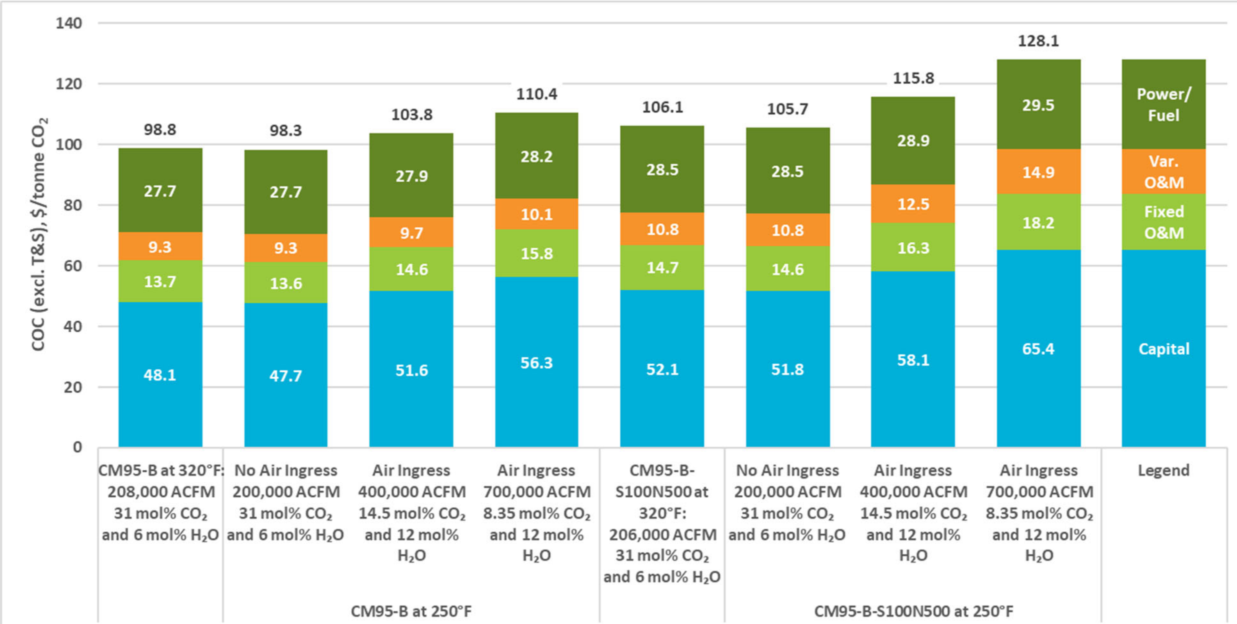
Exhibit ES-3. Summary of COC for sensitivity cases with FGD and SCR



Note: The SOx and NOx values are concentrations in the emissions stream requiring pretreatment prior to CO_2 scrubbing

The kiln off-gas streams in the base case and sensitivity cases with FGD and SCR are representative of the emissions stream directly from the cement kiln. In many cement plants, this stream is used for heating and drying raw meal solids, which increases the moisture and volumetric flowrate and decreases the CO_2 concentration entering the capture system due to air in-leakage via the raw mill units. As such, three additional scenarios were considered to evaluate the impacts of air in-leakage on the COC for case CM95-B (i.e., PH/PC kiln burning coal/coke fuel) and for case CM95-B-S100N500 (i.e., PH/PC kiln burning coal/coke fuel with FGD and SCR abatement of SOx and NOx). The results of these analyses, shown in Exhibit ES-4, are that with additional air in-leakage, COC can increase by as much as 11.7 percent for cases without FGD and SCR, and 20.7 percent for cases with SCR and FGD. The impacts of increasing air in-leakage are seen in the capital costs associated with larger vessels required to accommodate higher volumetric flowrates and with increased O&M costs associated with larger operating units. The deviation from base case costs is most evident in the cases that include FGD and SCR units, where costs rise at a faster rate due to additional unit operations and their associated parasitic loads and consumable usage rates. The most likely scenario for capture retrofits to existing cement plants is illustrated by the two right-side cases of Exhibit ES-4 (i.e., total COCs of \$115.8 and \$128.1/tonne CO_2), which include false air ingress from the raw mill circuit as well as FGD and SCR unit operations to preclean the resulting emissions stream prior to the Shell CANSOLV® island.

Exhibit ES-4. Summary of COC for sensitivity cases with air in-leakage



Sensitivities to the price of purchased power, the price of NG (i.e., fuel for the boiler described in Section 3.3), retrofit factor, operating days, capital charge factor (CCF), and cement plant size (in terms of CO_2 emissions per year) were analyzed for each of the base cases in Exhibit ES-1.

The results of these sensitivities, found in Section 5.11, are as follows:

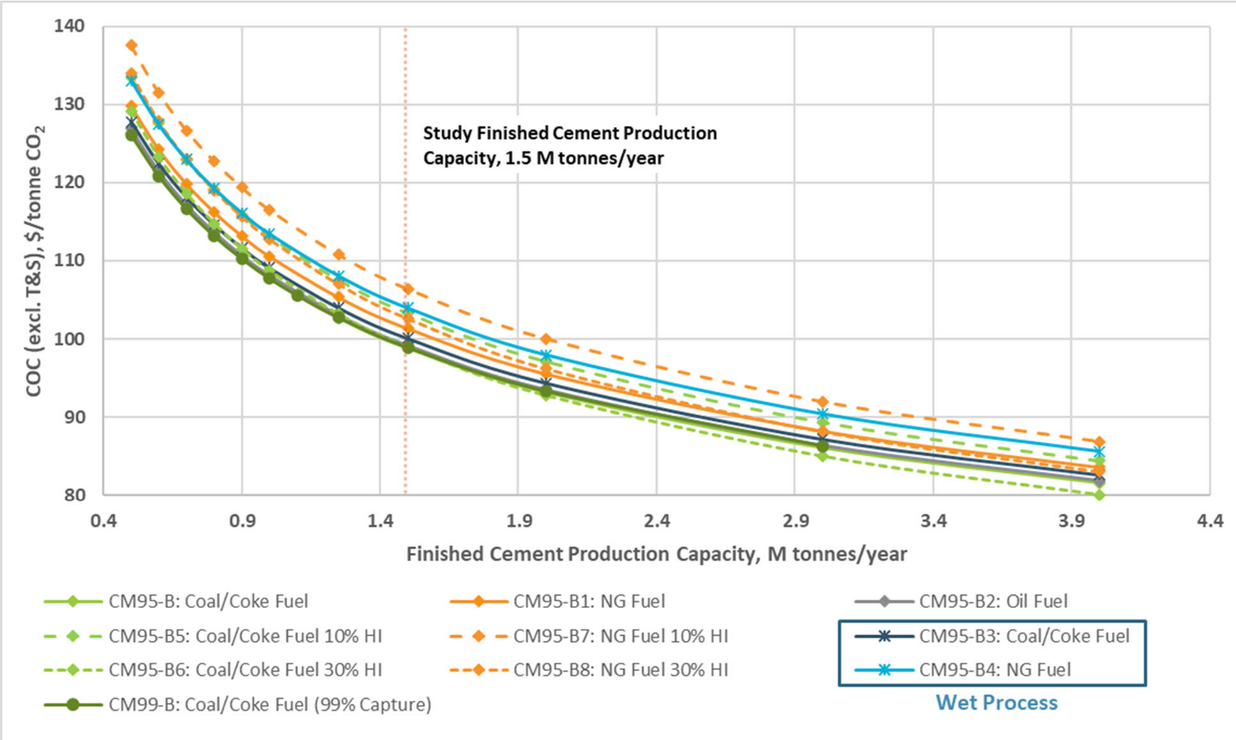
- As purchased power price increases, the COC also increases, as this study assumes that all electricity requirements are provided by purchasing power from the grid. The largest increase across the sensitivity range of $20–140/MWh was $15.5/tonne (i.e., a 15 percent increase). Based on this analysis, for every $5/MWh increase in purchased power price, the COC increases by 0.63–0.68 percent. Dependence on purchased power to meet auxiliary loads of the CO_2 capture system is an issue unique to the industrial sector. Traditionally, power needed to operate mechanical equipment for capture applications at electricity generating units is assumed to be readily available but represents a parasitic loss. The cement plants analyzed in this study do not include on-site power generation; therefore, electricity needed to operate all equipment to support the capture retrofit is purchased externally and is represented in COC cost summary charts such as Exhibit ES-4, and throughout the report, as part of the "Power/Fuel" COC component. To the extent this dependence on purchased power can be minimized, such as through on-site power generation, COC may improve, although any savings in purchased power costs would need to be balanced against the costs associated with on-site power generation.
- The sensitivity to NG price showed that as the NG price increased over the range of $3–10/MMBtu, the COC may rise as much as $30.2/tonne CO_2 (i.e., up to a 31 percent increase). Based on this analysis, for every $1/MMBtu increase in NG price, the COC increases by 3.0–4.7 percent. The primary function of purchased NG is to generate the steam required for solvent regeneration; therefore, improvements that can be made to

reduce the need for stripping steam, such as improved solvent carrying capacity, will limit the need for purchased NG and improve the COC.

- Varying the retrofit difficulty factor, which is intended to account for the additional costs associated with the difficulty of retrofitting an existing plant with space constraints, from 1.05 to 1.35 results in up to a $24.6/tonne CO_2 increase in COC (i.e., a 24 percent increase). The retrofit factors applied, along with the methodology for their application, to the cases in this study are discussed in Section 2.3.
- The capture island is assumed to operate 85 percent of the time (i.e., about 55 down days per year); however, varying the operating basis from 85 to 65 percent can increase the COC by as much as $29.0/tonne CO_2 (i.e., a 28 percent increase). Continued improvements to equipment reliability are a potential way to ensure a consistently high operating basis.
- The CCF assumed for this study was developed by NETL's Energy Markets Analysis Team based on market financial data specific to the cement sector. As CCF varies from 5 percent to 15 percent, the capture costs can increase by up to $62.0/tonne CO_2 (i.e., a 60 percent). Details of the financial factors used in this study are given in Section 2.2.
- Another factor that results from financial assumptions is the weighted average cost of capital (WACC), which is mathematically translated into the CCF used in this analysis. In addition to impacting the capital portion of the COC, WACC also impacts the levelized NG and power prices used to generate the fuel and power COC components. Sensitivity to WACC shows that COC increases by $7.7–8.8/tonne CO_2 (i.e., a 7.8–8.6 percent increase) when WACC varies by 1–15 percent. Based on this analysis, for every 1 percent increase in WACC, the COC increases by 0.78–0.87 percent.

By estimating the COC across a range of cement plant sizes, the effects of economies of scale are demonstrated, as normalized COC increases with decreasing plant size (i.e., decreasing amount of CO_2 available for capture). In real applications, equipment is often manufactured in discrete sizing and may require installation of several units in parallel to achieve higher-end throughput capacity, or conversely, the use of oversized/underutilized (i.e., economically non-optimal) equipment to support lower-end throughput capacity. This study assumed continuous equipment sizing (i.e., did not consider discrete equipment sizing) and availability for estimating purposes. Such factors, along with the additive effects of financial and design assumptions, would impact the outcome of the plant size sensitivities presented throughout Section 5, but the sensitivity estimates are considered appropriate within the accuracy of this study (according to AACE International [AACE] Class 4). A cumulative graph of the plant size sensitivity analyses is presented in Exhibit ES-5.

Exhibit ES-5. Summary of plant capacity sensitivity analyses for base cases



Note: HI = heat integration

The results in this study are representative of the assumptions regarding the reference cement plants and their CO_2 emissions streams. Scale and location will impact results for actual plants. Methods of CO_2 transport and storage (T&S) and associated costs are considerations that could ultimately change the economic impact of retrofitting CO_2 capture at a specific plant. T&S cost was considered as a $10/tonne CO_2 addition to the calculated COC, based on NETL's "QGESS: Carbon Dioxide Transport and Storage Costs in NETL Studies" guidance and host site assumptions detailed in the body of the report. [4]

As a supplemental analysis, the COC is broken into five categories: CO_2 capture system, compression, steam generation and purchased power, water, and miscellaneous shared costs. Such an analysis provides insight into the potential influence of capture system improvements on the overall cost of capture, highlights the cost categories that are not influenced by improvements to the capture system, and allows isolation of the cost contributions of different systems to quantify the impact of potential cost improvements.

Exhibit ES-6 shows the COC breakdown summary (excluding T&S), highlighting that the costs attributed to the CO_2 capture system and purchased power/steam generation make up 85 percent of the overall COC. Since the compression, water, and miscellaneous shared costs contribute relatively little to the COC, improvements to those categories are not as impactful as cost improvements to the CO_2 capture or purchased power/steam generation categories. Unlike power applications of CO_2 capture, where auxiliary loads are met with on-site generation and steam can be sourced from the existing steam cycle at the plant, purchased power and steam generation costs are a significant contributor to the COC. Alternate power and steam generation technologies, such as combined heat and power production units, might improve the COC by reducing purchased power costs, but would come with added capital expenditure and still the need to purchase fuel. The cost breakdown in Exhibit ES-6 is calculated based on the design assumptions employed in this study, and alternate process heating and power supply could potentially improve the COC based on the breakdown results.

Exhibit ES-6. COC breakdown (excl. T&S)

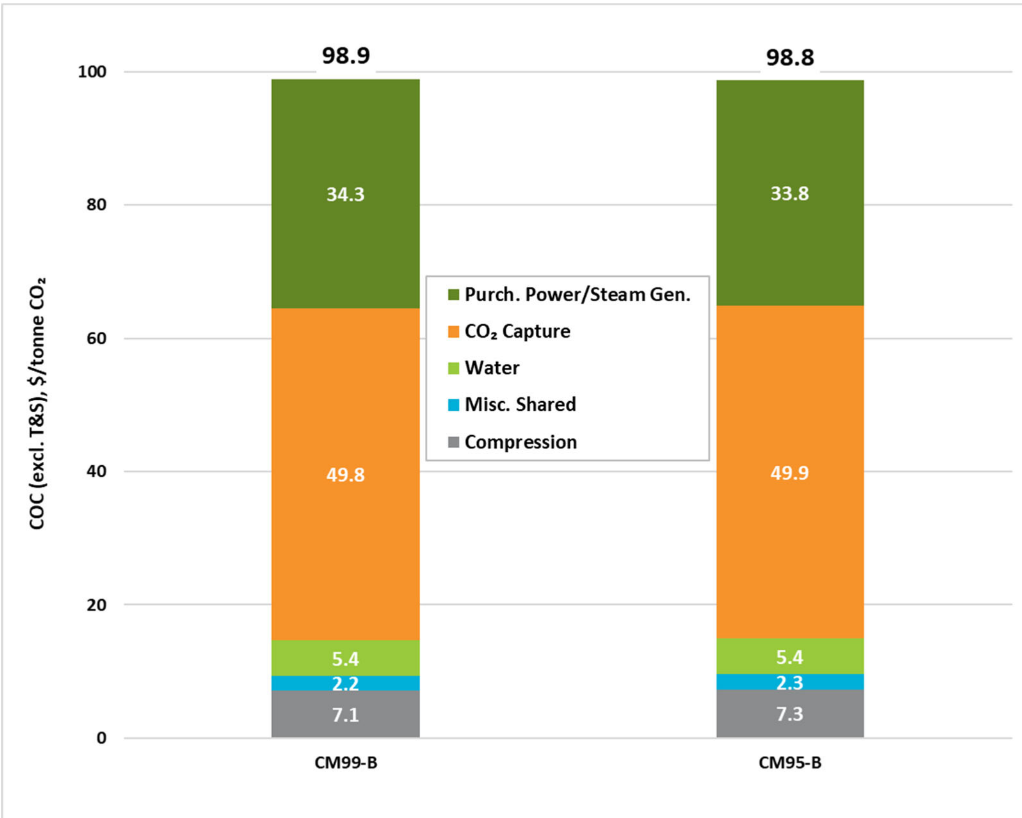
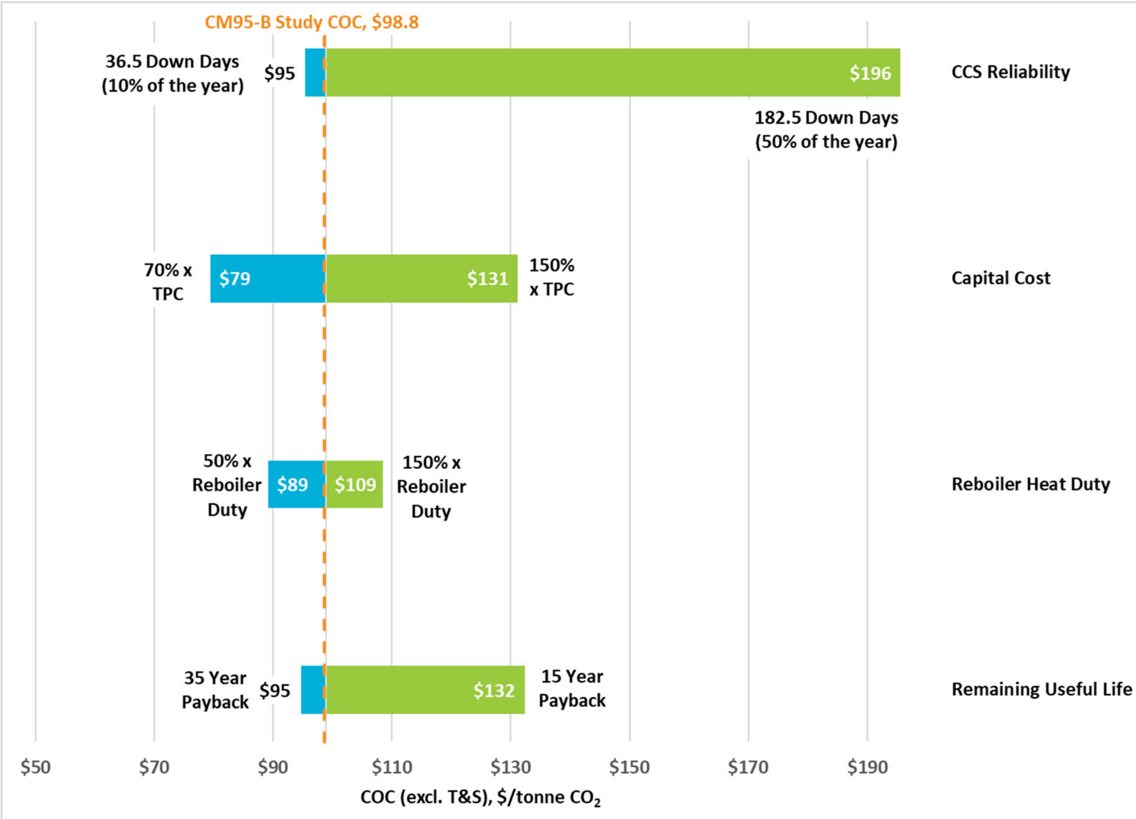


Exhibit ES-7 shows the relative impact of four key study assumptions: CO_2 capture system reliability (i.e., down days), capital cost (i.e., TPC), capture system reboiler heat duty, and remaining useful life of the cement plant. The case considered to generate Exhibit ES-7 is CM95-B, the pre-heater/pre-calciner kiln with coal/coke fuel and 95 percent CO_2 capture. Each parameter was varied individually across a range of values, to observe which has the most significant impact on and could, therefore, yield the greatest improvement in COC. The analysis suggests that improvements to the capture system power and steam requirements (e.g., solvent improvement, alternate heating or steam generation mechanisms) and capital cost reduction have the greatest potential to reduce capture costs.

Exhibit ES-7. COC vs. select study assumptions



Although there are currently no federal requirements for carbon capture at cement plants, historically in the electric power sector when pollution control processes fail, the entire plant comes offline to avoid violating flue gas emission limits. Improvements in system reliability will minimize the extent to which these unplanned down days occur, and this could be achieved through research on improved capture system tolerance to air pollutants, or robust response to transient operation. These improvements are shown in Exhibit ES-7 as variations in down days, and illustrate how significantly the capture cost can change with improvements (or deteriorations) in capture system reliability. Of all variables shown in Exhibit ES-7, operating basis, shown as a proxy for capture system reliability, has the most significant impact on cost, with COC rising to $196/tonne CO_2 (i.e., a 98 percent increase) when operation is cut to 50 percent. In addition to the capture system reliability, the reliability of the electrical power grid could impact the COC because the capture systems in this study rely on purchased electricity. This analysis suggests that, to add CO_2 capture to the cement kiln in case CM99-B, for instance, a 22 MW auxiliary power load is incurred. Deployment of CO_2 capture across the domestic cement fleet would require a significant increase of additional power consumption. Although grid impact and reliability was not considered as part of this analysis, ensuring the necessary generation and transmission capacity exists to meet this demand will be an important issue to assess regarding implementation of decarbonization in the U.S. cement industry.

Capital cost improvements were also shown to have a significant effect on capture cost. In the base case used for this example, capital cost accounts for approximately one third of the total

COC. Improvements in those areas having such significance would be expected to also show meaningful reductions in the cost of capture. The next-of-a-kind installations represented in this study would be expected to have costs toward the higher end of the range shown (i.e., \$131/tonne CO_2 at 150 percent of the TPC estimated for the base case), but as learning improves as a result of technology demonstrations and operating experience, costs will inevitably decrease, as has been observed with other air pollution control technologies. Capital cost improvements could be achieved with modular system design, improved unit operation reliability (eliminating redundancies), or through process improvements that would allow for smaller equipment design (such as enhancements in solvent carrying capacity).

The CO_2 capture solvent assumed for this analysis requires the use of stripping steam for regeneration, and this steam is raised in a supplemental NG-fired boiler. In Exhibit ES-7, changes in stripping steam requirement are indicated by reboiler duty. At the NG price assumed (\$4.61/MMBtu), a 50 percent reduction in reboiler duty brings the COC down to \$89/tonne CO_2 (i.e., a 10 percent reduction); however, the extent of the impact is still dependent upon NG price. At higher NG prices, the impact is expected to be greater than is demonstrated in this evaluation. Improvements in reboiler duty could be achieved via increasing solvent carrying capacity, for example.

The final variable that was considered in Exhibit ES-7 was the financial payback period, which was assumed to be equivalent to the remaining useful life of the cement plant prior to retrofit. Older facilities have shorter payback periods, since the plant has fewer remaining operating years over which to recover its costs. This would be reflected in less favorable financial terms and, therefore, increase the COC, as demonstated by the increase to \$132/tonne CO_2 (i.e., a 34 percent increase) with a 15-year payback period. Although the remaining useful life is not likely to be a parameter that can be improved through research and development (R&D), this could provide a better understanding regarding which facilities are the best candidates for retrofit, from an economic standpoint.

The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher than the presented estimates. Absent demonstrated first-of-a-kind plant costs, it is difficult to explicitly project fully mature, Nth-of-a-kind values. Consequently, the cost estimates provided herein represent neither first-of-a-kind nor Nth-of-a-kind costs but could be characterized as next-of-a-kind.

Applying a consistent methodology and presenting detailed equipment specifications and costs based on contemporary sources facilitates comparison between cases. Sensitivity analyses performed on a similar basis can be used to guide R&D, and generally improve upon publicly available estimates. Anticipated actual costs for projects based upon any of the cases presented herein are expected to deviate from the cost estimates in this report due to project- and site-specific considerations (e.g., contracting strategy, local labor costs and availability, seismic conditions, water quality, financing parameters, local environmental concerns, weather delays, market forces) that may make construction more costly.

1 INTRODUCTION

In the United States (U.S.), cement production contributed about 69 million (M) tonnes of carbon dioxide (CO_2) emissions in 2020, representing approximately 1.5 percent of total domestic CO_2 emissions based on reporting to the Environmental Protection Agency. [1] [2] This study evaluates the potential cost of capturing CO_2 as a retrofit application for representative cement kilns.

The cost of CO_2 capture (COC), excluding CO_2 transport and storage (T&S), in each case, as defined by Equation 1-1, considers the capital cost of installing equipment required for CO_2 capture and compression, as well as the balance of plant equipment (as detailed in Section 3.2 through Section 3.6), and operation and maintenance (O&M), purchased power, and fuel costs associated with capture operations. T&S costs in this study are applied as an addition to the COC based on the design basis assumptions regarding host site characteristics and the National Energy Technology Laboratory's (NETL) "Quality Guidelines for Energy System Studies [QGESS]: Carbon Dioxide Transport and Storage Costs in NETL Studies." [4] Throughout the report, "CO_2 capture retrofit system" refers to all incremental equipment required to prepare the CO_2 emissions stream for pipeline transport (i.e., compression and intercooling, auxiliary equipment, CO_2 capture systems, etc.). The representative cement plants themselves are not evaluated, but they are each characterized by their CO_2 emissions stream (i.e., the cement kiln off-gas) in terms of flowrate, temperature, pressure, and composition.

$$COC\left(\frac{\$}{tonne\ CO_2}\right) = \frac{TOC * CCF + FOM + VOM + PF + PP}{tonnes\ CO_2\ captured\ per\ year}$$

Equation 1-1: Cost of CO_2 Capture

Where:

- TOC – Total overnight costs of CO_2 capture retrofit system (details provided in Section 2)
- CCF – Capital charge factor, based on industry-specific financial assumptions as detailed in Section 2.2
- FOM – Annual fixed O&M costs
- VOM – Annual variable O&M costs
- PF – Purchased fuel
- PP – Purchased power

Estimates of financing scenarios specific to the cement industry were applied to the capital costs to account for return on equity and financing costs. Financial methodology and the resulting financial factors were developed by NETL's Energy Market Analysis Team in 2022 and are presented in Section 2.

1.1 DESIGN BASIS AND CASE MATRIX

CO_2 capture retrofit system performance and cost estimates are presented for the ten base cases defined in Exhibit 1-1. In addition, sensitivity studies related to the addition of a selective catalytic reduction (SCR) unit to treat oxides of nitrogen (NOx) and flue gas desulfurization

(FGD) to remove oxides of sulfur (SOx) are evaluated for select base cases (detailed in Section 6). Analysis of the base cement plants falls outside the scope of this study (i.e., cost of cement production before and after CO_2 capture). Any deviation in design basis assumptions employed for this study, could impact the COC results.

Exhibit 1-1. Case matrix

Case Number	CM99-B	CM95-B[A]	CM95-B1[A]	CM95-B2	CM95-B3[A]	CM95-B4[A]	CM95-B5	CM95-B6	CM95-B7	CM95-B8
Capture Rate	99 Percent	95 Percent								
Kiln Type	Pre-heater/Pre-calciner				Wet Process		Pre-heater/Pre-calciner			
Kiln Off-Gas CO_2 Concentration, mol %	31	31	25	30	17	13	31		25	
Kiln Fuel Type	Coal/Coke		NG	Oil	Coal/ Coke	NG	Coal/Coke		NG	
Heat Integration Potential, %	N/A	N/A	N/A	N/A	N/A	N/A	10	30	10	30

[A]Sensitivity cases regarding SOx and NOx concentrations are shown for these cases in Section 5.2, with SOx levels at 100, 300, and 500 ppm_v and NOx levels at 500, 1,000, and 1,500 ppm_v

In addition to the kiln off-gas characteristics listed in Exhibit 1-1, assumptions regarding the capture stream conditions (i.e., temperature and pressure) are shown in Exhibit 1-2. For sensitivity cases with FGD and SCR unit operations, the contaminant (i.e., SOx, NOx, and particulate matter [PM]) levels in Exhibit 1-2 are design targets for SOx, NOx, and PM abatement in those pre-treatment systems prior to introduction into the pre-scrubber of the solvent capture systems in this analysis. As increasing levels of contaminants may have a range of effects on solvents depending on the technology deployed, capture system-specific limitations should be addressed by individual technology providers in real applications.

Exhibit 1-2. CO_2 capture system inlet conditions

Parameter	Value
Temperature, °C (°F)	209 (408)
Pressure, MPa (psia)	0.10 (14.7)
SOx Concentration, ppm_v	37
NOx Concentration, ppm_v	40 (assuming 5 percent NO_2)
PM Concentration, milligrams per normal cubic meter	20 (maximum)

The base cases evaluated consider capture directly from the kiln off-gas. Kiln off-gas can be used to preheat raw meal and can be treated for pollutants before exhaust from such pre-processing unit operations. These steps, along with additional air in-leakage that occurs as part of these operations, lead to lower CO_2 concentrations, higher humidity, higher flow rates, and a lower temperature for the cement plant exhaust stream that would enter the CO_2 capture island. The lower flow rates and higher CO_2 concentrations of the base cases are, therefore, optimistic. To address the variation in flow rates and CO_2 concentration caused by kiln off-gas use in the pre-processing steps, additional cases are presented in Section 7.

Cases and sensitivity analyses selected in this study are meant to be representative of generic kilns in the existing domestic cement fleet and demonstrative of the impact of kiln off-gas quality on COC. Although each case is described by a particular kiln type, fuel type, heat integration potential, etc., these characterizations are anecdotal in nature. Cement plant owners implementing retrofit capture systems may find that base plant and kiln off-gas characteristics are different than those listed in the case matrix, and as such, should evaluate cost of retrofit capture on a case-by-case basis.

1.2 Process Modeling Assumptions

Process models were developed for each case based on guidance in NETL's QGESS "Process Modeling Design Parameters," and applicable model assumptions are shown in Exhibit 1-3. [5] NETL QGESS guidance is used throughout to normalize the basis of the analysis and allow comparison between NETL capture studies.

In addition to these process modeling assumptions, certain considerations regarding the availability of utility systems at the existing cement plant are necessary to estimate the costs of retrofit CO_2 capture applications. The design basis of this study assumes that for all cases:

- Sufficient plot plan space is available, and that space is properly located for the installation of the retrofit CO_2 capture system
- The existing plant's instrument air system capacity is adequate to support the additional instrument air needs of the retrofit CO_2 capture system
- The existing plant's fuel gas system is adequate to support the additional capacity of fuel gas required by the industrial boiler, which is used for steam generation to meet the heating needs of the solvent regeneration process

Exhibit 1-3. Process design assumptions

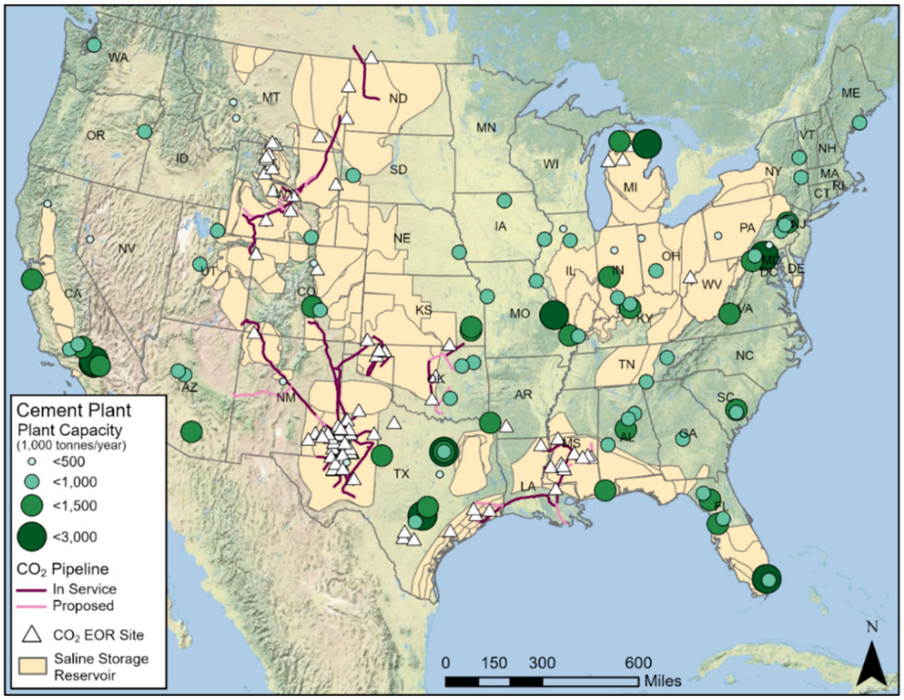
Site Characteristics		
Location		Greenfield, Midwestern U.S.
Topography		Level
Size, acres		10
Water Supply		50% Municipal and 50% Ground Water
Site Ambient Conditions		
Elevation, m (ft)		0 (0)
Barometric Pressure, MPa (psia)		0.101 (14.696)
Average Ambient Dry Bulb Temperature, °C (°F)		15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)		10.8 (51.5)
Design Ambient Relative Humidity, %		60
Cooling Water Temperature, °C (°F)		15.6 (60)
NG Characteristics[A]		
Component		**Volume %**
Methane	CH_4	93.1
Ethane	C_2H_6	3.2
Propane	C_3H_8	0.7
n-Butane	C_4H_{10}	0.4
Carbon Dioxide	CO_2	1.0
Nitrogen	N_2	1.6
Methanethiol[B]	CH_4S	5.75×10^{-6}
	LHV	**HHV**
kJ/kg (Btu/lb)	47,201 (20,293)	52,295 (22,483)
megajoule/standard cubic meter (Btu/standard cubic foot)	34.52 (927)	38.25 (1,027)
Air composition based on published psychrometric data, mass %		
Nitrogen	N_2	75.055
Oxygen	O_2	22.998
Argon	Ar	1.280
Water	H_2O	0.616
Carbon Dioxide	CO_2	0.050

[A]Fuel composition is normalized, and heating values are calculated using Aspen Plus®
[B]The sulfur content of natural gas is primarily composed of added mercaptan (methanethiol) with trace levels of hydrogen sulfide [6]

1.3 Cement Plant Sites and CO_2 End-Use

The final CO_2 product is prepared for pipeline transport to end users and as such, adheres to the specifications for CO_2 product purity, pressure, and temperature after capture and compression per NETL's QGESS "CO_2 Impurity Design Parameters" specifications. [7] Other uses for the CO_2 may be available, but those alternate possibilities were not considered for the purpose of this study. While detailed pipeline specifications such as pressure drop, length, and other characteristics, are not considered in this study, and as noted in Exhibit 1-3, the study assumes a generic midwestern plant for the purposes of consistency in process modeling, it is useful to highlight cement plant locations relative to end-use sites and transport mechanisms that could be utilized. Exhibit 1-4 shows the U.S. cement fleet and existing CO_2 infrastructure. The viability of adding capture to a representative plant would ultimately be dependent upon the project-specific costs for T&S of the CO_2 captured in addition to the capture costs, such as the COC evaluated in this study.

Exhibit 1-4. Cement plant locations and existing CO_2 infrastructure



2 Economic Analysis Overview

2.1 Cost Estimating Methodology

Detailed information pertaining to topics such as contracting strategy; engineering, procurement, and construction (EPC) contractor services; estimation of capital cost contingencies; owner's costs; cost estimate scope; economic assumptions; and finance structures are available in the 2019 revision of the QGESS "Cost Estimation Methodology for NETL Assessment of Power Plant Performance." [8] Select portions are repeated in this report for completeness. NETL QGESS guidance is used throughout to normalize the basis of the analysis and allow comparison between NETL capture studies.

The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher than the presented estimates. Absent demonstrated first-of-a-kind plant costs, it is difficult to explicitly project fully mature, Nth-of-a-kind values. Consequently, the cost estimates provided herein represent neither first-of-a-kind nor Nth-of-a-kind costs.

Applying a consistent methodology and presenting detailed equipment specifications and costs based on contemporary sources facilitates comparison between cases. Sensitivity analyses performed on a similar basis can be used to guide research and development (R&D), and generally improve upon publicly available estimates.

<u>Costs of Mature Technologies and Designs:</u>

The cost estimates for equipment that has been widely deployed at commercial scale reflect nth-of-a-kind on the technology commercialization maturity spectrum. The costs of such technologies have dropped over time due to "learning by doing" and risk reduction benefits that result from serial deployments as well as from continuing research and development. All process equipment in the estimates found herein is commercially available, so no process contingencies were added to those cases, except for the costs associated with the CO_2 capture system detailed in Section 3.1.

<u>Costs of Emerging Technologies and Designs</u>:

The cost estimates for the CO_2 capture system use the same cost estimating methodology as for mature technologies, which does not fully account for the unique cost premiums associated with the initial, complex integrations of emerging technologies in a commercial application. Thus, it is expected that addition of the CO_2 capture equipment may incur costs higher than those estimated for a mature technology. As such, process contingency of 17 percent is applied to the CANSOLV® CO_2 capture system based on engineering judgment and for consistency of process contingencies applied for similar technologies in other NETL studies. [9]

Other Factors:

Actual reported project costs for all the plant types are also expected to deviate from the cost estimates in this study due to project- and site-specific considerations (e.g., contracting strategy, local labor costs, seismic conditions, water quality, financing parameters, local environmental concerns, weather delays) that may make construction more costly. Such variations are not captured by the reported cost uncertainty.

2.1.1 Capital Costs

As illustrated in Exhibit 2-1, this study defines capital cost at five levels: BEC, EPCC, TPC, TOC, and TASC. BEC, EPCC, TPC, and TOC are "overnight" costs and are expressed in "base-year" dollars. The base year is the first year of capital expenditure. TASC is expressed in mixed, current-year dollars over the entire capital expenditure period, which is assumed to last three years. Capital expenditure is estimated assuming that the equipment is designed for full operating capacity 100 percent of the year. The cost estimates presented in this study are considered Class 4 estimates, as defined by AACE International (AACE) 16R-90. [10]

The Bare Erected Cost (BEC) comprises the cost of 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 BEC.

The Engineering, Procurement, and Construction Cost (EPCC) comprises the BEC plus the cost of services provided by the EPC contractor. EPC services include detailed design, contractor permitting (i.e., those permits that individual contractors must obtain to perform their scopes of work, as opposed to project permitting, which is not included here), and project/construction management costs.

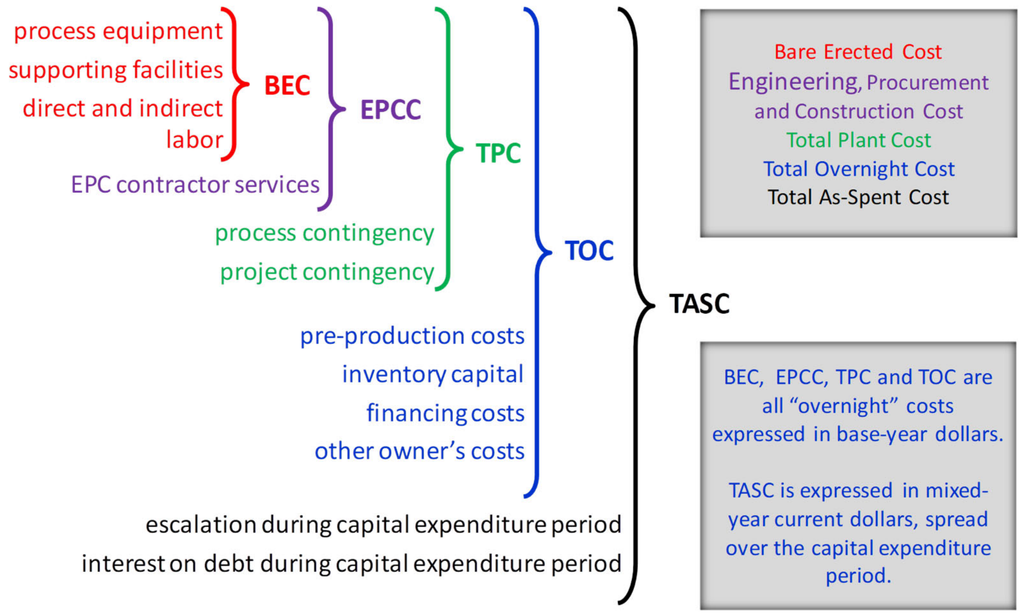
The Total Plant Cost (TPC) comprises the EPCC plus project and process contingencies.

AACE 16R-90 states that project contingency for a "budget-type" estimate (AACE Class 4 or 5) should be 15 to 30 percent of the sum of BEC, EPC fees, and process contingency. [10] Therefore, a 20 percent project contingency was added to each cost account across all cases.

The Total Overnight Cost (TOC) comprises the TPC plus all other overnight costs, including owner's costs. TOC does not include escalation during construction or interest during construction.

The Total As-Spent Cost (TASC) is the sum of all capital expenditures as they are incurred during the capital expenditure period including their escalation. TASC also includes interest during construction, comprising interest on debt and a return on equity.

Exhibit 2-1. Capital cost levels and their elements



2.1.1.1 Cost Estimate Basis and Classification

The TPC and O&M costs for each of the cases in the report were estimated based on adjusted vendor-furnished data and scaled estimates from previous NETL studies. Reference costs are scaled based on direction from NETL's QGESS "Capital Cost Scaling Methodology: Revision 4 Report." [11] An underlying assumption of this cost scaling methodology is that capital equipment is available and scalable at any size/capacity. In real applications, equipment may only be manufactured in discrete sizes, and so the costs presented herein could be optimistic. This is particularly applicable for the "Plant Capacity Sensitivity Analysis" found in the analysis subsections for each of the base cases (i.e., throughout Section 5). Those plant capacity sensitivity analyses are generated assuming continuous equipment capacities and costs and by scaling TPC based on the capture stream CO_2 flowrate, rather than by following the QGESS capital cost scaling methodology for every capacity across the plant size range. For the purposes of this study, it is assumed that margins of error associated with the cost scaling methodology for plant capacity sensitivities would be within the range of an AACE Class 4 estimate.

2.1.1.2 System Code-of-Accounts

The costs are grouped according to a process/system-oriented code of accounts. This type of code-of-account structure has the advantage of grouping all reasonably allocable components of a system or process, so they are included in the specific system account.[2]

2.1.1.3 Price Fluctuations

During the writing of this report, the prices of equipment and bulk materials used as reference costs fluctuated because of various market forces. All vendor quotes used to develop these

[2] This would not be the case had a facility, area, or commodity account structure been chosen instead.

estimates were adjusted to November 2022 dollars accounting for the price fluctuations. The Chemical Engineering Plant Cost Index [12] and the U.S. Bureau of Labor Statistics Chained Consumer Price Index (CPI) [13] were used as needed to adjust capital costs and bulk material costs, respectively. The cost of individual equipment types and materials may still deviate from the November 2022 reference point. November 2022 dollars are presented to normalize the basis of the analysis and allow comparison between NETL capture studies.

In addition to year dollar effects on the costs presented in this study, the location of the actual installation can influence pricing due to transport and shipping constraints, workforce availability, etc. It is assumed that these contingencies are covered within the range of accuracy of the report (AACE Class 4). The bulk of equipment was costed prior to 2021 and, therefore, costs do not reflect current supply chain stresses.

2.1.1.4 Owner's Costs

Owner's costs were estimated based on the 2019 revision of the QGESS "Cost Estimation Methodology for NETL Assessment of Power Plant Performance." [8] Owner's costs are split into three categories: pre-production costs, inventory capital, and other costs.

Pre-production allocations are expected to carry the specific plants through substantial completion, and to commercial operation. Substantial completion is intended to represent the transfer point of the facility from the EPC contractor (development entity) to the end user or owner, and is typically contingent on mutually acceptable equipment closeout, successful completion of facility-wide performance testing, and full closeout of commercial items. Exhibit 2-2 presents descriptions of the owner's costs estimated for the cases in this study.

Exhibit 2-2. Estimated amounts for owner's costs

Owner's Cost	Amounts
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
Production (Start-Up) Costs	• 6 months operating labor • 1-month maintenance materials at full capacity • 1-month non-fuel consumables at full capacity • 1-month waste disposal • 25% of one month's fuel cost at full capacity • 2% of TPC 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 [10] and EPRI TAG® [14] differ on the amount of fuel cost to include. This estimate follows EPRI TAG®.
Inventory Capital	• 0.5% of TPC for spare parts • 60-day supply (at full capacity) of fuel. Not applicable for natural gas

Owner's Cost	Amounts
	• 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 SCR catalysts AACE 16R-90 [10] does not include an inventory cost for fuel, but EPRI TAG® [14] does.
Land	• $3,000/acre, 10 acres • Note: This land cost is based on a site in a rural location. In many cement plants, acreage for additional equipment is limited by either geological complexity or with regards to land ownership, which would result in cost premiums that are higher than the value assumed herein.
Financing Costs	• 2.7% of TPC This financing cost (not included by AACE 16R-90 [10]) covers the cost of securing financing, including fees and closing costs but not including interest during construction (or allowance for funds used during construction). The "rule of thumb" estimate (2.7% of TPC) is based on a 2019 professional communication with Black & Veatch.
Other Owner's Costs	• 15% of TPC This additional lumped cost is not included by AACE 16R-90 [10] or EPRI TAG® [14]. The "rule of thumb" estimate (15% of TPC) is based on a 2019 professional communication with Black & Veatch: o Preliminary feasibility studies, including a front-end engineering design study o Economic development (costs for incentivizing local collaboration and support) o Construction and/or improvement of roads and/or railroad spurs outside of site boundary o Legal fees o Permitting costs 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) o Owner's contingency (sometimes called "management reserve"—these are funds to cover costs relating to delayed startup, fluctuations in equipment costs, unplanned labor incentives in excess of a five-day/ten-hour-per-day work week. Owner's contingency is not a part of project contingency) This lumped cost does not include o EPC risk premiums (costs estimates are based on an EPCM approach utilizing multiple subcontracts, in which the owner assumes project risks for performance, schedule, and cost) o Transmission interconnection: the cost of interconnecting with power transmission infrastructure beyond the plant busbar o Taxes on capital costs: all capital costs are assumed to be exempt from state and local taxes o Unusual site improvements: normal costs associated with improvements to the plant site are included in the BEC, assuming that 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, noise regulations

2.1.2 Operation and Maintenance Costs

The production costs or operating costs and related maintenance expenses pertain to those charges associated with operating and maintaining the CO_2 capture retrofit system over its expected life. The O&M costs calculated in this study are incremental costs related to the capture, compression, and ancillary equipment evaluated and, thus, are not indicative of the O&M costs of the base cement plant in each case.

These O&M costs include the following:

- Operating labor
- Maintenance – material and labor
- Administrative and support labor
- Consumables
- Fuel
- Waste disposal
- Co-product or by-product credit (that is, a negative cost for any by-products sold)

There are two components of O&M costs: fixed O&M, which is independent of production, and variable O&M, which is proportional to production. Taxes and insurance are included as fixed O&M costs, totaling two percent of the TPC.

2.1.2.1 Operating Labor

Operating labor cost was determined based on the number of operators required for the addition of capture, compression, and ancillary equipment. To operate the CO_2 capture island, 2.3 additional operators per shift are assumed, which is the difference in operating labor required for a supercritical pulverized coal power plant with and without capture, per NETL's "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" (the "Fossil Energy Baseline") results. [9] The average base labor rate used to determine annual cost is $40.72/hour. The associated labor burden is estimated at 30 percent of the base labor rate.

2.1.2.2 Maintenance Material and Labor

Maintenance cost was evaluated based on relationships of maintenance cost to initial capital cost. The annual maintenance material and labor costs are estimated to be equivalent to 0.96 and 0.63 percent of TPC, respectively.

2.1.2.3 Administrative Support and Labor

Labor administration and overhead charges are assessed at a rate of 25 percent of the burdened O&M labor.

2.1.2.4 Consumables

The cost of consumables, including fuel and purchased power to satisfy the auxiliary loads estimated for each case, was determined based on individual rates of consumption, the unit cost of each specific consumable commodity, and the plant annual operating hours. Quantities for major consumables such as natural gas (NG) for fuel and purchased power were taken from technology-specific energy and mass balance diagrams developed for each plant application. Natural gas fuel is purchased at $4.61/MMBtu, and power is purchased at a price of $67.3/MWh. Sensitivity analyses relating COC to purchased power price and NG price are detailed in Section 5.11.4 and Section 5.11.4, respectively. Other consumables were evaluated based on the quantity required using reference data.

The quantities for initial fills and daily consumables were calculated on a 100 percent operating basis. The annual cost for the daily consumables was then adjusted to incorporate the annual plant operating basis. It is assumed that the cement plant operates 85 percent of the year for all cases to provide comparability to other NETL studies, including power generation cases in the Fossil Energy Baseline. [9] A sensitivity to the operating basis is provided in Section 5.11.1 for the base cases, as plant operation varies widely for the cement industry. Initial fills of the consumables, fuels, and chemicals may be accounted for directly in the O&M tables or included with the equipment pricing in the capital cost.

2.1.2.5 Waste Disposal

Waste quantities and disposal costs were determined/evaluated similarly to the consumables. Waste streams are individually reported, and disposal costs are reported for each waste stream, where applicable.

2.2 Capital Charge Factors

The financial assumptions were developed by NETL's Energy Markets Analysis Team in December 2022 based on market data respective to the cement sector, which are summarized in Exhibit 2-3, where all values are expressed in real dollar terms. These factors are defined in detail the 2019 revision of the QGESS "Cost Estimation Methodology for NETL Assessment of Power Plant Performance." [5]

Exhibit 2-3. Financial assumptions for retrofit capture at cement plants

Financial Parameter	Value
Fixed Charge Rate	7.91%
TASC/TOC Ratio	1.118
Capital Charge Factor	8.84%
Debt/Equity Ratio	42/58
Operating Life/Depreciation Period	30 years
Interest on Debt	8.82%
Levered Return on Equity	4.90%
Weighted Average Cost of Capital	6.56%
Capital Expenditure Period	3 years
Capital Distribution	1st year – 10% 2nd year – 60% 3rd year – 30%

The figure of merit resulting from this economic analysis is the cost of CO_2 captured, which represents the levelized cost to the owner per tonne of CO_2 captured. This cost includes the capital expenditures, escalated at the assumed nominal general inflation rate of two percent per year, providing the stipulated rate of return on equity over the entire economic analysis period. Assuming all annual costs also escalate at the same inflation rate, the COC is essentially the sum of the O&M costs and the annualized capital cost charges, all normalized to the annual captured CO_2 flow rate.

For a CO_2 source with a higher flow rate (with the same emissions stream characteristics and at the same capture rate), a corresponding increase in the flow rate of the captured CO_2, requirement for consumables, size of capture equipment, etc., occurs; however, the COC is expected to be roughly equivalent or, in some cases, lower due to the economies of scale associated with the cost of the larger equipment. Ultimately, the capital charge factor (CCF), which is the product of the fixed charge rate and the TASC/TOC ratio, applied can have a dramatic effect on the COC calculated (see Equation 1-1 in Section 1). A sensitivity analysis evaluating this relationship, as well as the impact of weighted average cost of capital (WACC) on the COC of the base cases, is presented in Section 5.11.1.

2.3 Retrofit Factors

Engineering judgment was used to determine a generic retrofit factor to be applied to the cases in this study. A retrofit factor of 1.05 was applied to the TPC of the non-heat integration cases. A retrofit factor of 1.155 was applied to the TPC of the heat integration cases (i.e., cases CM95-B5 through CM95-B8) to account for additional retrofit difficulty associated with integrating heat users into existing heat sources within the base plant.

Without a formalized procedure for applying the retrofit factors, it is best to consider the retrofit factor as a single capital cost sensitivity, from which the true cost of a retrofit (which has overriding project and site-specific considerations) can be refined as more information is available for a specific design case. A sensitivity analysis examining the influence of the retrofit factor on COC is discussed in Section 5.11.3.

3 EQUIPMENT

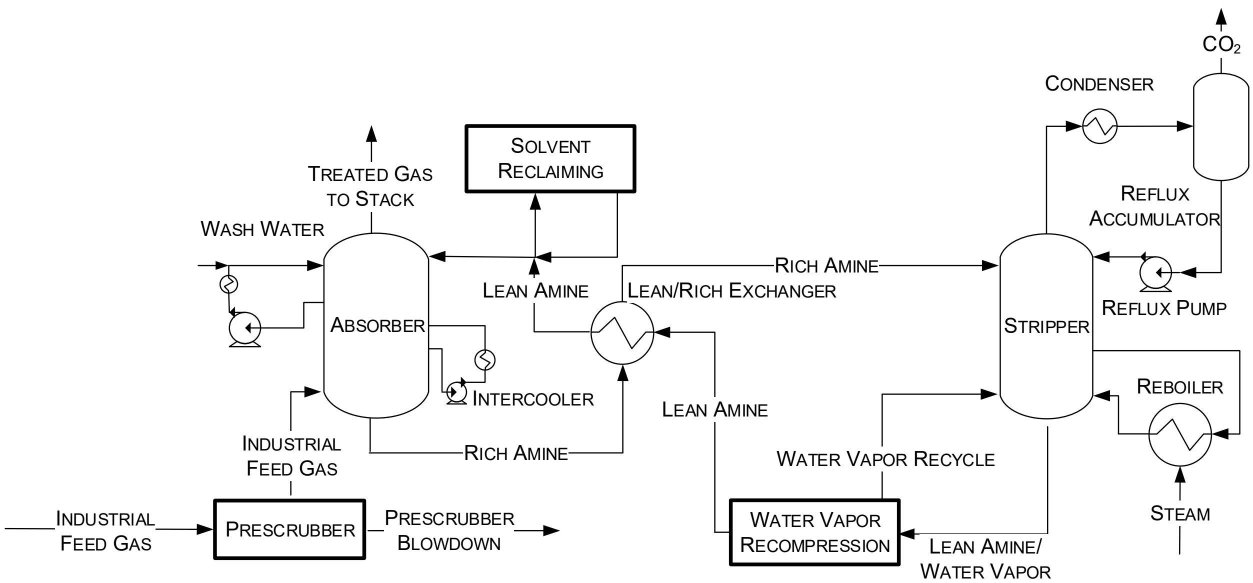
3.1 CO_2 CAPTURE AND PURIFICATION[3]

A CO_2 capture unit is modeled for CO_2 separation and purification prior to compression. In addition to capturing CO_2, the unit also polishes residual sulfur components in the capture stream. The performance and cost information for the CO_2 capture unit represented in this study are based on data provided by Shell in 2021. [15] All costs are scaled in accordance with the specifications identified in the QGESS "Capital Cost Scaling Methodology: Revision 4 Report." [11]

3.1.1 CANSOLV® Post-Combustion Capture

The CO_2 capture system uses the CANSOLV® CO_2 Capture technology commercially offered by Shell. This amine-based, post-combustion process is designed to recover high purity CO_2 from low purity streams that contain O_2, such as flue gas from coal-fired power plants, combustion turbine exhaust gas, and other industrial waste gas streams. A typical flowsheet for the process is shown in Exhibit 3-1.

Exhibit 3-1. Shell's CANSOLV® CO_2 capture typical process flow diagram



3.1.1.1 Pre-scrubber

The CO_2-laden gas from the kiln and from the NG-fired boiler is combined and sent through a booster fan to drive the gas through downstream equipment starting with the pre-scrubber inlet cooling section. The cooler is operated as a direct contact cooler that saturates and sub-cools the feed gas stream. Saturation and sub-cooling are beneficial to the system as they

[3] Much of the text and descriptions within this section were sourced, with permission, from data provided by Shell to NETL, unless otherwise noted. The information relates to a CO_2 capture system designed by Shell. [15]

improve the amine absorption capacity, thus reducing amine circulation rate. After the cooling section, the feed gas is scrubbed with caustic in the pre-scrubber sulfur polishing section. This step reduces the sulfur dioxide (SO_2) concentration entering the CO_2 absorber column to less than 1 ppm_v.

3.1.1.2 CO_2 Absorber

The CANSOLV® absorber is a single, rectangular, acid resistant, lined concrete structure containing stainless-steel packing, a typical design for large-scale units. There is a packed section used for CO_2 absorption, and another packed section used for water-wash. This specific absorber geometry and design provides several cost advantages over more traditional column configurations while maintaining equivalent or elevated performance. The feed gas enters the absorber and flows counter-current to the CANSOLV® solvent.

The lean solvent absorbs 90–99 percent of the inlet CO_2, depending on the design capture rate and operating conditions, and the remaining CO_2 exits the main absorber section and enters the water-wash section of the absorber. Prior to entering the bottom packing section, hot amine is collected, removed, and pumped through a heat exchanger to provide intercooling and maintain a low temperature favorable to absorption. The cooled amine is then sent back to the absorber just above the final packed section.

The water-wash section at the top of the absorber is used to remove volatiles or entrained amine from the treated gas, as well as to condense and retain water in the system. The wash water is removed from the bottom of the wash section, pumped through a heat exchanger, and is then re-introduced at the top of the wash section. This wash water is made up of recirculated wash water as well as water condensed from the treated gas; excess water resulting from condensation overflows to the lower absorption section through a chimney tray. The CO_2-lean gas treated in the water-wash section is then released to the atmosphere.

3.1.1.3 Amine Regeneration

The rich amine is collected at the bottom of the absorber and pumped through multiple parallel rich/lean heat exchangers where heat from the lean amine is exchanged with the rich amine. The CANSOLV® rich/lean solvent heat exchangers are a stainless-steel plate and frame type with a typical 5°C (9°F) approach temperature. The rich amine continues and enters the stripper near the top of the column.

The stripper is a stainless-steel vessel using structured stainless-steel packing. The regenerator reboiler uses low-pressure steam to boil water vapor from the solvent; this vapor flows upwards, counter-current to the rich amine flowing downward, and removes CO_2 from the amine. The CANSOLV® regenerator reboiler is a stainless-steel plate and frame type with a 3°C (5°F) approach temperature. Lean amine is collected in the stripper bottoms and flows to a flash vessel where water vapor is released. This lean solvent is then pumped through the same rich/lean heat exchanger to exchange heat from the lean amine to the rich amine and continues to the lean amine tank.

The water vapor and stripped CO_2 flow up the stripper where they are contacted with recycled reflux to condense a portion of the vapor and collect entrained solvent droplets. The remaining gas continues to the condenser where it is partially condensed. The two-phase mixture then flows to a reflux accumulator where the CO_2 product gas is separated and sent to the CO_2 compressor at approximately 0.2 MPa (29 psia), and the remaining water is collected and returned to the stripper as reflux.

The flow of steam to the regenerator reboiler is proportional to the rich amine flow to the stripper; however, the flow of low-pressure steam is also dependent on the stripper top temperature.

3.1.1.4 Amine Purification

The purpose of the amine purification, or amine reclaiming, section is to remove a portion of the heat-stable salts as well as ionic and non-ionic amine degradation products. The CANSOLV® amine purification (reclaiming) is essentially a distillation operation, in which the usable amine is boiled off the degraded solvent, which is recovered at the bottom of the column for disposal.

3.2 Centrifugal Compressor

An integrally geared centrifugal compressor is modeled for compressing the high-purity CO_2 for pipeline transport. A quote for an integrally geared centrifugal compressor was provided for the development of the Fossil Energy Baseline. [9] In addition to the compressor itself, intercooling exchangers and a triethylene glycol (TEG) dehydration unit are modeled as integral parts of the compression train. The TEG system removes residual water (H_2O) to achieve an outlet stream content of 500 ppm_v H_2O. The compressor discharges a nearly pure CO_2 stream at a pressure of 2,214.7 psia (2,200 psig), per QGESS specification. [7]

3.3 Industrial Boiler

The CO_2 capture unit detailed in Section 3.1.1 requires low-pressure steam at 71 psia for solvent regeneration. Since the base plant is not modeled, it is assumed that this heat requirement is met by a stand-alone NG-fired boiler. For heat integration cases (i.e., CM95-B6 through CM95-B8), base plant waste heat availability is accounted for by reducing the heat duty supplied by the boiler by 10 or 30 percent. A quote for an industrial steam boiler was obtained from CleaverBrooks in March 2021, from which costs were scaled per QGESS capital cost scaling methodology based on the performance estimates for each case analyzed. [11] [16] The quoted boiler produces superheated steam at 100 psig, so the total heat required from 71 psia steam for solvent regeneration was calculated, and the equivalent amount of heat delivered from the referenced boiler was modeled as part of the Aspen Plus® (Aspen) simulation. Boiler auxiliary power requirements for pumps and compressors were scaled based on the quoted information. Consumables include NG fuel and feedwater makeup.

3.4 Cooling Water Unit

As previously stated, no characterization of the base cement plant was performed; therefore, it is assumed that any cooling required by the retrofit capture equipment must be supplied by a stand-alone cooling water unit. Power consumption for the cooling water unit was calculated by methods consistent with those used to estimate cooling water unit performance in the Fossil Energy Baseline cases. Cost estimates for the cooling water system were scaled from Case B11A-BR of NETL's "Eliminating the Derate of Carbon Capture Retrofits" (Derate Study) based on the QGESS guidance for capital cost scaling. [17] [11]

3.5 Heat Exchangers

Cooling of the product CO_2 is required for all cases following compression to meet the pipeline temperature specification of 86°F. The cost for an after-cooler was scaled from the Fossil Energy Baseline Case B12B based on heat exchanger duty as predicted by Aspen, consistent with QGESS cost scaling methodology. [9] [11]

3.6 Ancillary Equipment, Buildings, and Structures

Ancillary equipment associated with implementing the capture equipment in this study include an accessory electrical plant and instrumentation and control (I&C) equipment. In addition, some site improvements, such as ground preparation and additional facilities, would be required for the construction and ongoing operation of the equipment considered. Estimates for these costs were scaled from previous estimates received by NETL for analogous work using QGESS guidance. [11]

3.7 Selective Catalytic Reduction

The sensitivity cases evaluated in Section 6 utilize an SCR, which uses 19 percent by weight (wt%) ammonia (NH_3) and a catalyst to reduce NOx to nitrogen (N_2) and H_2O in the kiln off-gas stream before comingling with the boiler flue gas stream to be treated in the CO_2 capture unit. The SCR system consists of three subsystems: reactor vessel, NH_3 storage and injection, and gas flow control. The SCR system is scaled from that of Case B12B.95 of the Fossil Energy Baseline based on gas flow according to QGESS guidance. [9] [11] It is assumed in this study that the SCR can achieve over 90 percent NOx reduction. Included in the cost of the SCR system is the NH_3 storage and injection system, which consists of unloading facilities, bulk storage tank, vaporizers, and dilution air skid.

3.8 Flue Gas Desulfurization

The sensitivity cases evaluated in Section 6 utilize a dry FGD process, which uses a lime spray dry absorber system to reduce SO_2 concentrations to levels that are treatable by the capture system pre-scrubber (i.e., 37 ppm_v in this analysis) prior to comingling with the boiler flue gas stream and entering the CO_2 capture process. Costs for the FGD are scaled from NETL's "Cost and Performance Baseline for Fossil Energy Plants Volume 3: Low Rank Coal and Natural Gas to Electricity" Case S12A based on gas flow according to QGESS guidance. [18] [11]

4 Cement Production Background

In 2020, the U.S. cement industry produced approximately 89.3 M tonnes of Portland cement and masonry cement, with sales at approximately $12.7 billion. [2] In the same year, the U.S. apparent consumption of cement was 102 M tonnes, meaning that imported cement filled the production gap. The United States Geological Survey (USGS) asserts in their 2021 *Minerals Commodity Summary* that U.S. cement production growth has been continuously constrained in recent years "by closed or idle plants, underutilized capacity at others, production disruptions from plant upgrades, and relatively inexpensive imports." Production trends for cement, as reported by the USGS, are shown in Exhibit 4-1. [2]

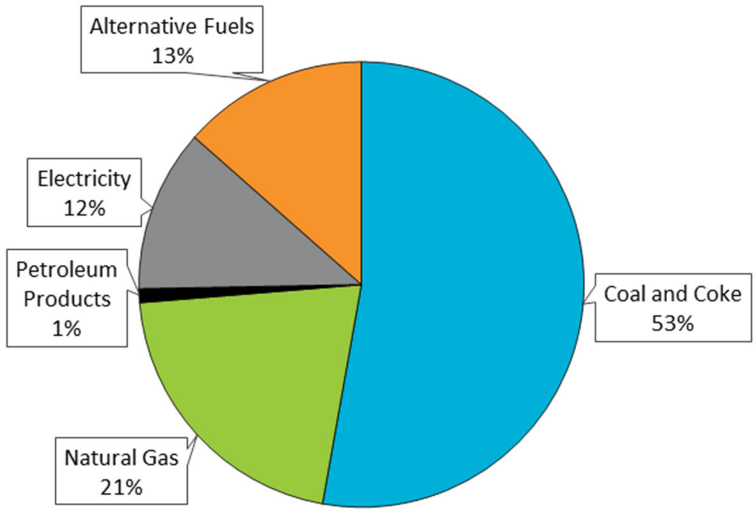
Exhibit 4-1. USGS cement production trends

Year	2016	2017	2018	2019	2020[A]
Portland Cement Production, M tonnes	84.7	86.4	86.4	88.0[A]	89.0
Apparent Portland Cement Consumption, M tonnes	95.2	97.2	98.5	103.0[A]	102.0
U.S. Market Satisfied by U.S. Production, %	89.0	88.9	87.7	85.4	87.3
PC Price, $/tonne[B]	111	117	121	123[A]	124

[A]Estimated
[B]Average mill value

There are three basic processes for producing Portland cement: wet process, semi-wet process, and dry process. The dry process can be of three configurations: long dry kiln, pre-heater dry kiln, or pre-heater/pre-calciner (PH/PC) kiln, with the latter being the most common kiln configuration in today's domestic fleet. The number of the more energy-intensive wet process kilns in the United States has declined by about 6 percent from more than 200 in 1974 to 10 in 2019, while the number of dry process kilns was reduced from about 200 to 110 over the same period. [19] Since 2008, approximately 85 percent of U.S. cement is produced using the dry-kiln process. [20] Both the dry- and wet-kiln processes utilize a multitude of different fuels to provide the heat necessary for drying, calcination, and sintering. Shown in Exhibit 4-2 is a breakdown of the fuel type consumed for 2019 as reported by the Portland Cement Association (PCA). [19] The values are given as a percentage of Btu consumed.

Exhibit 4-2. 2019 U.S. Portland cement energy consumption



Fuel burning to provide kiln heat is one of two CO_2 emissions sources, with the second resulting from the calcinations of calcium carbonate to form calcium oxide/calcium silicate species during the manufacturing process itself. Portland cement is manufactured by crushing limestone and clay/shale raw materials to a powder, and then feeding in dry or slurry form to a kiln. Inside the kiln, the raw materials are heated to 1,430–1,650°C (2,600–3,000°F) by in situ fuel firing. At these temperatures a chemical reaction takes place, fusing the raw materials into Portland cement clinker and generating CO_2. The clinker exits the kiln, is cooled, and is ground with gypsum to form Portland cement. [21] The gas exiting the kiln, "kiln off-gas," comprises the CO_2, SOx, NOx, PM etc. generated by combustion and calcination, diluted in combustion air.

Kiln off-gas can be used to preheat raw meal and can be treated for pollutants before exhaust from such pre-processing unit operations. These steps, along with additional air in-leakage that occurs as part of these operations, lead to lower CO_2 concentrations, higher humidity, higher flow rates, and a lower temperature for the cement plant exhaust stream that would enter the CO_2 capture island. The lower flow rates and higher CO_2 concentrations of the base cases are therefore optimistic. To address the variation in flow rates and CO_2 concentration caused by kiln off-gas use in the pre-processing steps, additional cases are presented in Section 7.

4.1 Size Range and Emissions Factors

In 2020, there were 98 U.S. cement plants in operation, including both wet and dry processing kilns, with a total production capacity of 89.3 M tonnes/year. [2] Of those 98 cement plants, 69 fall within the range of 0.5–1.5 M tonnes cement/year, and 31 fall within the range of 0.75–1.25 M tonnes cement/year. Cement production creates on average 0.922 tonnes CO_2 per tonne cement, according to PCA's "Environmental Product Declaration: Portland Cement." [3]

In 2019, the Global Cement and Concrete Association created a tool called Getting the Numbers Right for quantifying and tracking emissions data for the global cement industry. [22] The Getting the Numbers Right platform is a voluntary reporting system and does not include all cement plant data, but this system allows for a granular categorization of CO_2 emissions based on characteristics such as kiln type, production location, and more. The emissions for each kiln type in the domestic fleet can be estimated to model the performance and, thus, the cost of a capture system for each representative plant. The emissions stream calculations are presented in Exhibit 4-3.

Exhibit 4-3. Kiln off-gas emissions calculations for representative cement plants

Parameter	PH/PC Kilns	Wet Kilns	Units/Notes
Cement Production Rate	1,500,000	1,500,000	tonnes cement/year
Clinker Content of Finished Cement	91.4	91.4	% per PCA's Environmental Product Declaration: Portland Cement [3]
Clinker Production Rate	1,371,000	1,371,000	tonnes clinker/year
Total Emissions Rate	848 [22]	1,026 [22]	kg CO_{2e}/tonne clinker
Annual CO_2 Emissions from Kiln	1,162,608	1,406,646	tonnes CO_2/year
CO_2 Emissions from Kiln	297,370	359,790	lb/hr at 100 percent operation
Applicable Cases	CM99-B; CM95-B CM95-B1; CM95-B2 CM95-B5; CM95-B6 CM95-B7; CM95-B8	CM95-B3 CM95-B4	

Note: The additional emissions created by the NG-fired industrial boiler are not included in the kiln off-gas emissions calculations shown in this table. However, the cases in this study do consider capture from the comingled stream from kiln emissions, characterized by this table, as well as the emissions from the NG-fired industrial boiler

5 Base Cases: Cost and Performance Results

The representative kilns for this study produce 1.5 M tonnes/year of finished cement, assuming 91.4 percent clinker content. The flue gas from the NG-fired boiler detailed in Section 3.3 is combined with the kiln off-gas before CO_2 capture, purification, and compression. The resulting combined stream CO_2 content is shown, alongside the design assumptions regarding the kiln off-gas stream, in Exhibit 5-1.

Exhibit 5-1. Case summary description

Case Number	CM99-B	CM95-B	CM95-B1	CM95-B2[A]	CM95-B3	CM95-B4	CM95-B5	CM95-B6	CM95-B7	CM95-B8
Capture Rate	99 Percent	95 Percent								
Kiln Type[B]	Pre-heater/Pre-calciner				Wet Process		Pre-heater/Pre-calciner			
Kiln Off-Gas CO_2 Concentration, mol %	31	31	25	30	17	13	31		25	
Kiln Fuel Type	Coal/Coke		NG	Oil	Coal/ Coke	NG	Coal/Coke		NG	
Heat Integration Potential, %	N/A	N/A	N/A	N/A	N/A	N/A	10	30	10	30

[A]This case is comparable with a long-dry kiln utilizing coal/coke fuel
[B]Pre-heater/pre-calciner cases are comparable with pre-heater-only kilns

The kiln off-gas and boiler flue gas are combined and sent to the CANSOLV® capture unit. The resulting high-purity CO_2 stream (i.e., Stream 3 in Exhibit 5-2) is then compressed, dehydrated, and cooled for pipeline transport. Water and solids recovered from the CANSOLV® and compression systems are sent to waste treatment. Exhibit 5-2 shows a simplified block flow diagram for this process, and Exhibit 5-3 shows the simplified stream table for this process for case CM95-B for illustrative purposes. Energy and mass balance diagrams and stream tables are provided for all base cases in Appendix A: Energy and Mass Balances.

Exhibit 5-2. Simplified block flow diagram for base cases

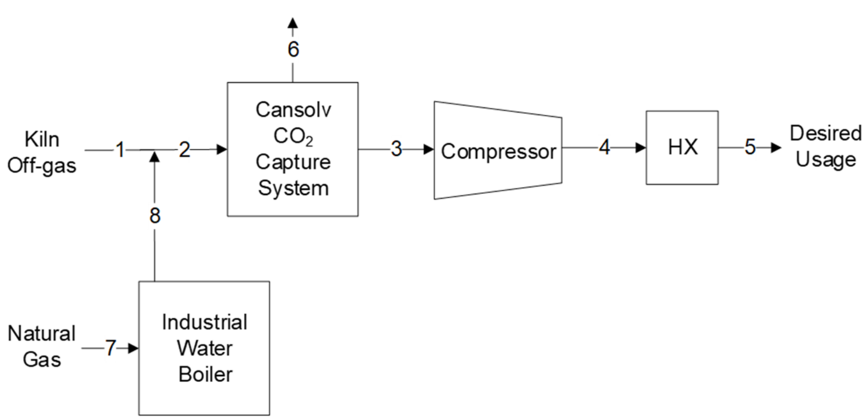


Exhibit 5-3. Simplified stream table for case CM95-B

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0041	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3075	0.1996	0.9809	0.9995	0.9995	0.0138	0.0100	0.0869
H_2O	0.0595	0.1164	0.0191	0.0005	0.0005	0.0385	0.0000	0.1758
N_2	0.6051	0.6556	0.0000	0.0000	0.0000	0.9084	0.0160	0.7083
O_2	0.0278	0.0242	0.0000	0.0000	0.0000	0.0335	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,966	19,520	3,773	3,702	3,702	14,089	794	9,554
V-L Flowrate (kg/hr)	323,399	589,270	164,159	162,862	162,862	395,220	13,765	265,870
Temperature (°C)	160	153	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	243.66	334.50	44.08	-78.54	-231.09	101.35	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,036.64	-3,399.39	-8,973.63	-9,042.09	-9,194.65	-512.99	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.450	30.188	43.513	43.997	43.997	28.052	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,972	43,034	8,317	8,161	8,161	31,061	1,751	21,063
V-L Flowrate (lb/hr)	712,974	1,299,117	361,908	359,050	359,050	871,311	30,346	586,144
Temperature (°F)	320	307	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	104.8	143.8	18.9	-33.8	-99.4	43.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,735.4	-1,461.5	-3,858.0	-3,887.4	-3,953.0	-220.5	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.054	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

5.1 Case CM99-B

5.1.1 Performance Results

Case CM99-B represents a PH/PC kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 99 percent of the CO_2 in the combined emissions stream from the cement kiln and the natural gas-fired industrial boiler. The performance summary for case CM99-B is provided in Exhibit 5-4, and the emission summary is provided in Exhibit 5-5.

Exhibit 5-4. CM99-B performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	99
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	674 (639)
Natural Gas Feed Flow, kg/hr (lb/hr)	15,057 (33,194)
HHV Thermal Input, kWt	218,718
LHV Thermal Input, kWt	197,414
Raw Water Withdrawal, m^3/min (gpm)	5.9 (1,556)
Raw Water Consumption[B], m^3/min (gpm)	4.0 (1,062)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,510
Cooling Tower Fans, kWe	790
CO_2 Capture System Auxiliaries, kWe	5,000
CO_2 Compression, kWe	13,270
Feedwater Pumps, kWe	60
Forced Draft Fans, kWe	530
Ground Water Pumps, kWe	140
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	430
SCR, kWe	–
Transformer Losses, kWe	140
Total Auxiliaries, MWe	**22**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-5. CM99-B emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	186 (205)	0.160 (0.320)
PM	<48 (<53)	<0.035 (<0.070)
CO_2	13,658 (15,055)	12 (23)
CO_2[B]	–	11 (21)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.1.2 Economic Analysis Results

Owner's costs (Exhibit 5-6), capital costs (Exhibit 5-7), and O&M costs (Exhibit 5-8) for case CM99-B are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-9 shows the resulting COC.

Exhibit 5-6. Owners' costs for case CM99-B

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,959	$2
1-Month Maintenance Materials	$539	$0
1-Month Non-Fuel Consumables	$644	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,463	$8
Total	**$15,611**	**$10**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,135	$1
0.5% of TPC (spare parts)	$2,866	$2
Total	**$4,001**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$85,970	$57
Financing Costs	$15,475	$10
TOC	**$694,192**	**$458**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$776,123**	**$512**

Exhibit 5-7. Capital costs for case CM99-B

	Case:	CM99-B							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3						Feedwater & Miscellaneous BOP Systems				
3.1	Feedwater System	$1,084	$1,858	$929	$0	$3,870	$677	$0	$909	$5,456	$4
3.2	Water Makeup & Pretreating	$2,825	$283	$1,601	$0	$4,708	$824	$0	$1,106	$6,639	$4
3.3	Other Feedwater Subsystems	$535	$175	$167	$0	$877	$154	$0	$206	$1,237	$1
3.4	Industrial Boiler Package w/Deaerator	$7,132	$0	$2,073	$0	$9,205	$1,611	$0	$2,163	$12,979	$9
3.5	Other Boiler Plant Systems	$129	$47	$118	$0	$294	$51	$0	$69	$415	$0
3.6	NG Pipeline and Start-Up System	$1,069	$46	$34	$0	$1,150	$201	$0	$270	$1,621	$1
3.7	Waste Water Treatment Equipment	$5,591	$0	$3,427	$0	$9,017	$1,578	$0	$2,119	$12,714	$8
3.9	Miscellaneous Plant Equipment	$145	$19	$73	$0	$237	$41	$0	$56	$334	$0
	Subtotal	**$18,509**	**$2,427**	**$8,422**	**$0**	**$29,359**	**$5,138**	**$0**	**$6,899**	**$41,396**	**$27**
	5						Flue Gas Cleanup				
5.1	CANSOLV® CO_2 Capture System	$95,299	$41,893	$87,975	$0	$225,167	$39,404	$38,278	$60,570	$363,419	$240
5.4	CO_2 Compression & Drying	$26,221	$3,933	$8,767	$0	$38,922	$6,811	$0	$9,147	$54,880	$36
5.5	CO_2 Compressor Aftercooler	$221	$35	$95	$0	$350	$61	$0	$82	$494	$0
5.12	Gas Cleanup Foundations	$0	$107	$93	$0	$200	$35	$0	$47	$282	$0
	Subtotal	**$121,741**	**$45,968**	**$96,930**	**$0**	**$264,639**	**$46,312**	**$38,278**	**$69,846**	**$419,075**	**$276**
	7						Ductwork & Stack				
7.3	Ductwork	$0	$2,612	$1,815	$0	$4,428	$775	$0	$1,041	$6,243	$4
7.4	Stack	$10,413	$0	$6,051	$0	$16,464	$2,881	$0	$3,869	$23,214	$15
7.5	Duct & Stack Foundations	$0	$233	$277	$0	$510	$89	$0	$120	$720	$0
	Subtotal	**$10,413**	**$2,846**	**$8,143**	**$0**	**$21,402**	**$3,745**	**$0**	**$5,029**	**$30,177**	**$20**
	9						Cooling Water System				
9.1	Cooling Towers	$2,511	$0	$777	$0	$3,288	$575	$0	$773	$4,635	$3
9.2	Circulating Water Pumps	$267	$0	$19	$0	$286	$50	$0	$67	$403	$0
9.3	Circulating Water System Aux.	$3,168	$0	$419	$0	$3,587	$628	$0	$843	$5,058	$3
9.4	Circulating Water Piping	$0	$1,465	$1,327	$0	$2,792	$489	$0	$656	$3,936	$3
9.5	Make-up Water System	$328	$0	$421	$0	$749	$131	$0	$176	$1,056	$1
9.6	Component Cooling Water System	$228	$0	$175	$0	$403	$71	$0	$95	$569	$0
9.7	Circulating Water System Foundations	$0	$159	$264	$0	$423	$74	$0	$99	$596	$0
	Subtotal	**$6,502**	**$1,624**	**$3,401**	**$0**	**$11,527**	**$2,017**	**$0**	**$2,709**	**$16,253**	**$11**
	11						Accessory Electric Plant				
11.2	Station Service Equipment	$4,019	$0	$345	$0	$4,364	$764	$0	$1,026	$6,153	$4
11.3	Switchgear & Motor Control	$6,239	$0	$1,083	$0	$7,322	$1,281	$0	$1,721	$10,324	$7
11.4	Conduit & Cable Tray	$0	$811	$2,337	$0	$3,149	$551	$0	$740	$4,439	$3
11.5	Wire & Cable	$0	$2,148	$3,840	$0	$5,988	$1,048	$0	$1,407	$8,442	$6
	Subtotal	**$10,259**	**$2,959**	**$7,604**	**$0**	**$20,822**	**$3,644**	**$0**	**$4,893**	**$29,359**	**$19**
	12						Instrumentation & Control				
12.8	Instrument Wiring & Tubing	$554	$443	$1,773	$0	$2,771	$485	$0	$651	$3,907	$3
12.9	Other I&C Equipment	$681	$0	$1,577	$0	$2,258	$395	$0	$531	$3,184	$2
	Subtotal	**$1,235**	**$443**	**$3,350**	**$0**	**$5,029**	**$880**	**$0**	**$1,182**	**$7,091**	**$5**
	13						Improvements to Site				
13.1	Site Preparation	$0	$37	$757	$0	$794	$139	$0	$187	$1,120	$1
13.2	Site Improvements	$0	$176	$234	$0	$410	$72	$0	$96	$578	$0
13.3	Site Facilities	$202	$0	$212	$0	$414	$72	$0	$97	$583	$0
	Subtotal	**$202**	**$214**	**$1,202**	**$0**	**$1,618**	**$283**	**$0**	**$380**	**$2,281**	**$2**
	14						Buildings & Structures				
14.5	Circulation Water Pumphouse	$0	$83	$66	$0	$149	$26	$0	$35	$211	$0
	Subtotal	**$0**	**$83**	**$66**	**$0**	**$149**	**$26**	**$0**	**$35**	**$211**	**$0**
	Total	**$168,861**	**$56,565**	**$129,120**	**$0**	**$354,545**	**$62,045**	**$38,278**	**$90,974**	**$545,843**	**$360**
					Retrofit Values	**$372,272**	**$65,148**	**$40,192**	**$95,522**	**$573,135**	**$378**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies).

Exhibit 5-8. Initial and annual O&M costs for case CM99-B

Case:	CM99-B				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operating (%):	85
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.83
Maintenance Labor:					$3,668,063	$2.85
Administrative & Support Labor:					$1,183,672	$0.92
Property Taxes and Insurance:					$11,462,696	$8.89
Total:					**$17,381,055**	**$13.49**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$4,160,006	$3.23
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,120	$2.24	$0	$776,887	$0.60
Makeup and Waste Water Treatment Chemicals (ton):	0	3.3	$647.04	$0	$669,911	$0.52
CO_2 Capture System Chemicals[A]:	Proprietary				$4,364,841	$3.39
Triethylene Glycol (gal):	w/equip.	304	$8.00	$0	$755,362	$0.59
Subtotal:				**$0**	**$6,567,001**	**$5.10**
Waste Disposal						
Triethylene Glycol (gal):		304	$0.41	$0	$38,879	$0.03
Thermal Reclaimer Unit Waste (ton):		1.68	$44.70	$0	$23,337	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$440	$0.00
Subtotal:				**$0**	**$62,656**	**$0.05**
Variable Operating Costs Total:				**$0**	**$12,131,751**	**$9.41**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	17,911	$4.61	$0	$25,623,439	$19.88
Purchased Power (MWh):	0	22	$67.28	$0	$10,956,094	$8.50
Total:				**$0**	**$36,579,534**	**$28.39**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

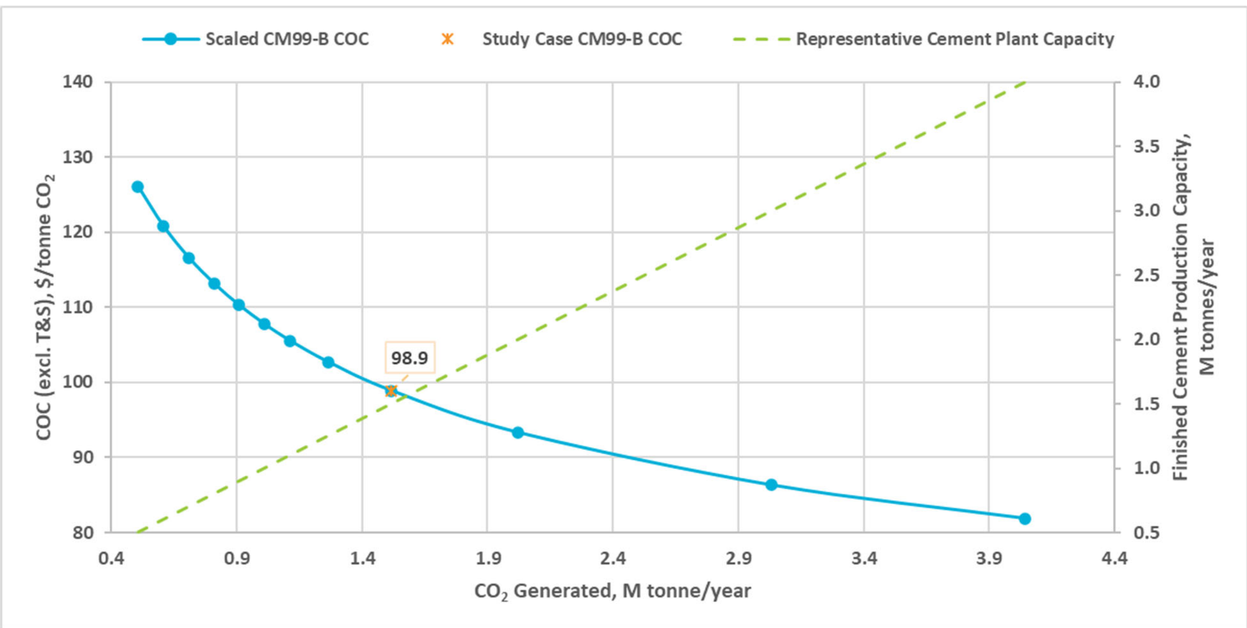
Exhibit 5-9. COC for case CM99-B

Cost	$/tonne CO_2
Capital	47.6
Fixed	13.5
Variable	9.4
Purchased Power and Fuel	28.4
Total COC (excl. T&S)	**98.9**
Total COC (incl. T&S)	**108.9**

5.1.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 generated for capture, is shown in Exhibit 5-10. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the NG-fired boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $39.8/tonne CO_2 (i.e., 46 percent increase in normalized capture cost).

Exhibit 5-10. Case CM99-B finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.2 CASE CM95-B

5.2.1 Performance Results

Case CM95-B represents a PH/PC kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B is provided in Exhibit 5-11, and the emissions summary is provided in Exhibit 5-12.

Exhibit 5-11. CM95-B performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	619 (587)
Natural Gas Feed Flow, kg/hr (lb/hr)	13,765 (30,346)
HHV Thermal Input, kWt	199,949
LHV Thermal Input, kWt	180,474
Raw Water Withdrawal, m^3/min (gpm)	5.4 (1,433)
Raw Water Consumption[B], m^3/min (gpm)	3.7 (970)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,390
Cooling Tower Fans, kWe	730
CO_2 Capture System Auxiliaries, kWe	4,600
CO_2 Compression, kWe	12,490
Feedwater Pumps, kWe	60
Forced Draft Fans, kWe	480
Ground Water Pumps, kWe	130
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	400
SCR, kWe	–
Transformer Losses, kWe	130
Total Auxiliaries, MWe	**20**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-12. CM95-B emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	179 (197)	0.154 (0.307)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	64,108 (70,667)	55 (110)
CO_2[B]	–	50 (101)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.2.2 Economic Analysis Results

Owner's costs (Exhibit 5-13), capital costs (Exhibit 5-14), and O&M costs (Exhibit 5-15) for case CM95-B are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-16 shows the resulting COC.

Exhibit 5-13. Owners' costs for case CM95-B

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,844	$2
1-Month Maintenance Materials	$512	$0
1-Month Non-Fuel Consumables	$593	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$10,888	$8
Total	**$14,843**	**$10**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,046	$1
0.5% of TPC (spare parts)	$2,722	$2
Total	**$3,768**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$81,656	$57
Financing Costs	$14,698	$10
TOC	**$659,341**	**$462**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$737,159**	**$517**

Exhibit 5-14. Capital costs for case CM95-B

	Case:	CM95-B							Estimate Type:	Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,019	$1,746	$873	$0	$3,638	$637	$0	$855	$5,129	$4
3.2	Water Makeup & Pretreating	$2,661	$266	$1,508	$0	$4,434	$776	$0	$1,042	$6,252	$4
3.3	Other Feedwater Subsystems	$494	$162	$154	$0	$810	$142	$0	$190	$1,142	$1
3.4	Industrial Boiler Package w/Deaerator	$6,584	$0	$1,914	$0	$8,499	$1,487	$0	$1,997	$11,983	$8
3.5	Other Boiler Plant Systems	$119	$43	$109	$0	$271	$47	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,023	$44	$33	$0	$1,100	$193	$0	$259	$1,551	$1
3.7	Waste Water Treatment Equipment	$5,340	$0	$3,273	$0	$8,612	$1,507	$0	$2,024	$12,143	$9
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$17,381**	**$2,280**	**$7,935**	**$0**	**$27,596**	**$4,829**	**$0**	**$6,485**	**$38,911**	**$27**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$89,836	$39,492	$82,933	$0	$212,260	$37,146	$36,084	$57,098	$342,588	$240
5.4	CO_2 Compression & Drying	$25,270	$3,791	$8,449	$0	$37,510	$6,564	$0	$8,815	$52,889	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.12	Gas Cleanup Foundations	$0	$104	$91	$0	$195	$34	$0	$46	$275	$0
	Subtotal	**$115,316**	**$43,420**	**$91,563**	**$0**	**$250,299**	**$43,802**	**$36,084**	**$66,037**	**$396,222**	**$278**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,542	$1,766	$0	$4,308	$754	$0	$1,012	$6,074	$4
7.4	Stack	$10,390	$0	$6,037	$0	$16,427	$2,875	$0	$3,860	$23,163	$16
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,390**	**$2,774**	**$8,079**	**$0**	**$21,243**	**$3,718**	**$0**	**$4,992**	**$29,953**	**$21**
	9					Cooling Water System					
9.1	Cooling Towers	$2,357	$0	$729	$0	$3,086	$540	$0	$725	$4,351	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$376	$0
9.3	Circulating Water System Aux.	$3,008	$0	$398	$0	$3,406	$596	$0	$800	$4,803	$3
9.4	Circulating Water Piping	$0	$1,391	$1,260	$0	$2,651	$464	$0	$623	$3,737	$3
9.5	Make-up Water System	$315	$0	$405	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$403	$71	$0	$95	$568	$0
	Subtotal	**$6,146**	**$1,543**	**$3,227**	**$0**	**$10,915**	**$1,910**	**$0**	**$2,565**	**$15,390**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,902	$0	$335	$0	$4,236	$741	$0	$996	$5,973	$4
11.3	Switchgear & Motor Control	$6,057	$0	$1,051	$0	$7,108	$1,244	$0	$1,670	$10,022	$7
11.4	Conduit & Cable Tray	$0	$787	$2,269	$0	$3,056	$535	$0	$718	$4,310	$3
11.5	Wire & Cable	$0	$2,085	$3,727	$0	$5,812	$1,017	$0	$1,366	$8,195	$6
	Subtotal	**$9,958**	**$2,873**	**$7,382**	**$0**	**$20,213**	**$3,537**	**$0**	**$4,750**	**$28,500**	**$20**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$549	$439	$1,757	$0	$2,746	$481	$0	$645	$3,872	$3
12.9	Other I&C Equipment	$675	$0	$1,563	$0	$2,238	$392	$0	$526	$3,156	$2
	Subtotal	**$1,224**	**$439**	**$3,321**	**$0**	**$4,984**	**$872**	**$0**	**$1,171**	**$7,028**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$37	$746	$0	$783	$137	$0	$184	$1,104	$1
13.2	Site Improvements	$0	$174	$230	$0	$404	$71	$0	$95	$570	$0
13.3	Site Facilities	$199	$0	$209	$0	$408	$71	$0	$96	$575	$0
	Subtotal	**$199**	**$211**	**$1,186**	**$0**	**$1,595**	**$279**	**$0**	**$375**	**$2,250**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$160,615**	**$53,618**	**$122,754**	**$0**	**$336,987**	**$58,973**	**$36,084**	**$86,409**	**$518,453**	**$363**
					Retrofit Values	**$353,837**	**$61,921**	**$37,888**	**$90,729**	**$544,376**	**$382**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-15. Initial and annual O&M costs for case CM95-B

Case:	CM95-B				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operating (%):	85
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$3,484,006	$2.87
Administrative & Support Labor:					$1,137,658	$0.94
Property Taxes and Insurance:					$10,887,520	$8.98
Total:					**$16,575,809**	**$13.67**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,226,010	$4.31
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,032	$2.24	$0	$715,598	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$617,061	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,743	$3.30
Triethylene Glycol (gal):	w/equip.	286	$8.00	$0	$710,807	$0.59
Subtotal:				**$0**	**$6,049,209**	**$4.99**
Waste Disposal						
Triethylene Glycol (gal):		286	$0.41	$0	$36,586	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,430	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$422	$0.00
Subtotal:				**$0**	**$60,438**	**$0.05**
Variable Operating Costs Total:				**$0**	**$11,335,656**	**$9.35**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,374	$4.61	$0	$23,424,656	$19.32
Purchased Power (MWh):	0	20	$67.28	$0	$10,224,686	$8.43
Total:				**$0**	**$33,649,342**	**$27.75**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

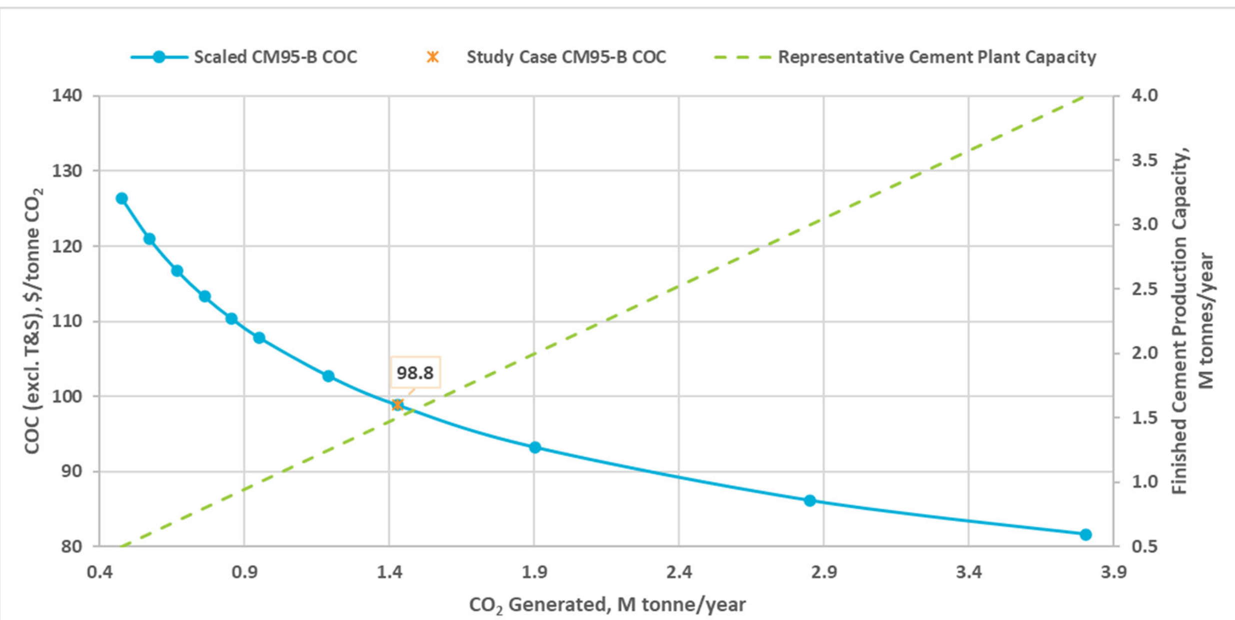
Exhibit 5-16. COC for case CM95-B

Cost	$/tonne CO_2
Capital	48.1
Fixed	13.7
Variable	9.3
Purchased Power and Fuel	27.7
Total COC (excl. T&S)	**98.8**
Total COC (incl. T&S)	**108.8**

5.2.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-17. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $44.8/tonne CO_2 (i.e., 55 percent increase in normalized capture cost).

Exhibit 5-17. Case CM95-B finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.3 Case CM95-B1

5.3.1 Performance Results

Case CM95-B1 represents a PH/PC kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B1 is provided in Exhibit 5-18, and the emissions summary is provided in Exhibit 5-19.

Exhibit 5-18. CM95-B1 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	603 (571)
Natural Gas Feed Flow, kg/hr (lb/hr)	13,244 (29,198)
HHV Thermal Input, kWt	192,385
LHV Thermal Input, kWt	173,647
Raw Water Withdrawal, m^3/min (gpm)	5.3 (1,399)
Raw Water Consumption, m^3/min (gpm)	3.4 (890)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,360
Cooling Tower Fans, kWe	710
CO_2 Capture System Auxiliaries, kWe	4,700
CO_2 Compression, kWe	12,390
Feedwater Pumps, kWe	50
Forced Draft Fans, kWe	460
Ground Water Pumps, kWe	130
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	400
SCR, kWe	–
Transformer Losses, kWe	130
Total Auxiliaries, MWe	**20**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-19. CM95-B1 emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	196 (216)	0.169 (0.337)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	63,591 (70,097)	55 (109)
CO_2[B]	–	50 (100)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.3.2 Economic Analysis Results

Owner's costs (Exhibit 5-20), capital costs (Exhibit 5-21), and O&M costs (Exhibit 5-22) for case CM99-B are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-23 shows the resulting COC.

Exhibit 5-20. Owners' costs for case CM95-B1

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,897	$2
1-Month Maintenance Materials	$525	$0
1-Month Non-Fuel Consumables	$698	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,154	$8
Total	**$15,280**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,259	$1
0.5% of TPC (spare parts)	$2,789	$2
Total	**$4,047**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$83,657	$59
Financing Costs	$15,058	$11
TOC	**$675,757**	**$478**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$755,513**	**$534**

Exhibit 5-21. Capital costs for case CM95-B1

	Case:	CM95-B1							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$992	$1,700	$850	$0	$3,542	$620	$0	$832	$4,994	$4
3.2	Water Makeup & Pretreating	$2,614	$261	$1,481	$0	$4,356	$762	$0	$1,024	$6,142	$4
3.3	Other Feedwater Subsystems	$477	$157	$149	$0	$783	$137	$0	$184	$1,104	$1
3.4	Industrial Boiler Package w/Deaerator	$6,362	$0	$1,850	$0	$8,212	$1,437	$0	$1,930	$11,579	$8
3.5	Other Boiler Plant Systems	$115	$42	$105	$0	$262	$46	$0	$62	$370	$0
3.6	NG Pipeline and Start-Up System	$1,004	$43	$32	$0	$1,080	$189	$0	$254	$1,522	$1
3.7	Waste Water Treatment Equipment	$5,708	$0	$3,498	$0	$9,206	$1,611	$0	$2,163	$12,981	$9
3.9	Miscellaneous Plant Equipment	$140	$18	$71	$0	$229	$40	$0	$54	$324	$0
	Subtotal	**$17,412**	**$2,222**	**$8,036**	**$0**	**$27,670**	**$4,842**	**$0**	**$6,502**	**$39,014**	**$28**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$93,146	$40,946	$85,987	$0	$220,079	$38,514	$37,413	$59,201	$355,208	$251
5.4	CO_2 Compression & Drying	$25,147	$3,772	$8,408	$0	$37,326	$6,532	$0	$8,772	$52,630	$37
5.5	CO_2 Compressor Aftercooler	$208	$33	$89	$0	$331	$58	$0	$78	$466	$0
5.12	Gas Cleanup Foundations	$0	$110	$97	$0	$207	$36	$0	$49	$291	$0
	Subtotal	**$118,500**	**$44,862**	**$94,581**	**$0**	**$257,943**	**$45,140**	**$37,413**	**$68,099**	**$408,596**	**$289**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,715	$1,886	$0	$4,601	$805	$0	$1,081	$6,488	$5
7.4	Stack	$10,443	$0	$6,068	$0	$16,511	$2,889	$0	$3,880	$23,280	$16
7.5	Duct & Stack Foundations	$0	$232	$275	$0	$506	$89	$0	$119	$714	$1
	Subtotal	**$10,443**	**$2,946**	**$8,230**	**$0**	**$21,618**	**$3,783**	**$0**	**$5,080**	**$30,482**	**$22**
	9					Cooling Water System					
9.1	Cooling Towers	$2,313	$0	$715	$0	$3,028	$530	$0	$712	$4,270	$3
9.2	Circulating Water Pumps	$244	$0	$17	$0	$261	$46	$0	$61	$368	$0
9.3	Circulating Water System Aux.	$2,962	$0	$392	$0	$3,354	$587	$0	$788	$4,729	$3
9.4	Circulating Water Piping	$0	$1,370	$1,240	$0	$2,610	$457	$0	$613	$3,680	$3
9.5	Make-up Water System	$311	$0	$400	$0	$711	$124	$0	$167	$1,002	$1
9.6	Component Cooling Water System	$213	$0	$164	$0	$377	$66	$0	$89	$532	$0
9.7	Circulating Water System Foundations	$0	$149	$248	$0	$397	$70	$0	$93	$560	$0
	Subtotal	**$6,044**	**$1,519**	**$3,176**	**$0**	**$10,739**	**$1,879**	**$0**	**$2,524**	**$15,142**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,895	$0	$334	$0	$4,229	$740	$0	$994	$5,963	$4
11.3	Switchgear & Motor Control	$6,047	$0	$1,049	$0	$7,096	$1,242	$0	$1,667	$10,005	$7
11.4	Conduit & Cable Tray	$0	$786	$2,265	$0	$3,051	$534	$0	$717	$4,302	$3
11.5	Wire & Cable	$0	$2,082	$3,721	$0	$5,802	$1,015	$0	$1,364	$8,182	$6
	Subtotal	**$9,942**	**$2,868**	**$7,369**	**$0**	**$20,179**	**$3,531**	**$0**	**$4,742**	**$28,452**	**$20**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$549	$439	$1,756	$0	$2,744	$480	$0	$645	$3,870	$3
12.9	Other I&C Equipment	$675	$0	$1,562	$0	$2,237	$391	$0	$526	$3,154	$2
	Subtotal	**$1,224**	**$439**	**$3,319**	**$0**	**$4,982**	**$872**	**$0**	**$1,171**	**$7,024**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$37	$746	$0	$783	$137	$0	$184	$1,103	$1
13.2	Site Improvements	$0	$174	$230	$0	$404	$71	$0	$95	$570	$0
13.3	Site Facilities	$199	$0	$209	$0	$408	$71	$0	$96	$575	$0
	Subtotal	**$199**	**$211**	**$1,185**	**$0**	**$1,594**	**$279**	**$0**	**$375**	**$2,248**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$78	$62	$0	$140	$25	$0	$33	$198	$0
	Subtotal	**$0**	**$78**	**$62**	**$0**	**$140**	**$25**	**$0**	**$33**	**$198**	**$0**
	Total	**$163,763**	**$55,144**	**$125,958**	**$0**	**$344,865**	**$60,351**	**$37,413**	**$88,526**	**$531,156**	**$375**
					Retrofit Values	**$362,108**	**$63,369**	**$39,284**	**$92,952**	**$557,714**	**$394**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-22. Initial and annual O&M costs for case CM95-B1

Case:	**CM95-B1**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
			Operating & Maintenance Labor			
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
			Fixed Operating Costs			
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.89
Maintenance Labor:					$3,569,369	$2.97
Administrative & Support Labor:					$1,158,998	$0.96
Property Taxes and Insurance:					$11,154,279	$9.27
Total:					**$16,949,271**	**$14.09**
			Variable Operating Costs			
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,354,054	$4.45
			Consumables			
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,007	$2.24	$0	$698,314	$0.58
Makeup and Waste Water Treatment Chemicals (ton):	0	3.0	$647.04	$0	$602,157	$0.50
CO_2 Capture System Chemicals[A]:			Proprietary		$5,113,187	$4.25
Triethylene Glycol (gal):	w/equip.	284	$8.00	$0	$705,073	$0.59
Subtotal:				**$0**	**$7,118,730**	**$5.92**
			Waste Disposal			
Triethylene Glycol (gal):		284	$0.41	$0	$36,291	$0.03
Thermal Reclaimer Unit Waste (ton):		1.68	$44.70	$0	$23,241	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$452	$0.00
Subtotal:				**$0**	**$59,983**	**$0.05**
Variable Operating Costs Total:				**$0**	**$12,532,767**	**$10.42**
			Fuel and Purchased Power Costs			
Natural Gas (MMBTU):	0	15,755	$4.61	$0	$22,538,505	$18.74
Purchased Power (MWh):	0	20	$67.28	$0	$10,184,609	$8.47
Total:				**$0**	**$32,723,113**	**$27.20**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

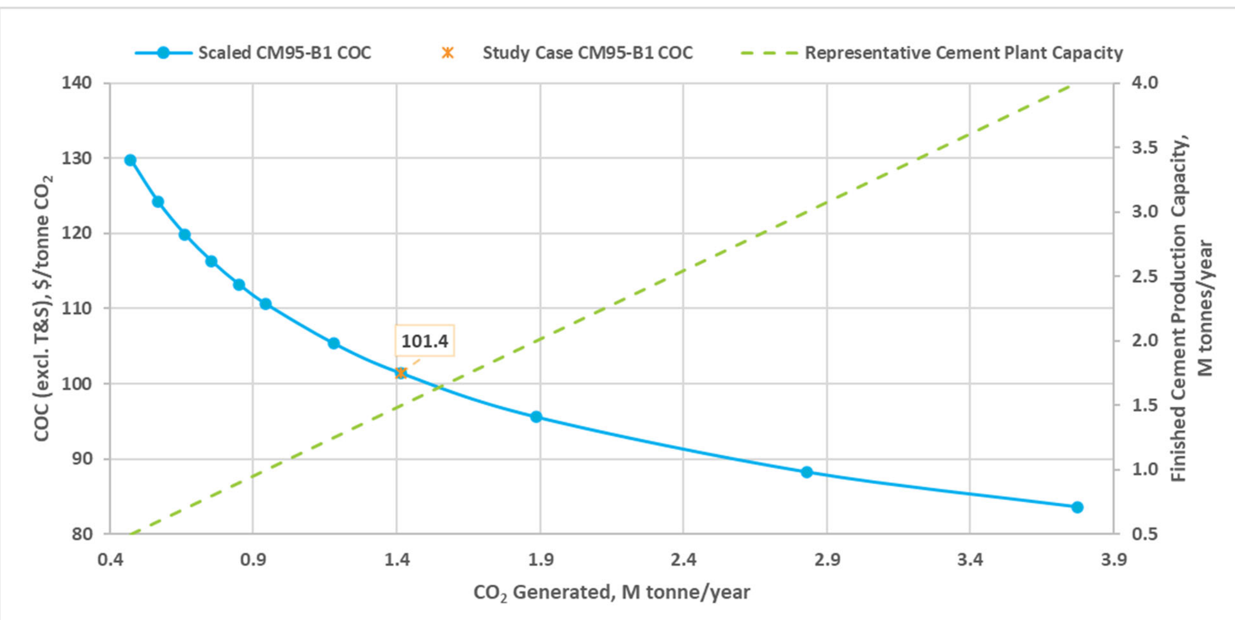
Exhibit 5-23. COC for case CM95-B1

Cost	$/tonne CO_2
Capital	49.7
Fixed	14.1
Variable	10.4
Purchased Power and Fuel	27.2
Total COC (excl. T&S)	**101.4**
Total COC (incl. T&S)	**111.4**

5.3.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-24. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $46.2/tonne CO_2 (i.e., 55 percent increase in normalized capture cost).

Exhibit 5-24. Case CM95-B1 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.4 Case CM95-B2

5.4.1 Performance Results

Case CM95-B2 represents a PH/PC kiln that burns oil fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B2 is provided in Exhibit 5-25, and the emissions summary is provided in Exhibit 5-26.

Exhibit 5-25. CM95-B2 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	618 (586)
Natural Gas Feed Flow, kg/hr (lb/hr)	13,684 (30,169)
HHV Thermal Input, kWt	198,784
LHV Thermal Input, kWt	179,423
Raw Water Withdrawal, m^3/min (gpm)	5.4 (1,431)
Raw Water Consumption[B], m^3/min (gpm)	3.6 (962)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,390
Cooling Tower Fans, kWe	730
CO_2 Capture System Auxiliaries, kWe	4,600
CO_2 Compression, kWe	12,470
Feedwater Pumps, kWe	60
Forced Draft Fans, kWe	480
Ground Water Pumps, kWe	130
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	400
SCR, kWe	–
Transformer Losses, kWe	130
Total Auxiliaries, MWe	**20**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-26. CM95-B2 emissions summary

Emission	tonne/yr (ton/year)[A]	kg/tonne$_{clinker}$ (lb/ton$_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	181 (199)	0.155 (0.310)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	64,029 (70,579)	55 (110)
CO_2[B]	–	50 (100)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.4.2 Economic Analysis Results

Owner's costs (Exhibit 5-27), capital costs (Exhibit 5-28), and O&M costs (Exhibit 5-29) for case CM95-B2 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-30 shows the resulting COC.

Exhibit 5-27. Owners' costs for case CM95-B2

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,850	$2
1-Month Maintenance Materials	$514	$0
1-Month Non-Fuel Consumables	$609	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$10,918	$8
Total	**$14,898**	**$10**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,079	$1
0.5% of TPC (spare parts)	$2,730	$2
Total	**$3,808**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$81,888	$57
Financing Costs	$14,740	$10
TOC	**$661,257**	**$464**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$739,301**	**$519**

Exhibit 5-28. Capital costs for case CM95-B2

Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/(tonne CO_2/year)
	Case:	CM95-B2							Estimate Type:	Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,014	$1,739	$869	$0	$3,623	$634	$0	$851	$5,108	$4
3.2	Water Makeup & Pretreating	$2,658	$266	$1,506	$0	$4,430	$775	$0	$1,041	$6,247	$4
3.3	Other Feedwater Subsystems	$492	$161	$153	$0	$806	$141	$0	$189	$1,136	$1
3.4	Industrial Boiler Package w/Deaerator	$6,550	$0	$1,904	$0	$8,455	$1,480	$0	$1,987	$11,921	$8
3.5	Other Boiler Plant Systems	$119	$43	$108	$0	$270	$47	$0	$63	$381	$0
3.6	NG Pipeline and Start-Up System	$1,020	$44	$33	$0	$1,097	$192	$0	$258	$1,547	$1
3.7	Waste Water Treatment Equipment	$5,389	$0	$3,303	$0	$8,691	$1,521	$0	$2,042	$12,255	$9
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$231	$40	$0	$54	$326	$0
	Subtotal	**$17,383**	**$2,272**	**$7,949**	**$0**	**$27,603**	**$4,831**	**$0**	**$6,487**	**$38,921**	**$27**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$90,227	$39,664	$83,294	$0	$213,184	$37,307	$36,241	$57,347	$344,080	$241
5.4	CO_2 Compression & Drying	$25,245	$3,787	$8,441	$0	$37,473	$6,558	$0	$8,806	$52,837	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$469	$0
5.12	Gas Cleanup Foundations	$0	$105	$92	$0	$196	$34	$0	$46	$277	$0
	Subtotal	**$115,682**	**$43,589**	**$91,916**	**$0**	**$251,187**	**$43,958**	**$36,241**	**$66,277**	**$397,663**	**$279**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,558	$1,778	$0	$4,336	$759	$0	$1,019	$6,113	$4
7.4	Stack	$10,394	$0	$6,040	$0	$16,434	$2,876	$0	$3,862	$23,172	$16
7.5	Duct & Stack Foundations	$0	$232	$275	$0	$507	$89	$0	$119	$715	$1
	Subtotal	**$10,394**	**$2,790**	**$8,093**	**$0**	**$21,277**	**$3,724**	**$0**	**$5,000**	**$30,001**	**$21**
	9					Cooling Water System					
9.1	Cooling Towers	$2,355	$0	$728	$0	$3,083	$540	$0	$725	$4,347	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$266	$47	$0	$63	$375	$0
9.3	Circulating Water System Aux.	$3,006	$0	$398	$0	$3,403	$596	$0	$800	$4,799	$3
9.4	Circulating Water Piping	$0	$1,390	$1,259	$0	$2,649	$464	$0	$622	$3,735	$3
9.5	Make-up Water System	$315	$0	$404	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$151	$251	$0	$403	$70	$0	$95	$568	$0
	Subtotal	**$6,140**	**$1,541**	**$3,224**	**$0**	**$10,906**	**$1,909**	**$0**	**$2,563**	**$15,377**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,900	$0	$335	$0	$4,235	$741	$0	$995	$5,971	$4
11.3	Switchgear & Motor Control	$6,054	$0	$1,050	$0	$7,105	$1,243	$0	$1,670	$10,018	$7
11.4	Conduit & Cable Tray	$0	$787	$2,268	$0	$3,055	$535	$0	$718	$4,308	$3
11.5	Wire & Cable	$0	$2,084	$3,726	$0	$5,810	$1,017	$0	$1,365	$8,192	$6
	Subtotal	**$9,954**	**$2,871**	**$7,379**	**$0**	**$20,204**	**$3,536**	**$0**	**$4,748**	**$28,488**	**$20**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$549	$439	$1,757	$0	$2,746	$480	$0	$645	$3,871	$3
12.9	Other I&C Equipment	$675	$0	$1,563	$0	$2,238	$392	$0	$526	$3,155	$2
	Subtotal	**$1,224**	**$439**	**$3,320**	**$0**	**$4,983**	**$872**	**$0**	**$1,171**	**$7,027**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$37	$746	$0	$783	$137	$0	$184	$1,104	$1
13.2	Site Improvements	$0	$174	$230	$0	$404	$71	$0	$95	$570	$0
13.3	Site Facilities	$199	$0	$209	$0	$408	$71	$0	$96	$575	$0
	Subtotal	**$199**	**$211**	**$1,185**	**$0**	**$1,595**	**$279**	**$0**	**$375**	**$2,249**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$200	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$200**	**$0**
	Total	**$160,978**	**$53,792**	**$123,129**	**$0**	**$337,898**	**$59,132**	**$36,241**	**$86,654**	**$519,926**	**$365**
					Retrofit Values	**$354,793**	**$62,089**	**$38,053**	**$90,987**	**$545,922**	**$383**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-29. Initial and annual O&M costs for case CM95-B2

Case:	**CM95-B2**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$3,493,903	$2.88
Administrative & Support Labor:					$1,140,132	$0.94
Property Taxes and Insurance:					$10,918,447	$9.01
Total:					**$16,619,107**	**$13.72**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,240,855	$4.33
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,031	$2.24	$0	$714,705	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$616,291	$0.51
CO_2 Capture System Chemicals[A]:		Proprietary			$4,174,883	$3.45
Triethylene Glycol (gal):	w/equip.	286	$8.00	$0	$709,924	$0.59
Subtotal:				**$0**	**$6,215,802**	**$5.13**
Waste Disposal						
Triethylene Glycol (gal):		286	$0.41	$0	$36,540	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,401	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$425	$0.00
Subtotal:				**$0**	**$60,365**	**$0.05**
Variable Operating Costs Total:				**$0**	**$11,517,022**	**$9.51**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,279	$4.61	$0	$23,288,195	$19.23
Purchased Power (MWh):	0	20	$67.28	$0	$10,214,667	$8.43
Total:				**$0**	**$33,502,862**	**$27.66**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

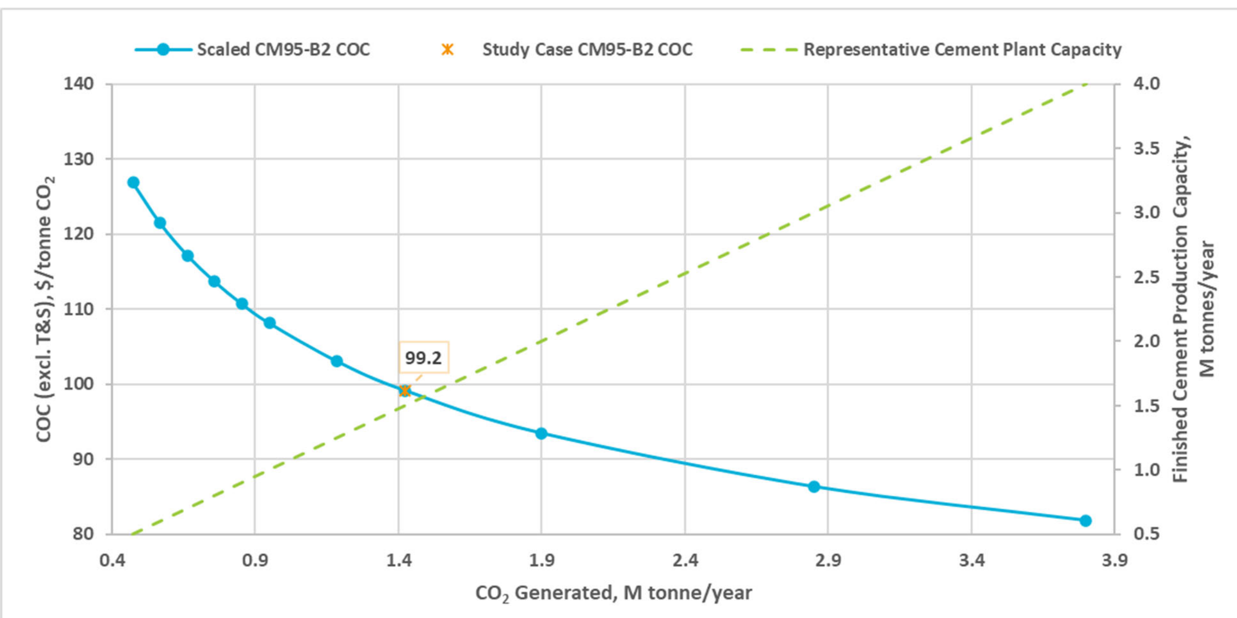
Exhibit 5-30. COC for case CM95-B2

Cost	\$/tonne CO_2
Capital	48.3
Fixed	13.7
Variable	9.5
Purchased Power and Fuel	27.7
Total COC (excl. T&S)	**99.2**
Total COC (incl. T&S)	**109.2**

5.4.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-31. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by \$45.0/tonne CO_2 (i.e., 55 percent increase in normalized capture cost).

Exhibit 5-31. Case CM95-B2 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.5 Case CM95-B3

5.5.1 Performance Results

Case CM95-B3 represents a wet process kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B3 is provided in Exhibit 5-32, and the emissions summary is provided in Exhibit 5-33.

Exhibit 5-32. CM95-B3 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	696 (660)
Natural Gas Feed Flow, kg/hr (lb/hr)	14,941 (32,940)
HHV Thermal Input, kWt	217,044
LHV Thermal Input, kWt	195,903
Raw Water Withdrawal, m^3/min (gpm)	6.1 (1,623)
Raw Water Consumption[B], m^3/min (gpm)	1.9 (514)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,570
Cooling Tower Fans, kWe	830
CO_2 Capture System Auxiliaries, kWe	6,100
CO_2 Compression, kWe	14,780
Feedwater Pumps, kWe	60
Forced Draft Fans, kWe	520
Ground Water Pumps, kWe	150
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	480
SCR, kWe	–
Transformer Losses, kWe	160
Total Auxiliaries, MWe	**25**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-33. CM95-B3 emissions summary

Emission	tonne/yr (ton/year)[A]	kg/tonne$_{clinker}$ (lb/ton$_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	294 (324)	0.252 (0.504)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	75,864 (83,626)	65 (130)
CO_2[B]	–	60 (119)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.5.2 Economic Analysis Results

Owner's costs (Exhibit 5-34), capital costs (Exhibit 5-35), and O&M costs (Exhibit 5-36) for case CM95-B3 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-37 shows the resulting COC.

Exhibit 5-34. Owners' costs for case CM95-B3

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,293	$2
1-Month Maintenance Materials	$618	$0
1-Month Non-Fuel Consumables	$922	$1
1-Month Waste Disposal	$7	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$13,132	$8
Total	**$17,972**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,686	$1
0.5% of TPC (spare parts)	$3,283	$2
Total	**$4,969**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$98,488	$58
Financing Costs	$17,728	$11
TOC	**$795,743**	**$471**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$889,660**	**$527**

Exhibit 5-35. Capital costs for case CM95-B3

	Case:	CM95-B3							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,078	$1,848	$924	$0	$3,849	$674	$0	$905	$5,428	$3
3.2	Water Makeup & Pretreating	$2,913	$291	$1,651	$0	$4,855	$850	$0	$1,141	$6,846	$4
3.3	Other Feedwater Subsystems	$532	$174	$166	$0	$871	$152	$0	$205	$1,229	$1
3.4	Industrial Boiler Package w/Deaerator	$7,083	$0	$2,059	$0	$9,143	$1,600	$0	$2,149	$12,891	$8
3.5	Other Boiler Plant Systems	$129	$47	$117	$0	$292	$51	$0	$69	$412	$0
3.6	NG Pipeline and Start-Up System	$1,065	$46	$34	$0	$1,145	$200	$0	$269	$1,615	$1
3.7	Waste Water Treatment Equipment	$9,939	$0	$6,092	$0	$16,030	$2,805	$0	$3,767	$22,603	$13
3.9	Miscellaneous Plant Equipment	$144	$19	$73	$0	$237	$41	$0	$56	$333	$0
	Subtotal	**$22,882**	**$2,425**	**$11,115**	**$0**	**$36,422**	**$6,374**	**$0**	**$8,559**	**$51,356**	**$30**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$111,237	$48,899	$102,689	$0	$262,825	$45,994	$44,680	$70,700	$424,200	$251
5.4	CO_2 Compression & Drying	$28,003	$4,201	$9,363	$0	$41,567	$7,274	$0	$9,768	$58,609	$35
5.5	CO_2 Compressor Aftercooler	$241	$38	$103	$0	$383	$67	$0	$90	$540	$0
5.12	Gas Cleanup Foundations	$0	$140	$123	$0	$264	$46	$0	$62	$372	$0
	Subtotal	**$139,482**	**$53,279**	**$112,278**	**$0**	**$305,039**	**$53,382**	**$44,680**	**$80,620**	**$483,721**	**$287**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$3,606	$2,506	$0	$6,111	$1,069	$0	$1,436	$8,617	$5
7.4	Stack	$10,555	$0	$6,133	$0	$16,688	$2,920	$0	$3,922	$23,530	$14
7.5	Duct & Stack Foundations	$0	$233	$277	$0	$510	$89	$0	$120	$719	$0
	Subtotal	**$10,555**	**$3,839**	**$8,916**	**$0**	**$23,309**	**$4,079**	**$0**	**$5,478**	**$32,866**	**$19**
	9					Cooling Water System					
9.1	Cooling Towers	$2,594	$0	$802	$0	$3,396	$594	$0	$798	$4,788	$3
9.2	Circulating Water Pumps	$277	$0	$20	$0	$297	$52	$0	$70	$418	$0
9.3	Circulating Water System Aux.	$3,253	$0	$430	$0	$3,683	$645	$0	$866	$5,193	$3
9.4	Circulating Water Piping	$0	$1,504	$1,362	$0	$2,866	$502	$0	$674	$4,042	$2
9.5	Make-up Water System	$335	$0	$430	$0	$765	$134	$0	$180	$1,078	$1
9.6	Component Cooling Water System	$234	$0	$180	$0	$414	$72	$0	$97	$584	$0
9.7	Circulating Water System Foundations	$0	$163	$270	$0	$433	$76	$0	$102	$611	$0
	Subtotal	**$6,693**	**$1,667**	**$3,494**	**$0**	**$11,854**	**$2,074**	**$0**	**$2,786**	**$16,714**	**$10**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$4,231	$0	$363	$0	$4,594	$804	$0	$1,080	$6,478	$4
11.3	Switchgear & Motor Control	$6,569	$0	$1,140	$0	$7,709	$1,349	$0	$1,812	$10,869	$6
11.4	Conduit & Cable Tray	$0	$854	$2,461	$0	$3,315	$580	$0	$779	$4,674	$3
11.5	Wire & Cable	$0	$2,261	$4,042	$0	$6,304	$1,103	$0	$1,481	$8,888	$5
	Subtotal	**$10,800**	**$3,115**	**$8,006**	**$0**	**$21,922**	**$3,836**	**$0**	**$5,152**	**$30,909**	**$18**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$563	$450	$1,801	$0	$2,814	$492	$0	$661	$3,968	$2
12.9	Other I&C Equipment	$692	$0	$1,602	$0	$2,294	$401	$0	$539	$3,234	$2
	Subtotal	**$1,255**	**$450**	**$3,403**	**$0**	**$5,108**	**$894**	**$0**	**$1,200**	**$7,202**	**$4**
	13					Improvements to Site					
13.1	Site Preparation	$0	$38	$775	$0	$813	$142	$0	$191	$1,147	$1
13.2	Site Improvements	$0	$181	$239	$0	$420	$73	$0	$99	$592	$0
13.3	Site Facilities	$207	$0	$217	$0	$424	$74	$0	$100	$597	$0
	Subtotal	**$207**	**$219**	**$1,231**	**$0**	**$1,657**	**$290**	**$0**	**$389**	**$2,336**	**$1**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$85	$68	$0	$153	$27	$0	$36	$216	$0
	Subtotal	**$0**	**$85**	**$68**	**$0**	**$153**	**$27**	**$0**	**$36**	**$216**	**$0**
	Total	**$191,873**	**$65,080**	**$148,512**	**$0**	**$405,464**	**$70,956**	**$44,680**	**$104,220**	**$625,321**	**$370**
					Retrofit Values	**$74,504**	**$46,914**	**$109,431**	**$656,587**	**$389**	**$74,504**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-36. Initial and annual O&M costs for case CM95-B3

Case:	**CM95-B3**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.74
Maintenance Labor:					$4,202,154	$2.93
Administrative & Support Labor:					$1,317,195	$0.92
Property Taxes and Insurance:					$13,131,732	$9.15
Total:					**$19,717,705**	**$13.74**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$6,303,231	$4.39
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,168	$2.24	$0	$810,196	$0.56
Makeup and Waste Water Treatment Chemicals (ton):	0	3.5	$647.04	$0	$698,633	$0.49
CO_2 Capture System Chemicals[A]:		Proprietary			$7,058,911	$4.92
Triethylene Glycol (gal):	w/equip.	339	$8.00	$0	$841,153	$0.59
Subtotal:				**$0**	**$9,408,893**	**$6.56**
Waste Disposal						
Triethylene Glycol (gal):		339	$0.41	$0	$43,295	$0.03
Thermal Reclaimer Unit Waste (ton):		2.00	$44.70	$0	$27,726	$0.02
Pre-scrubber Blowdown Waste (ton):		0.04	$44.70	$0	$587	$0.00
Subtotal:				**$0**	**$71,608**	**$0.05**
Variable Operating Costs Total:				**$0**	**$15,783,732**	**$11.00**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	17,774	$4.61	$0	$25,427,342	$17.72
Purchased Power (MWh):	0	25	$67.28	$0	$12,348,775	$8.61
Total:				**$0**	**$37,776,117**	**$26.32**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

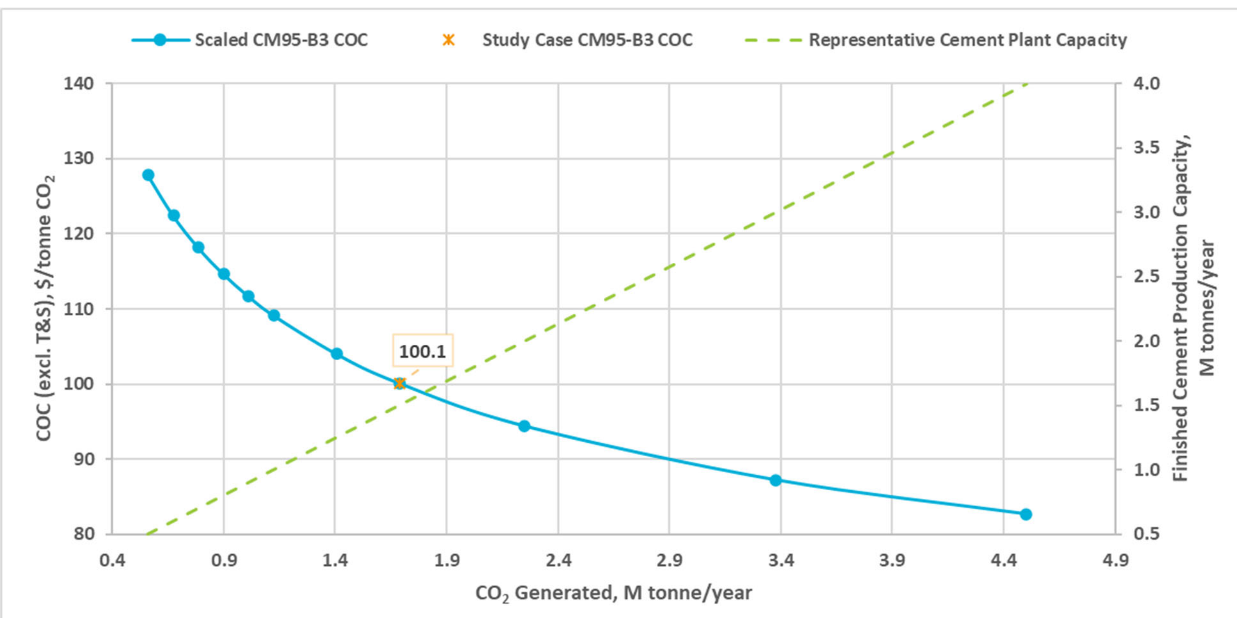
Exhibit 5-37. COC for case CM95-B3

Cost	\$/tonne CO_2
Capital	49.0
Fixed	13.7
Variable	11.0
Purchased Power and Fuel	26.3
Total COC (excl. T&S)	**100.1**
Total COC (incl. T&S)	**110.1**

5.5.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-38. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by \$45.1/tonne CO_2 (i.e., 55 percent increase in normalized capture cost).

Exhibit 5-38. Case CM95-B3 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.6 CASE CM95-B4

5.6.1 Performance Results

Case CM95-B4 represents a wet process kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B4 is provided in Exhibit 5-39, and the emissions summary is provided in Exhibit 5-40.

Exhibit 5-39. CM95-B4 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	672 (637)
Natural Gas Feed Flow, kg/hr (lb/hr)	14,261 (31,440)
HHV Thermal Input, kWt	207,162
LHV Thermal Input, kWt	186,984
Raw Water Withdrawal, m^3/min (gpm)	6.0 (1,572)
Raw Water Consumption[B], m^3/min (gpm)	0.6 (171)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,530
Cooling Tower Fans, kWe	800
CO_2 Capture System Auxiliaries, kWe	6,400
CO_2 Compression, kWe	14,650
Feedwater Pumps, kWe	60
Forced Draft Fans, kWe	500
Ground Water Pumps, kWe	140
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	480
SCR, kWe	–
Transformer Losses, kWe	160
Total Auxiliaries, MWe	**25**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-40. CM95-B4 emissions summary

Emission	tonne/yr (ton/year)[A]	kg/tonne$_{clinker}$ (lb/ton$_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	350 (386)	0.301 (0.601)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	75,189 (82,881)	65 (129)
CO_2[B]	–	59 (118)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.6.2 Economic Analysis Results

Owner's costs (Exhibit 5-41), capital costs (Exhibit 5-42), and O&M costs (Exhibit 5-43) for case CM95-B4 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-44 shows the resulting COC.

Exhibit 5-41. Owners' costs for case CM95-B4

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,416	$2
1-Month Maintenance Materials	$647	$0
1-Month Non-Fuel Consumables	$1,040	$1
1-Month Waste Disposal	$7	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$13,746	$8
Total	**$18,855**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,925	$1
0.5% of TPC (spare parts)	$3,436	$2
Total	**$5,362**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$103,092	$62
Financing Costs	$18,557	$11
TOC	**$833,149**	**$498**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$931,480**	**$557**

Exhibit 5-42. Capital costs for case CM95-B4

	Case:	CM95-B4							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,044	$1,789	$895	$0	$3,728	$652	$0	$876	$5,256	$3
3.2	Water Makeup & Pretreating	$2,846	$285	$1,613	$0	$4,744	$830	$0	$1,115	$6,688	$4
3.3	Other Feedwater Subsystems	$510	$167	$159	$0	$836	$146	$0	$196	$1,179	$1
3.4	Industrial Boiler Package w/Deaerator	$6,795	$0	$1,976	$0	$8,771	$1,535	$0	$2,061	$12,367	$7
3.5	Other Boiler Plant Systems	$123	$45	$112	$0	$280	$49	$0	$66	$395	$0
3.6	NG Pipeline and Start-Up System	$1,041	$45	$34	$0	$1,119	$196	$0	$263	$1,578	$1
3.7	Waste Water Treatment Equipment	$11,741	$0	$7,196	$0	$18,937	$3,314	$0	$4,450	$26,701	$16
3.9	Miscellaneous Plant Equipment	$143	$19	$72	$0	$234	$41	$0	$55	$330	$0
	Subtotal	**$24,243**	**$2,349**	**$12,056**	**$0**	**$38,649**	**$6,764**	**$0**	**$9,082**	**$54,495**	**$33**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$117,890	$51,824	$108,831	$0	$278,545	$48,745	$47,353	$74,929	$449,572	$269
5.4	CO_2 Compression & Drying	$27,853	$4,178	$9,312	$0	$41,343	$7,235	$0	$9,716	$58,294	$35
5.5	CO_2 Compressor Aftercooler	$240	$38	$103	$0	$380	$67	$0	$89	$536	$0
5.12	Gas Cleanup Foundations	$0	$156	$137	$0	$293	$51	$0	$69	$414	$0
	Subtotal	**$145,983**	**$56,197**	**$118,383**	**$0**	**$320,562**	**$56,098**	**$47,353**	**$84,803**	**$508,816**	**$304**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$4,084	$2,838	$0	$6,921	$1,211	$0	$1,627	$9,759	$6
7.4	Stack	$10,632	$0	$6,178	$0	$16,810	$2,942	$0	$3,950	$23,702	$14
7.5	Duct & Stack Foundations	$0	$233	$276	$0	$509	$89	$0	$120	$717	$0
	Subtotal	**$10,632**	**$4,316**	**$9,292**	**$0**	**$24,240**	**$4,242**	**$0**	**$5,696**	**$34,179**	**$20**
	9					Cooling Water System					
9.1	Cooling Towers	$2,531	$0	$783	$0	$3,314	$580	$0	$779	$4,672	$3
9.2	Circulating Water Pumps	$270	$0	$19	$0	$289	$51	$0	$68	$407	$0
9.3	Circulating Water System Aux.	$3,188	$0	$422	$0	$3,610	$632	$0	$848	$5,090	$3
9.4	Circulating Water Piping	$0	$1,474	$1,335	$0	$2,810	$492	$0	$660	$3,962	$2
9.5	Make-up Water System	$330	$0	$423	$0	$753	$132	$0	$177	$1,061	$1
9.6	Component Cooling Water System	$230	$0	$176	$0	$406	$71	$0	$95	$572	$0
9.7	Circulating Water System Foundations	$0	$160	$265	$0	$425	$74	$0	$100	$600	$0
	Subtotal	**$6,548**	**$1,634**	**$3,424**	**$0**	**$11,606**	**$2,031**	**$0**	**$2,727**	**$16,365**	**$10**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$4,237	$0	$363	$0	$4,600	$805	$0	$1,081	$6,486	$4
11.3	Switchgear & Motor Control	$6,577	$0	$1,141	$0	$7,718	$1,351	$0	$1,814	$10,882	$7
11.4	Conduit & Cable Tray	$0	$855	$2,464	$0	$3,319	$581	$0	$780	$4,680	$3
11.5	Wire & Cable	$0	$2,264	$4,047	$0	$6,311	$1,104	$0	$1,483	$8,899	$5
	Subtotal	**$10,814**	**$3,119**	**$8,016**	**$0**	**$21,948**	**$3,841**	**$0**	**$5,158**	**$30,947**	**$18**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$563	$450	$1,802	$0	$2,815	$493	$0	$662	$3,969	$2
12.9	Other I&C Equipment	$692	$0	$1,603	$0	$2,295	$402	$0	$539	$3,235	$2
	Subtotal	**$1,255**	**$450**	**$3,404**	**$0**	**$5,110**	**$894**	**$0**	**$1,201**	**$7,205**	**$4**
	13					Improvements to Site					
13.1	Site Preparation	$0	$38	$775	$0	$814	$142	$0	$191	$1,147	$1
13.2	Site Improvements	$0	$181	$239	$0	$420	$74	$0	$99	$592	$0
13.3	Site Facilities	$207	$0	$217	$0	$424	$74	$0	$100	$597	$0
	Subtotal	**$207**	**$219**	**$1,232**	**$0**	**$1,658**	**$290**	**$0**	**$390**	**$2,337**	**$1**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$84	$67	$0	$150	$26	$0	$35	$212	$0
	Subtotal	**$0**	**$84**	**$67**	**$0**	**$150**	**$26**	**$0**	**$35**	**$212**	**$0**
	Total	**$199,681**	**$68,369**	**$155,873**	**$0**	**$423,923**	**$74,187**	**$47,353**	**$109,093**	**$654,555**	**$391**
					Retrofit Values	**$445,120**	**$77,896**	**$49,720**	**$114,547**	**$687,283**	**$411**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-43. Initial and annual O&M costs for case CM95-B4

Case:	**CM95-B4**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.75
Maintenance Labor:					$4,398,611	$3.09
Administrative & Support Labor:					$1,366,309	$0.96
Property Taxes and Insurance:					$13,745,661	$9.66
Total:					**$20,577,206**	**$14.47**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$6,597,917	$4.64
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,132	$2.24	$0	$784,839	$0.55
Makeup and Waste Water Treatment Chemicals (ton):	0	3.4	$647.04	$0	$676,768	$0.48
CO_2 Capture System Chemicals[A]:	Proprietary				$8,309,532	$5.84
Triethylene Glycol (gal):	w/equip.	336	$8.00	$0	$833,662	$0.59
Subtotal:				**$0**	**$10,604,801**	**$7.46**
Waste Disposal						
Triethylene Glycol (gal):		336	$0.41	$0	$42,909	$0.03
Thermal Reclaimer Unit Waste (ton):		1.98	$44.70	$0	$27,479	$0.02
Pre-scrubber Blowdown Waste (ton):		0.05	$44.70	$0	$668	$0.00
Subtotal:				**$0**	**$71,056**	**$0.05**
Variable Operating Costs Total:				**$0**	**$17,273,774**	**$12.15**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,965	$4.61	$0	$24,269,645	$17.06
Purchased Power (MWh):	0	25	$67.28	$0	$12,383,843	$8.71
Total:				**$0**	**$36,653,488**	**$25.77**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

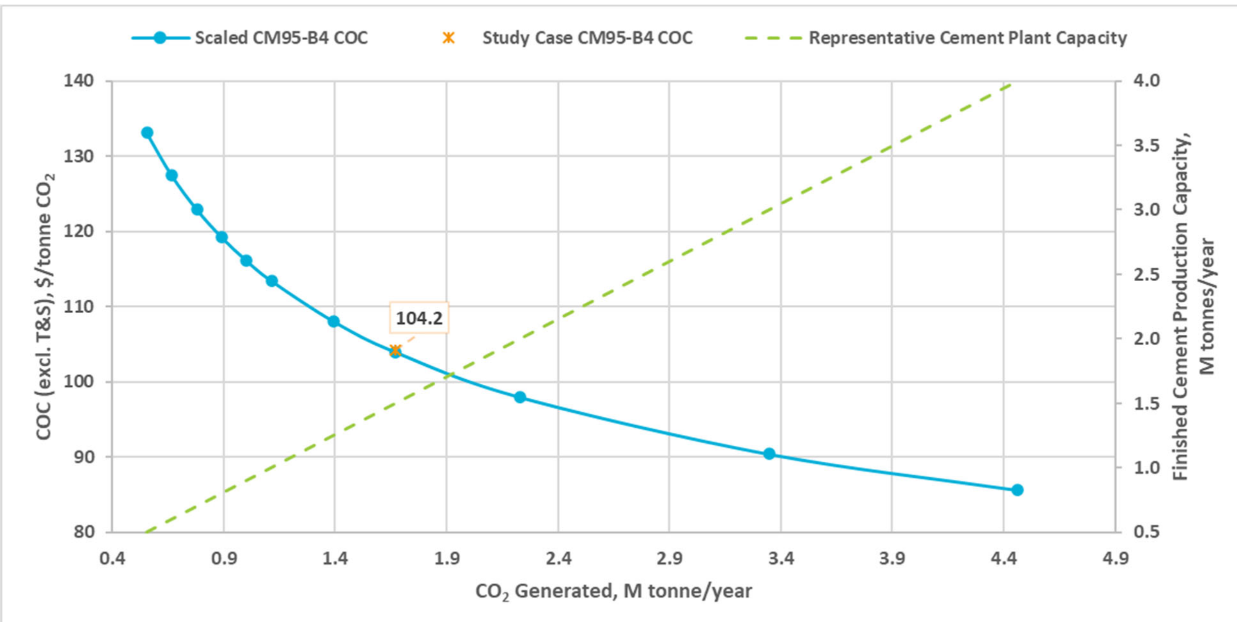
Exhibit 5-44. COC for case CM95-B4

Cost	$/tonne CO_2
Capital	51.8
Fixed	14.5
Variable	12.1
Purchased Power and Fuel	25.8
Total COC (excl. T&S)	**104.2**
Total COC (incl. T&S)	**114.2**

5.6.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-45. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $47.4/tonne CO_2 (i.e., 55 percent increase in normalized capture cost).

Exhibit 5-45. Case CM95-B4 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.7 Case CM95-B5

5.7.1 Performance Results

Case CM95-B5 represents a PH/PC kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. To demonstrate the impact of the potential for heat integration on COC, the base cement plant is assumed to provide 10 percent of the capture system heating needs. This heat integration reduces the consumption of NG in the industrial boiler to provide solvent regeneration heat. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B5 is provided in Exhibit 5-46, and the emissions summary is provided in Exhibit 5-47.

Exhibit 5-46. CM95-B5 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	607 (576)
Natural Gas Feed Flow, kg/hr (lb/hr)	12,188 (26,870)
HHV Thermal Input, kWt	177,047
LHV Thermal Input, kWt	159,802
Raw Water Withdrawal, m^3/min (gpm)	5.3 (1,406)
Raw Water Consumption[B], m^3/min (gpm)	3.6 (960)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,360
Cooling Tower Fans, kWe	720
CO_2 Capture System Auxiliaries, kWe	4,400
CO_2 Compression, kWe	12,180
Feedwater Pumps, kWe	50
Forced Draft Fans, kWe	430
Ground Water Pumps, kWe	130
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	390
SCR, kWe	–
Transformer Losses, kWe	130
Total Auxiliaries, MWe	**20**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-47. CM95-B5 emissions summary

Emission	tonne/yr (ton/year)[A]	kg/tonne$_{clinker}$ (lb/ton$_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	169 (186)	0.145 (0.290)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	62,543 (68,942)	54 (107)
CO_2[B]	–	49 (98)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.7.2 Economic Analysis Results

Owner's costs (Exhibit 5-48), capital costs (Exhibit 5-49), and O&M costs (Exhibit 5-50) for case CM95-B5 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-51 shows the resulting COC.

Exhibit 5-48. Owners' costs for case CM95-B5

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,003	$2
1-Month Maintenance Materials	$550	$0
1-Month Non-Fuel Consumables	$558	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,680	$8
Total	**$15,796**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$979	$1
0.5% of TPC (spare parts)	$2,920	$2
Total	**$3,899**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$87,599	$63
Financing Costs	$15,768	$11
TOC	**$707,054**	**$508**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$790,503**	**$568**

Exhibit 5-49. Capital costs for case CM95-B5

	Case:	CM95-B5							Estimate Type:	Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$937	$1,605	$803	$0	$3,345	$585	$0	$786	$4,716	$3
3.2	Water Makeup & Pretreating	$2,623	$262	$1,486	$0	$4,372	$765	$0	$1,027	$6,164	$4
3.3	Other Feedwater Subsystems	$443	$145	$138	$0	$727	$127	$0	$171	$1,025	$1
3.4	Industrial Boiler Package w/Deaerator	$5,909	$0	$1,718	$0	$7,627	$1,335	$0	$1,792	$10,754	$8
3.5	Other Boiler Plant Systems	$107	$39	$97	$0	$243	$43	$0	$57	$343	$0
3.6	NG Pipeline and Start-Up System	$964	$41	$31	$0	$1,037	$181	$0	$244	$1,462	$1
3.7	Waste Water Treatment Equipment	$5,195	$0	$3,184	$0	$8,379	$1,466	$0	$1,969	$11,814	$8
3.9	Miscellaneous Plant Equipment	$137	$18	$70	$0	$225	$39	$0	$53	$317	$0
	Subtotal	**$16,315**	**$2,111**	**$7,527**	**$0**	**$25,953**	**$4,542**	**$0**	**$6,099**	**$36,594**	**$26**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$87,542	$38,483	$80,815	$0	$206,841	$36,197	$35,163	$55,640	$333,841	$240
5.4	CO_2 Compression & Drying	$24,886	$3,733	$8,320	$0	$36,939	$6,464	$0	$8,681	$52,084	$37
5.5	CO_2 Compressor Aftercooler	$206	$33	$88	$0	$326	$57	$0	$77	$460	$0
5.12	Gas Cleanup Foundations	$0	$101	$88	$0	$189	$33	$0	$44	$266	$0
	Subtotal	**$112,634**	**$42,350**	**$89,312**	**$0**	**$244,295**	**$42,752**	**$35,163**	**$64,442**	**$386,651**	**$278**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,443	$1,698	$0	$4,141	$725	$0	$973	$5,838	$4
7.4	Stack	$10,351	$0	$6,015	$0	$16,365	$2,864	$0	$3,846	$23,075	$17
7.5	Duct & Stack Foundations	$0	$230	$274	$0	$504	$88	$0	$118	$711	$1
	Subtotal	**$10,351**	**$2,673**	**$7,986**	**$0**	**$21,010**	**$3,677**	**$0**	**$4,937**	**$29,624**	**$21**
	9					Cooling Water System					
9.1	Cooling Towers	$2,322	$0	$718	$0	$3,040	$532	$0	$714	$4,287	$3
9.2	Circulating Water Pumps	$245	$0	$17	$0	$262	$46	$0	$62	$370	$0
9.3	Circulating Water System Aux.	$2,972	$0	$393	$0	$3,365	$589	$0	$791	$4,744	$3
9.4	Circulating Water Piping	$0	$1,374	$1,244	$0	$2,619	$458	$0	$615	$3,692	$3
9.5	Make-up Water System	$312	$0	$401	$0	$713	$125	$0	$167	$1,005	$1
9.6	Component Cooling Water System	$214	$0	$164	$0	$378	$66	$0	$89	$534	$0
9.7	Circulating Water System Foundations	$0	$150	$249	$0	$399	$70	$0	$94	$562	$0
	Subtotal	**$6,065**	**$1,524**	**$3,187**	**$0**	**$10,776**	**$1,886**	**$0**	**$2,532**	**$15,194**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,850	$0	$330	$0	$4,180	$732	$0	$982	$5,894	$4
11.3	Switchgear & Motor Control	$5,977	$0	$1,037	$0	$7,014	$1,227	$0	$1,648	$9,890	$7
11.4	Conduit & Cable Tray	$0	$777	$2,239	$0	$3,016	$528	$0	$709	$4,253	$3
11.5	Wire & Cable	$0	$2,058	$3,678	$0	$5,736	$1,004	$0	$1,348	$8,087	$6
	Subtotal	**$9,827**	**$2,835**	**$7,284**	**$0**	**$19,946**	**$3,491**	**$0**	**$4,687**	**$28,124**	**$20**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$547	$438	$1,750	$0	$2,735	$479	$0	$643	$3,856	$3
12.9	Other I&C Equipment	$672	$0	$1,557	$0	$2,229	$390	$0	$524	$3,143	$2
	Subtotal	**$1,219**	**$438**	**$3,307**	**$0**	**$4,964**	**$869**	**$0**	**$1,167**	**$6,999**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$37	$742	$0	$778	$136	$0	$183	$1,098	$1
13.2	Site Improvements	$0	$173	$229	$0	$402	$70	$0	$94	$567	$0
13.3	Site Facilities	$198	$0	$208	$0	$405	$71	$0	$95	$571	$0
	Subtotal	**$198**	**$210**	**$1,178**	**$0**	**$1,586**	**$277**	**$0**	**$373**	**$2,236**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$78	$62	$0	$141	$25	$0	$33	$198	$0
	Subtotal	**$0**	**$78**	**$62**	**$0**	**$141**	**$25**	**$0**	**$33**	**$198**	**$0**
	Total	**$156,608**	**$52,219**	**$119,844**	**$0**	**$328,670**	**$57,517**	**$35,163**	**$84,270**	**$505,621**	**$363**
					Retrofit Values	**$379,614**	**$66,432**	**$40,613**	**$97,332**	**$583,992**	**$420**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-50. Initial and annual O&M costs for case CM95-B5

Case:	**CM95-B5**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.90
Maintenance Labor:					$3,737,548	$3.16
Administrative & Support Labor:					$1,201,043	$1.02
Property Taxes and Insurance:					$11,679,837	$9.87
Total:					**$17,685,053**	**$14.95**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,606,322	$4.74
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,012	$2.24	$0	$701,804	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.0	$647.04	$0	$605,166	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary				$3,695,663	$3.12
Triethylene Glycol (gal):	w/equip.	279	$8.00	$0	$693,453	$0.59
Subtotal:				**$0**	**$5,696,087**	**$4.81**
Waste Disposal						
Triethylene Glycol (gal):		279	$0.41	$0	$35,692	$0.03
Thermal Reclaimer Unit Waste (ton):		1.65	$44.70	$0	$22,858	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$400	$0.00
Subtotal:				**$0**	**$58,950**	**$0.05**
Variable Operating Costs Total:				**$0**	**$11,361,359**	**$9.60**
Fuel Cost						
Natural Gas (MMBTU):	0	14,499	$4.61	$0	$20,741,568	$17.53
Purchased Power (MWh):	0	20	$67.28	$0	$9,914,088	$8.38
Total:				**$0**	**$30,655,656**	**$25.91**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

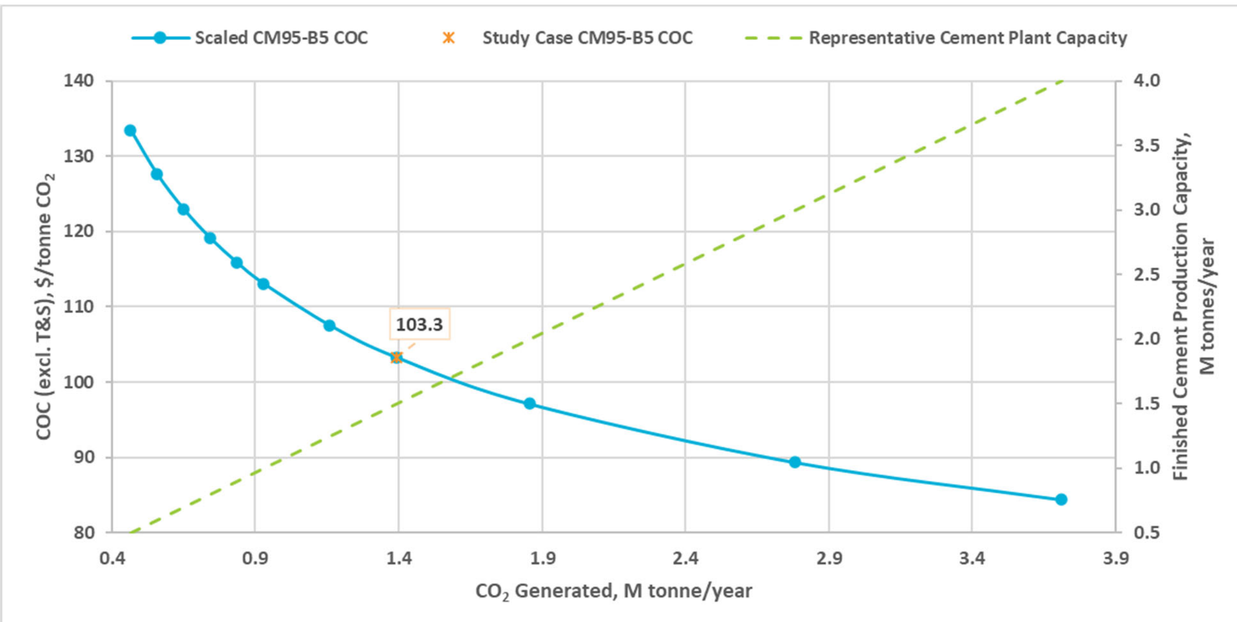
Exhibit 5-51. COC for case CM95-B5

Cost	$/tonne CO_2
Capital	52.8
Fixed	14.9
Variable	9.6
Purchased Power and Fuel	25.9
Total COC (excl. T&S)	**103.3**
Total COC (incl. T&S)	**113.3**

5.7.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-52. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $49.0/tonne CO_2 (i.e., 58 percent increase in normalized capture cost).

Exhibit 5-52. Case CM95-B5 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.8 Case CM95-B6

5.8.1 Performance Results

Case CM95-B6 represents a PH/PC kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. To demonstrate the impact of the potential for heat integration on COC, the base cement plant is assumed to provide 30 percent of the capture system heating needs. This heat integration reduces the consumption of NG in the industrial boiler to provide solvent regeneration heat. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B6 is provided in Exhibit 5-53, and the emissions summary is provided in Exhibit 5-54.

Exhibit 5-53. CM95-B6 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	585 (555)
Natural Gas Feed Flow, kg/hr (lb/hr)	9,188 (20,257)
HHV Thermal Input, kWt	133,472
LHV Thermal Input, kWt	120,472
Raw Water Withdrawal, m^3/min (gpm)	5.1 (1,351)
Raw Water Consumption[B], m^3/min (gpm)	3.6 (939)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,310
Cooling Tower Fans, kWe	690
CO_2 Capture System Auxiliaries, kWe	4,100
CO_2 Compression, kWe	11,600
Feedwater Pumps, kWe	40
Forced Draft Fans, kWe	320
Ground Water Pumps, kWe	120
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	360
SCR, kWe	–
Transformer Losses, kWe	120
Total Auxiliaries, MWe	**19**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-54. CM95-B6 emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	150 (165)	0.129 (0.257)
Particulate	<49 (<54)	<0.035 (<0.070)
CO_2	59,564 (65,658)	51 (102)
CO_2[B]	–	47 (93)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.8.2 Economic Analysis Results

Owner's costs (Exhibit 5-55), capital costs (Exhibit 5-56), and O&M costs (Exhibit 5-57) for case CM95-B6 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-58 shows the resulting COC.

Exhibit 5-55. Owners' costs for case CM95-B6

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,885	$2
1-Month Maintenance Materials	$522	$0
1-Month Non-Fuel Consumables	$482	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,090	$8
Total	**$14,984**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$832	$1
0.5% of TPC (spare parts)	$2,772	$2
Total	**$3,604**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$83,172	$63
Financing Costs	$14,971	$11
TOC	**$671,212**	**$506**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$750,431**	**$566**

Exhibit 5-56. Capital costs for case CM95-B6

	Case:	CM95-B6						Estimate Type:		Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					**Feedwater & Miscellaneous BOP Systems**					
3.1	Feedwater System	$771	$1,321	$661	$0	$2,752	$482	$0	$647	$3,881	$3
3.2	Water Makeup & Pretreating	$2,548	$255	$1,444	$0	$4,246	$743	$0	$998	$5,987	$5
3.3	Other Feedwater Subsystems	$345	$113	$107	$0	$565	$99	$0	$133	$797	$1
3.4	Industrial Boiler Package w/Deaerator	$4,595	$0	$1,336	$0	$5,931	$1,038	$0	$1,394	$8,363	$6
3.5	Other Boiler Plant Systems	$83	$30	$75	$0	$189	$33	$0	$44	$266	$0
3.6	NG Pipeline and Start-Up System	$839	$36	$27	$0	$903	$158	$0	$212	$1,273	$1
3.7	Waste Water Treatment Equipment	$4,910	$0	$3,009	$0	$7,919	$1,386	$0	$1,861	$11,166	$8
3.9	Miscellaneous Plant Equipment	$128	$17	$65	$0	$209	$37	$0	$49	$295	$0
	Subtotal	**$14,218**	**$1,772**	**$6,724**	**$0**	**$22,714**	**$3,975**	**$0**	**$5,338**	**$32,027**	**$24**
	5					**Flue Gas Cleanup**					
5.1	CANSOLV® CO_2 Capture System	$82,932	$36,456	$76,559	$0	$195,947	$34,291	$33,311	$52,710	$316,258	$239
5.4	CO_2 Compression & Drying	$24,156	$3,624	$8,077	$0	$35,856	$6,275	$0	$8,426	$50,557	$38
5.5	CO_2 Compressor Aftercooler	$197	$31	$85	$0	$313	$55	$0	$74	$442	$0
5.12	Gas Cleanup Foundations	$0	$94	$82	$0	$176	$31	$0	$41	$248	$0
	Subtotal	**$107,285**	**$40,205**	**$84,802**	**$0**	**$232,292**	**$40,651**	**$33,311**	**$61,251**	**$367,505**	**$277**
	7					**Ductwork & Stack**					
7.3	Ductwork	$0	$2,250	$1,564	$0	$3,814	$667	$0	$896	$5,377	$4
7.4	Stack	$10,269	$0	$5,967	$0	$16,235	$2,841	$0	$3,815	$22,892	$17
7.5	Duct & Stack Foundations	$0	$226	$269	$0	$495	$87	$0	$116	$699	$1
	Subtotal	**$10,269**	**$2,477**	**$7,800**	**$0**	**$20,545**	**$3,595**	**$0**	**$4,828**	**$28,968**	**$22**
	9					**Cooling Water System**					
9.1	Cooling Towers	$2,252	$0	$697	$0	$2,949	$516	$0	$693	$4,158	$3
9.2	Circulating Water Pumps	$237	$0	$17	$0	$253	$44	$0	$60	$357	$0
9.3	Circulating Water System Aux.	$2,898	$0	$383	$0	$3,282	$574	$0	$771	$4,627	$3
9.4	Circulating Water Piping	$0	$1,340	$1,214	$0	$2,554	$447	$0	$600	$3,601	$3
9.5	Make-up Water System	$306	$0	$393	$0	$699	$122	$0	$164	$986	$1
9.6	Component Cooling Water System	$209	$0	$160	$0	$369	$65	$0	$87	$520	$0
9.7	Circulating Water System Foundations	$0	$146	$243	$0	$390	$68	$0	$92	$549	$0
	Subtotal	**$5,902**	**$1,487**	**$3,107**	**$0**	**$10,496**	**$1,837**	**$0**	**$2,466**	**$14,799**	**$11**
	11					**Accessory Electric Plant**					
11.2	Station Service Equipment	$3,754	$0	$322	$0	$4,076	$713	$0	$958	$5,747	$4
11.3	Switchgear & Motor Control	$5,828	$0	$1,011	$0	$6,839	$1,197	$0	$1,607	$9,643	$7
11.4	Conduit & Cable Tray	$0	$758	$2,183	$0	$2,941	$515	$0	$691	$4,147	$3
11.5	Wire & Cable	$0	$2,006	$3,586	$0	$5,593	$979	$0	$1,314	$7,885	$6
	Subtotal	**$9,582**	**$2,764**	**$7,103**	**$0**	**$19,448**	**$3,403**	**$0**	**$4,570**	**$27,422**	**$21**
	12					**Instrumentation & Control**					
12.8	Instrument Wiring & Tubing	$543	$434	$1,737	$0	$2,714	$475	$0	$638	$3,827	$3
12.9	Other I&C Equipment	$667	$0	$1,545	$0	$2,212	$387	$0	$520	$3,119	$2
	Subtotal	**$1,210**	**$434**	**$3,282**	**$0**	**$4,926**	**$862**	**$0**	**$1,158**	**$6,946**	**$5**
	13					**Improvements to Site**					
13.1	Site Preparation	$0	$36	$733	$0	$769	$135	$0	$181	$1,085	$1
13.2	Site Improvements	$0	$171	$226	$0	$397	$70	$0	$93	$560	$0
13.3	Site Facilities	$195	$0	$205	$0	$401	$70	$0	$94	$565	$0
	Subtotal	**$195**	**$207**	**$1,164**	**$0**	**$1,567**	**$274**	**$0**	**$368**	**$2,210**	**$2**
	14					**Buildings & Structures**					
14.5	Circulation Water Pumphouse	$0	$77	$61	$0	$137	$24	$0	$32	$194	$0
	Subtotal	**$0**	**$77**	**$61**	**$0**	**$137**	**$24**	**$0**	**$32**	**$194**	**$0**
	Total	**$148,661**	**$49,422**	**$114,042**	**$0**	**$312,126**	**$54,622**	**$33,311**	**$80,012**	**$480,070**	**$362**
					Retrofit Values	**$360,505**	**$63,088**	**$38,474**	**$92,414**	**$554,481**	**$418**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-57. Initial and annual O&M costs for case CM95-B6

Case:	CM95-B6				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operating (%):	85
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.95
Maintenance Labor:					$3,548,680	$3.15
Administrative & Support Labor:					$1,153,826	$1.02
Property Taxes and Insurance:					$11,089,624	$9.84
Total:					**$16,858,754**	**$14.96**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,323,019	$4.72
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	972	$2.24	$0	$674,328	$0.60
Makeup and Waste Water Treatment Chemicals (ton):	0	2.9	$647.04	$0	$581,474	$0.52
CO_2 Capture System Chemicals[A]:	Proprietary				$3,000,582	$2.66
Triethylene Glycol (gal):	w/equip.	266	$8.00	$0	$660,419	$0.59
Subtotal:				**$0**	**$4,916,803**	**$4.36**
Waste Disposal						
Triethylene Glycol (gal):		266	$0.41	$0	$33,992	$0.03
Thermal Reclaimer Unit Waste (ton):		1.57	$44.70	$0	$21,769	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$357	$0.00
Subtotal:				**$0**	**$56,118**	**$0.05**
Variable Operating Costs Total:				**$0**	**$10,295,940**	**$9.14**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	10,930	$4.61	$0	$15,636,684	$13.88
Purchased Power (MWh):	0	19	$67.28	$0	$9,347,998	$8.30
Total:				**$0**	**$24,984,682**	**$22.17**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

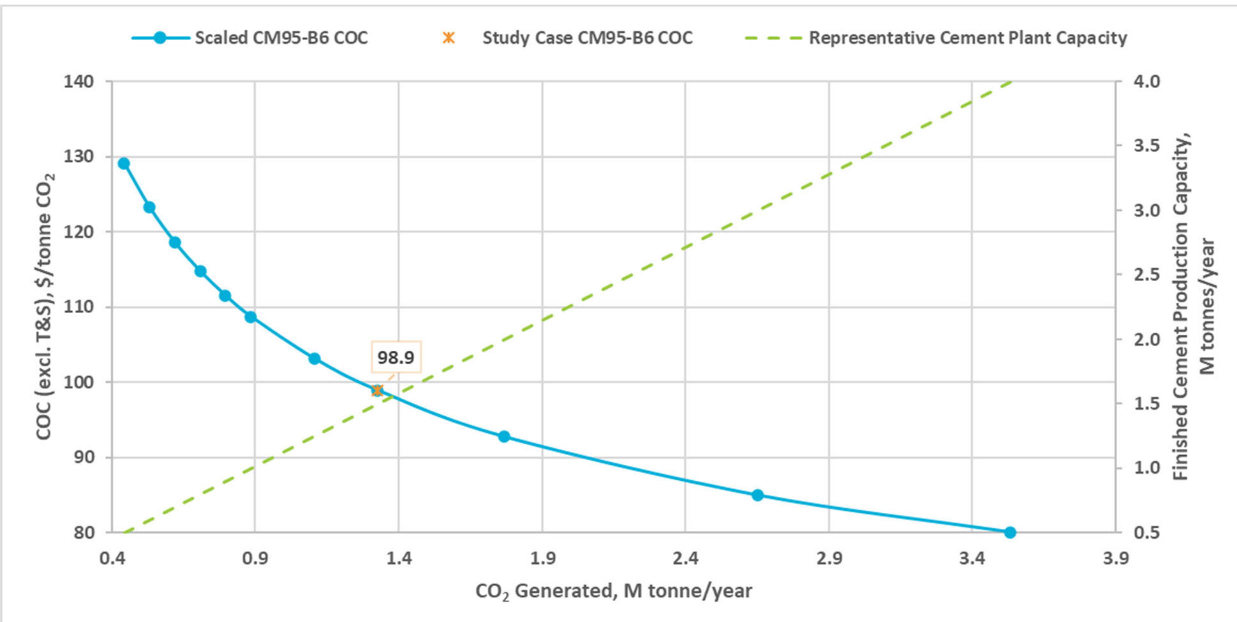
Exhibit 5-58. COC for case CM95-B6

Cost	$/tonne CO_2
Capital	52.7
Fixed	15.0
Variable	9.1
Purchased Power and Fuel	22.2
Total COC (excl. T&S)	**98.9**
Total COC (incl. T&S)	**108.9**

5.8.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-59. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $49.0/tonne CO_2 (i.e., 61 percent increase in normalized capture cost).

Exhibit 5-59. Case CM95-B6 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.9 CASE CM95-B7

5.9.1 Performance Results

Case CM95-B7 represents a PH/PC kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. To demonstrate the impact of the potential for heat integration on COC, the base cement plant is assumed to provide 10 percent of the capture system heating needs. This heat integration reduces the consumption of NG in the industrial boiler to provide solvent regeneration heat. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B7 is provided in Exhibit 5-60, and the emissions summary is provided in Exhibit 5-61.

Exhibit 5-60. CM95-B7 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	592 (561)
Natural Gas Feed Flow, kg/hr (lb/hr)	11,705 (25,805)
HHV Thermal Input, kWt	170,028
LHV Thermal Input, kWt	153,467
Raw Water Withdrawal, m^3/min (gpm)	5.2 (1,372)
Raw Water Consumption[B], m^3/min (gpm)	3.3 (881)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,330
Cooling Tower Fans, kWe	700
CO_2 Capture System Auxiliaries, kWe	4,600
CO_2 Compression, kWe	12,090
Feedwater Pumps, kWe	50
Forced Draft Fans, kWe	410
Ground Water Pumps, kWe	120
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	390
SCR, kWe	–
Transformer Losses, kWe	130
Total Auxiliaries, MWe	**20**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-61. CM95-B7 emissions summary

Emission	tonne/yr (ton/year)[A]	kg/tonne$_{clinker}$ (lb/ton$_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	187 (206)	0.160 (0.320)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	62,063 (68,412)	53 (107)
CO_2[B]	–	49 (97)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.9.2 Economic Analysis Results

Owner's costs (Exhibit 5-62), capital costs (Exhibit 5-63), and O&M costs (Exhibit 5-64) for case CM95-B7 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-65 shows the resulting COC.

Exhibit 5-62. Owners' costs for case CM95-B7

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,066	$2
1-Month Maintenance Materials	$565	$0
1-Month Non-Fuel Consumables	$672	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,996	$9
Total	**$16,305**	**$12**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,210	$1
0.5% of TPC (spare parts)	$2,999	$2
Total	**$4,210**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$89,972	$65
Financing Costs	$16,195	$12
TOC	**$726,493**	**$526**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$812,237**	**$588**

Exhibit 5-63. Capital costs for case CM95-B7

	Case:	CM95-B7						Estimate Type:		Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$911	$1,561	$781	$0	$3,253	$569	$0	$764	$4,586	$3
3.2	Water Makeup & Pretreating	$2,578	$258	$1,461	$0	$4,296	$752	$0	$1,010	$6,057	$4
3.3	Other Feedwater Subsystems	$428	$140	$133	$0	$701	$123	$0	$165	$989	$1
3.4	Industrial Boiler Package w/Deaerator	$5,700	$0	$1,657	$0	$7,357	$1,287	$0	$1,729	$10,373	$8
3.5	Other Boiler Plant Systems	$103	$38	$94	$0	$234	$41	$0	$55	$331	$0
3.6	NG Pipeline and Start-Up System	$945	$41	$30	$0	$1,016	$178	$0	$239	$1,433	$1
3.7	Waste Water Treatment Equipment	$5,571	$0	$3,415	$0	$8,986	$1,573	$0	$2,112	$12,670	$9
3.9	Miscellaneous Plant Equipment	$136	$18	$69	$0	$223	$39	$0	$52	$314	$0
	Subtotal	**$16,371**	**$2,055**	**$7,640**	**$0**	**$26,066**	**$4,562**	**$0**	**$6,126**	**$36,753**	**$27**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$91,065	$40,032	$84,066	$0	$215,163	$37,653	$36,578	$57,879	$347,273	$251
5.4	CO_2 Compression & Drying	$24,773	$3,716	$8,283	$0	$36,772	$6,435	$0	$8,642	$51,849	$38
5.5	CO_2 Compressor Aftercooler	$204	$32	$88	$0	$324	$57	$0	$76	$457	$0
5.12	Gas Cleanup Foundations	$0	$107	$94	$0	$201	$35	$0	$47	$283	$0
	Subtotal	**$116,042**	**$43,887**	**$92,531**	**$0**	**$252,460**	**$44,180**	**$36,578**	**$66,644**	**$399,862**	**$290**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,621	$1,821	$0	$4,442	$777	$0	$1,044	$6,264	$5
7.4	Stack	$10,407	$0	$6,048	$0	$16,455	$2,880	$0	$3,867	$23,201	$17
7.5	Duct & Stack Foundations	$0	$230	$273	$0	$503	$88	$0	$118	$709	$1
	Subtotal	**$10,407**	**$2,851**	**$8,142**	**$0**	**$21,400**	**$3,745**	**$0**	**$5,029**	**$30,174**	**$22**
	9					Cooling Water System					
9.1	Cooling Towers	$2,280	$0	$705	$0	$2,985	$522	$0	$701	$4,209	$3
9.2	Circulating Water Pumps	$240	$0	$17	$0	$257	$45	$0	$60	$362	$0
9.3	Circulating Water System Aux.	$2,927	$0	$387	$0	$3,314	$580	$0	$779	$4,673	$3
9.4	Circulating Water Piping	$0	$1,354	$1,226	$0	$2,579	$451	$0	$606	$3,637	$3
9.5	Make-up Water System	$308	$0	$396	$0	$704	$123	$0	$166	$993	$1
9.6	Component Cooling Water System	$211	$0	$162	$0	$373	$65	$0	$88	$526	$0
9.7	Circulating Water System Foundations	$0	$148	$245	$0	$393	$69	$0	$92	$554	$0
	Subtotal	**$5,966**	**$1,501**	**$3,138**	**$0**	**$10,606**	**$1,856**	**$0**	**$2,492**	**$14,954**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,853	$0	$331	$0	$4,183	$732	$0	$983	$5,898	$4
11.3	Switchgear & Motor Control	$5,981	$0	$1,038	$0	$7,019	$1,228	$0	$1,649	$9,896	$7
11.4	Conduit & Cable Tray	$0	$777	$2,241	$0	$3,018	$528	$0	$709	$4,255	$3
11.5	Wire & Cable	$0	$2,059	$3,680	$0	$5,739	$1,004	$0	$1,349	$8,093	$6
	Subtotal	**$9,834**	**$2,837**	**$7,289**	**$0**	**$19,959**	**$3,493**	**$0**	**$4,690**	**$28,143**	**$20**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$547	$438	$1,751	$0	$2,735	$479	$0	$643	$3,857	$3
12.9	Other I&C Equipment	$672	$0	$1,557	$0	$2,230	$390	$0	$524	$3,144	$2
	Subtotal	**$1,220**	**$438**	**$3,308**	**$0**	**$4,965**	**$869**	**$0**	**$1,167**	**$7,001**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$37	$742	$0	$779	$136	$0	$183	$1,098	$1
13.2	Site Improvements	$0	$173	$229	$0	$402	$70	$0	$94	$567	$0
13.3	Site Facilities	$198	$0	$208	$0	$405	$71	$0	$95	$572	$0
	Subtotal	**$198**	**$210**	**$1,179**	**$0**	**$1,586**	**$278**	**$0**	**$373**	**$2,236**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$77	$61	$0	$139	$24	$0	$33	$195	$0
	Subtotal	**$0**	**$77**	**$61**	**$0**	**$139**	**$24**	**$0**	**$33**	**$195**	**$0**
	Total	**$160,038**	**$53,856**	**$123,287**	**$0**	**$337,181**	**$59,007**	**$36,578**	**$86,553**	**$519,318**	**$376**
					Retrofit Values	**$389,444**	**$68,153**	**$42,247**	**$99,969**	**$599,812**	**$434**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-64. Initial and annual O&M costs for case CM95-B7

Case:	**CM95-B7**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.91
Maintenance Labor:					$3,838,798	$3.27
Administrative & Support Labor:					$1,226,356	$1.04
Property Taxes and Insurance:					$11,996,245	$10.22
Total:					**$18,128,024**	**$15.44**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,758,198	$4.90
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	988	$2.24	$0	$685,179	$0.58
Makeup and Waste Water Treatment Chemicals (ton):	0	2.9	$647.04	$0	$590,830	$0.50
CO_2 Capture System Chemicals[A]:	Proprietary				$4,894,445	$4.17
Triethylene Glycol (gal):	w/equip.	277	$8.00	$0	$688,127	$0.59
Subtotal:				**$0**	**$6,858,580**	**$5.84**
Waste Disposal						
Triethylene Glycol (gal):		277	$0.41	$0	$35,418	$0.03
Thermal Reclaimer Unit Waste (ton):		1.64	$44.70	$0	$22,682	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$430	$0.00
Subtotal:				**$0**	**$58,530**	**$0.05**
Variable Operating Costs Total:				**$0**	**$12,675,308**	**$10.80**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	13,924	$4.61	$0	$19,919,320	$16.97
Purchased Power (MWh):	0	20	$67.28	$0	$9,929,117	$8.46
Total:				**$0**	**$29,848,437**	**$25.42**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

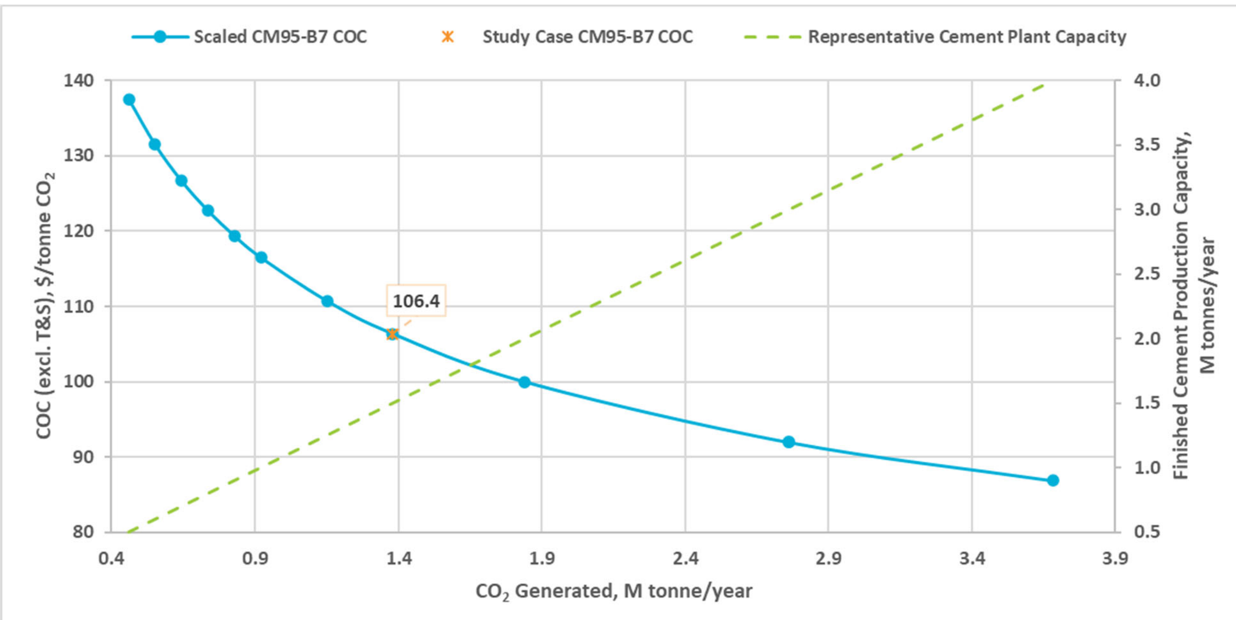
Exhibit 5-65. COC for case CM95-B7

Cost	$/tonne CO_2
Capital	54.7
Fixed	15.4
Variable	10.8
Purchased Power and Fuel	25.4
Total COC (excl. T&S)	**106.4**
Total COC (incl. T&S)	**116.4**

5.9.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-66. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $50.7/tonne CO_2 (i.e., 58 percent increase in normalized capture cost).

Exhibit 5-66. Case CM95-B7 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

5.10 Case CM95-B8

5.10.1 Performance Results

Case CM95-B8 represents a PH/PC kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. To demonstrate the impact of the potential for heat integration on COC, the base cement plant is assumed to provide 30 percent of the capture system heating needs. This heat integration reduces the consumption of NG in the industrial boiler to provide solvent regeneration heat. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream from the cement kiln and the industrial boiler. The performance summary for case CM95-B8 is provided in Exhibit 5-67, and the emissions summary is provided in Exhibit 5-68.

Exhibit 5-67. CM95-B8 performance summary

Performance Summary	
Cement Production Rate, M tonnes/year	1.50
Clinker Percentage	91.4
Clinker Production Rate, M tonnes/year	1.37
CO_2 Capture Rate, %	95
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	568 (538)
Natural Gas Feed Flow, kg/hr (lb/hr)	8,797 (19,394)
HHV Thermal Input, kWt	127,788
LHV Thermal Input, kWt	115,341
Raw Water Withdrawal, m^3/min (gpm)	5.0 (1,315)
Raw Water Consumption[B], m^3/min (gpm)	3.2 (858)
Auxiliary Load Summary	
Ash Handling, kWe	–
Baghouse, kWe	–
Circulating Water Pumps, kWe	1,280
Cooling Tower Fans, kWe	670
CO_2 Capture System Auxiliaries, kWe	4,300
CO_2 Compression, kWe	11,530
Feedwater Pumps, kWe	40
Forced Draft Fans, kWe	310
Ground Water Pumps, kWe	120
Flue Gas Desulfurizer, kWe	–
Miscellaneous Balance of Plant[A], kWe	370
SCR, kWe	–
Transformer Losses, kWe	120
Total Auxiliaries, MWe	**19**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads
[B]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged

Exhibit 5-68. CM95-B8 emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	168 (185)	0.144 (0.288)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	59,175 (65,229)	51 (102)
CO_2[B]	–	46 (93)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis, assuming 91.4 percent clinker

5.10.2 Economic Analysis Results

Owner's costs (Exhibit 5-69), capital costs (Exhibit 5-70), and O&M costs (Exhibit 5-71) for case CM95-B8 are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 5-72 shows the resulting COC.

Exhibit 5-69. Owners' costs for case CM95-B8

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,958	$2
1-Month Maintenance Materials	$539	$0
1-Month Non-Fuel Consumables	$617	$0
1-Month Waste Disposal	$5	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,456	$9
Total	**$15,575**	**$12**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,105	$1
0.5% of TPC (spare parts)	$2,864	$2
Total	**$3,969**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$85,917	$65
Financing Costs	$15,465	$12
TOC	**$693,706**	**$527**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$775,580**	**$589**

Exhibit 5-70. Capital costs for case CM95-B8

	Case:	CM95-B8						Estimate Type:		Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$748	$1,282	$641	$0	$2,671	$467	$0	$628	$3,766	$3
3.2	Water Makeup & Pretreating	$2,499	$250	$1,416	$0	$4,165	$729	$0	$979	$5,872	$4
3.3	Other Feedwater Subsystems	$332	$109	$103	$0	$544	$95	$0	$128	$767	$1
3.4	Industrial Boiler Package w/Deaerator	$4,421	$0	$1,285	$0	$5,706	$999	$0	$1,341	$8,045	$6
3.5	Other Boiler Plant Systems	$80	$29	$73	$0	$181	$32	$0	$43	$256	$0
3.6	NG Pipeline and Start-Up System	$822	$35	$27	$0	$883	$155	$0	$208	$1,246	$1
3.7	Waste Water Treatment Equipment	$5,296	$0	$3,246	$0	$8,542	$1,495	$0	$2,007	$12,045	$9
3.9	Miscellaneous Plant Equipment	$126	$17	$64	$0	$207	$36	$0	$49	$292	$0
	Subtotal	**$14,323**	**$1,722**	**$6,855**	**$0**	**$22,900**	**$4,007**	**$0**	**$5,381**	**$32,289**	**$25**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$86,959	$38,227	$80,276	$0	$205,462	$35,956	$34,929	$55,269	$331,615	$252
5.4	CO_2 Compression & Drying	$24,067	$3,610	$8,047	$0	$35,724	$6,252	$0	$8,395	$50,371	$38
5.5	CO_2 Compressor Aftercooler	$196	$31	$84	$0	$312	$55	$0	$73	$439	$0
5.12	Gas Cleanup Foundations	$0	$101	$88	$0	$189	$33	$0	$44	$266	$0
	Subtotal	**$111,222**	**$41,969**	**$88,495**	**$0**	**$241,686**	**$42,295**	**$34,929**	**$63,782**	**$382,691**	**$291**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,440	$1,696	$0	$4,136	$724	$0	$972	$5,831	$4
7.4	Stack	$10,335	$0	$6,005	$0	$16,340	$2,860	$0	$3,840	$23,040	$17
7.5	Duct & Stack Foundations	$0	$226	$268	$0	$494	$86	$0	$116	$697	$1
	Subtotal	**$10,335**	**$2,666**	**$7,969**	**$0**	**$20,970**	**$3,670**	**$0**	**$4,928**	**$29,568**	**$22**
	9					Cooling Water System					
9.1	Cooling Towers	$2,207	$0	$683	$0	$2,889	$506	$0	$679	$4,074	$3
9.2	Circulating Water Pumps	$231	$0	$16	$0	$248	$43	$0	$58	$349	$0
9.3	Circulating Water System Aux.	$2,850	$0	$377	$0	$3,227	$565	$0	$758	$4,551	$3
9.4	Circulating Water Piping	$0	$1,318	$1,194	$0	$2,512	$440	$0	$590	$3,542	$3
9.5	Make-up Water System	$302	$0	$388	$0	$690	$121	$0	$162	$973	$1
9.6	Component Cooling Water System	$205	$0	$158	$0	$363	$64	$0	$85	$512	$0
9.7	Circulating Water System Foundations	$0	$144	$239	$0	$384	$67	$0	$90	$541	$0
	Subtotal	**$5,796**	**$1,462**	**$3,055**	**$0**	**$10,313**	**$1,805**	**$0**	**$2,423**	**$14,541**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$3,761	$0	$323	$0	$4,084	$715	$0	$960	$5,758	$4
11.3	Switchgear & Motor Control	$5,839	$0	$1,013	$0	$6,851	$1,199	$0	$1,610	$9,661	$7
11.4	Conduit & Cable Tray	$0	$759	$2,187	$0	$2,946	$516	$0	$692	$4,154	$3
11.5	Wire & Cable	$0	$2,010	$3,593	$0	$5,603	$980	$0	$1,317	$7,900	$6
	Subtotal	**$9,599**	**$2,769**	**$7,116**	**$0**	**$19,484**	**$3,410**	**$0**	**$4,579**	**$27,473**	**$21**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$543	$434	$1,738	$0	$2,716	$475	$0	$638	$3,829	$3
12.9	Other I&C Equipment	$668	$0	$1,546	$0	$2,213	$387	$0	$520	$3,121	$2
	Subtotal	**$1,211**	**$434**	**$3,284**	**$0**	**$4,929**	**$863**	**$0**	**$1,158**	**$6,950**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$36	$734	$0	$770	$135	$0	$181	$1,086	$1
13.2	Site Improvements	$0	$171	$227	$0	$398	$70	$0	$93	$561	$0
13.3	Site Facilities	$196	$0	$205	$0	$401	$70	$0	$94	$565	$0
	Subtotal	**$196**	**$207**	**$1,165**	**$0**	**$1,568**	**$274**	**$0**	**$369**	**$2,211**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$75	$60	$0	$135	$24	$0	$32	$191	$0
	Subtotal	**$0**	**$75**	**$60**	**$0**	**$135**	**$24**	**$0**	**$32**	**$191**	**$0**
	Total	**$152,682**	**$51,304**	**$117,999**	**$0**	**$321,985**	**$56,347**	**$34,929**	**$82,652**	**$495,913**	**$377**
					Retrofit Values	**$371,893**	**$65,081**	**$40,342**	**$95,463**	**$572,780**	**$435**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 5-71. Initial and annual O&M costs for case CM95-B8

Case:	**CM95-B8**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
			Operating & Maintenance Labor			
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
			Fixed Operating Costs			
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.95
Maintenance Labor:					$3,665,791	$3.27
Administrative & Support Labor:					$1,183,104	$1.06
Property Taxes and Insurance:					$11,455,597	$10.23
Total:					**$17,371,117**	**$15.52**
			Variable Operating Costs			
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,498,687	$4.91
			Consumables			
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	947	$2.24	$0	$656,692	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	2.8	$647.04	$0	$566,266	$0.51
CO_2 Capture System Chemicals[A]:		Proprietary			$4,415,227	$3.94
Triethylene Glycol (gal):	w/equip.	264	$8.00	$0	$656,109	$0.59
Subtotal:				**$0**	**$6,294,294**	**$5.62**
			Waste Disposal			
Triethylene Glycol (gal):		264	$0.41	$0	$33,770	$0.03
Thermal Reclaimer Unit Waste (ton):		1.56	$44.70	$0	$21,627	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$388	$0.00
Subtotal:				**$0**	**$55,785**	**$0.05**
Variable Operating Costs Total:				**$0**	**$11,848,765**	**$10.59**
			Fuel and Purchased Power Costs			
Natural Gas (MMBTU):	0	10,465	$4.61	$0	$14,970,738	$13.37
Purchased Power (MWh):	0	19	$67.28	$0	$9,388,075	$8.39
Total:				**$0**	**$24,358,813**	**$21.76**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

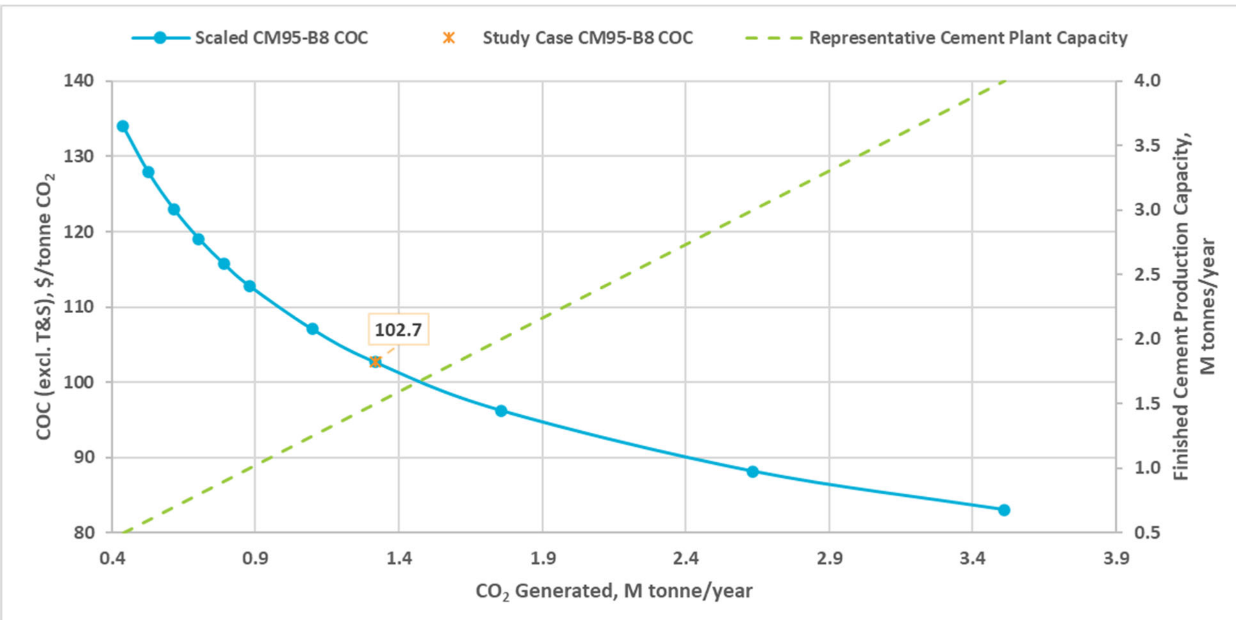
Exhibit 5-72. COC for case CM95-B8

Cost	$/tonne CO_2
Capital	54.8
Fixed	15.5
Variable	10.6
Purchased Power and Fuel	21.8
Total COC (excl. T&S)	**102.7**
Total COC (incl. T&S)	**112.7**

5.10.3 Plant Capacity Sensitivity Analysis

An analysis of the sensitivity of COC to the base plant's finished cement capacity, as it relates to the total CO_2 available for capture, is shown in Exhibit 5-73. The COC is affected by both the CO_2 generated in the cement manufacturing process and the CO_2 produced by the industrial boiler, which supplies steam to serve the heating needs of the capture system. This sensitivity analysis assumes that the CO_2 produced by the NG-fired boiler is linearly related to the CO_2 produced by the kiln. The results of this sensitivity analysis show that as the finished cement production capacity decreases from 4 M tonnes/year to 0.5 M tonnes/year (i.e., 87.5 percent decrease), the COC increases by $50.9/tonne CO_2 (i.e., 61 percent increase in normalized capture cost).

Exhibit 5-73. Case CM95-B8 finished cement production capacity sensitivity



Note: CO_2 emissions shown include those from both the cement kiln and the NG-fired boiler

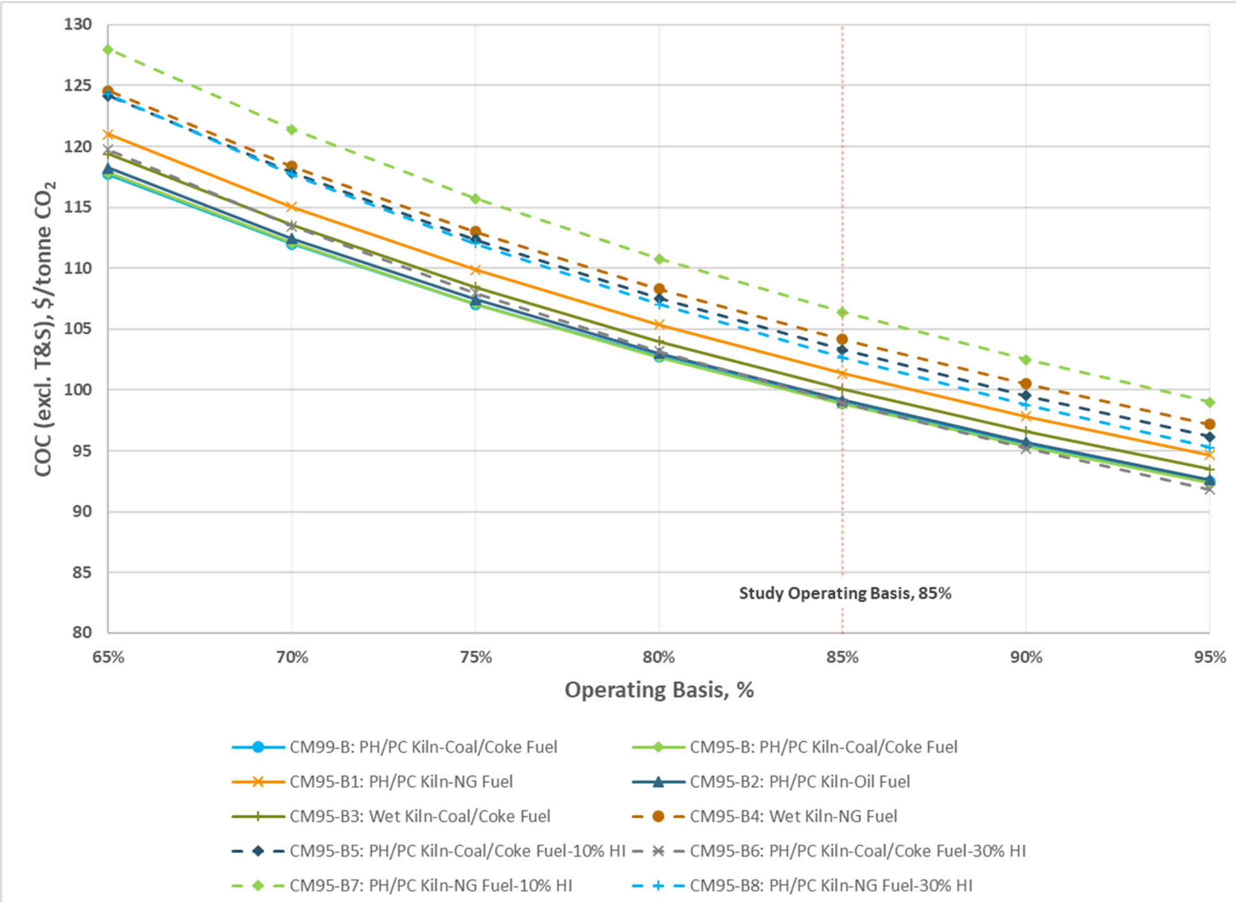
5.11 Economic Sensitivity Analyses

In addition to the sensitivity analyses regarding plant capacities presented for each base case, effects of varying financial assumptions made in this study were evaluated for the base cases.

5.11.1 Operating Basis

All capital costs were estimated at 100 percent operating basis (i.e., assuming equipment is designed for full capacity utilization with no down days). However, in cement plant operations, down days (i.e., reduced utilization) are expected to allow for periodic maintenance and to account for unexpected process upsets and outages. As such, costs for maintenance materials, consumables, waste disposal, and fuel use were each estimated based on an 85 percent operating basis (i.e., 85 percent utilization). Evaluating the effect of operating basis on the COC is important for gauging the impact of equipment utilization on normalized costs. Exhibit 5-74 shows the results of this sensitivity analysis, where COC rises by \$25.2–29.0/tonne CO_2 as the operating basis decreases from 95 to 65 percent.

Exhibit 5-74. COC (excl. T&S) vs. operating basis

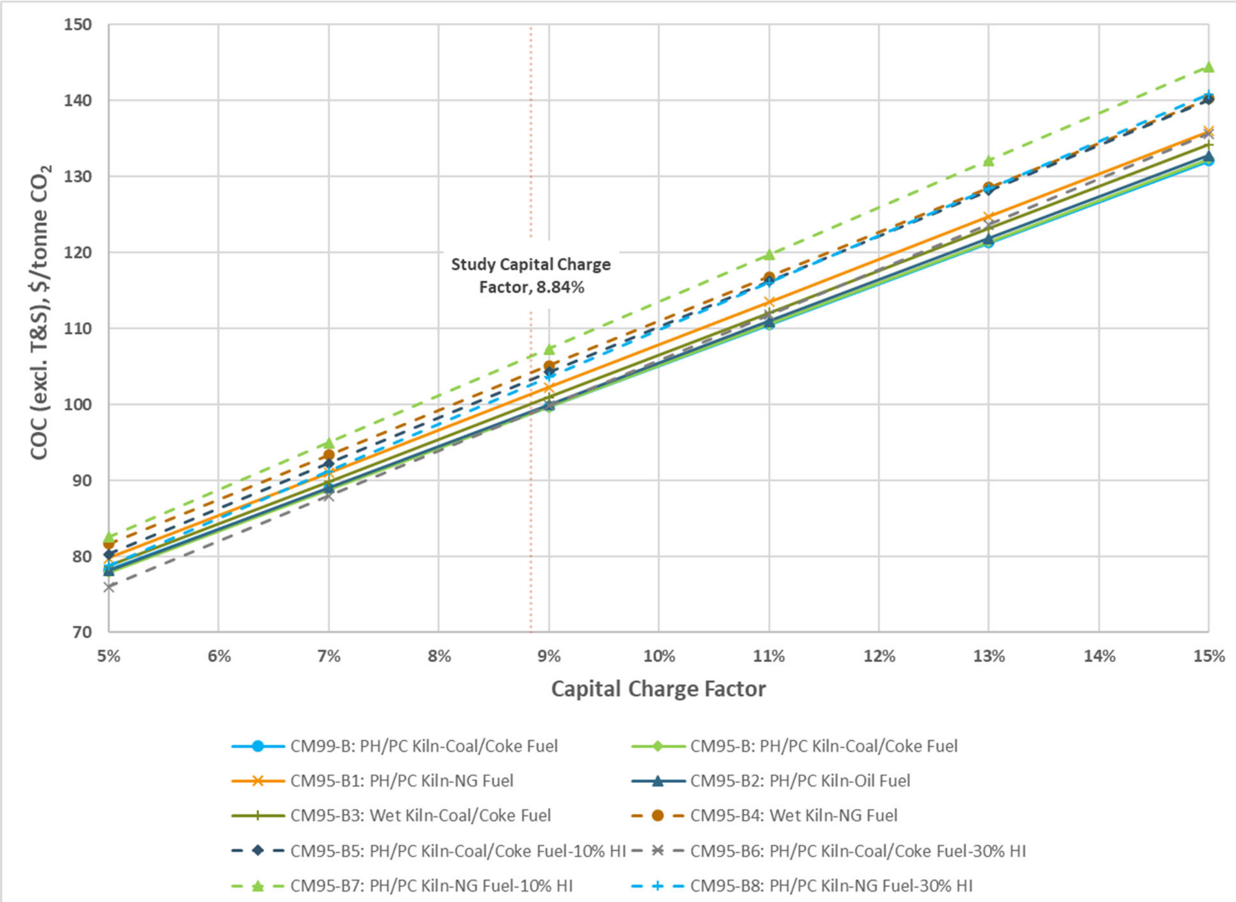


Note: HI = heat integration

5.11.2 Capital Charge Factor

The CCF used to estimate the capital component of the COC for each case were determined by the Energy Markets Analysis Team and are market dependent. The financial assumptions are detailed in Section 2.2 but could vary depending on economic conditions, among other factors. For instance, changing payback period assumptions (i.e., 20-year payback period instead of 30-year), debt-to-equity ratios, rates of return and taxes could each affect the CCF. As such, the COC for each case was evaluated across a range of CCFs of 5–15 percent (Exhibit 5-75).

Exhibit 5-75. COC (excl. T&S) vs. CCF

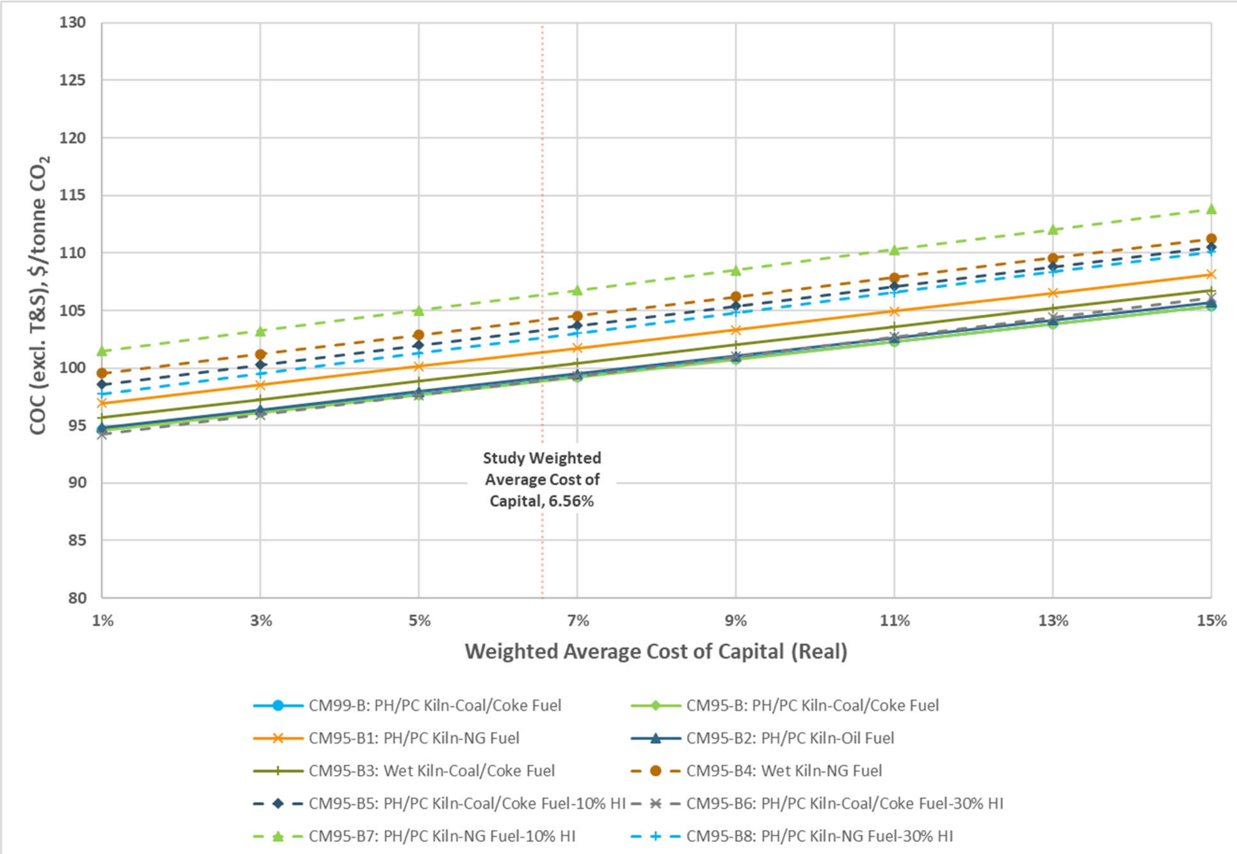


Note: HI = heat integration

The results show that changing financial assumptions can have a large effect on the COC. The largest change when varying the CCF over a range of 5–15 percent is an increase of $62.0/tonne CO_2. The CCF used for the study cases, details of which have been given previously in Section 2.2, are representative of a project-specific CCF in the cement industry. In addition to the cement industry's market influences on CCF, the maturity of a technology, specifically a capture technology like the CANSOLV® units employed in this study, may also affect the CCF. As solvent-based CO_2 capture systems are becoming more prevalent and the learning-by-doing improves, the low end of the CCF sensitivity curve demonstrated in this analysis may be a more reasonable representation.

The CCF is a factor developed to levelize project capital costs across the project life based on financial assumptions. Another factor that results from financial assumptions is the WACC, which is mathematically translated into the CCF used in this analysis. In addition to impacting the capital portion of the COC, WACC also impacts the levelized NG and power prices used to generate the fuel and power COC components. Exhibit 5-76 shows COC sensitivity to WACC, where the COC increases by $7.7–8.8/tonne CO_2 when WACC varies by 1–15 percent. Based on this analysis, for every 1 percent increase in WACC, the COC increases by 0.78–0.87 percent.

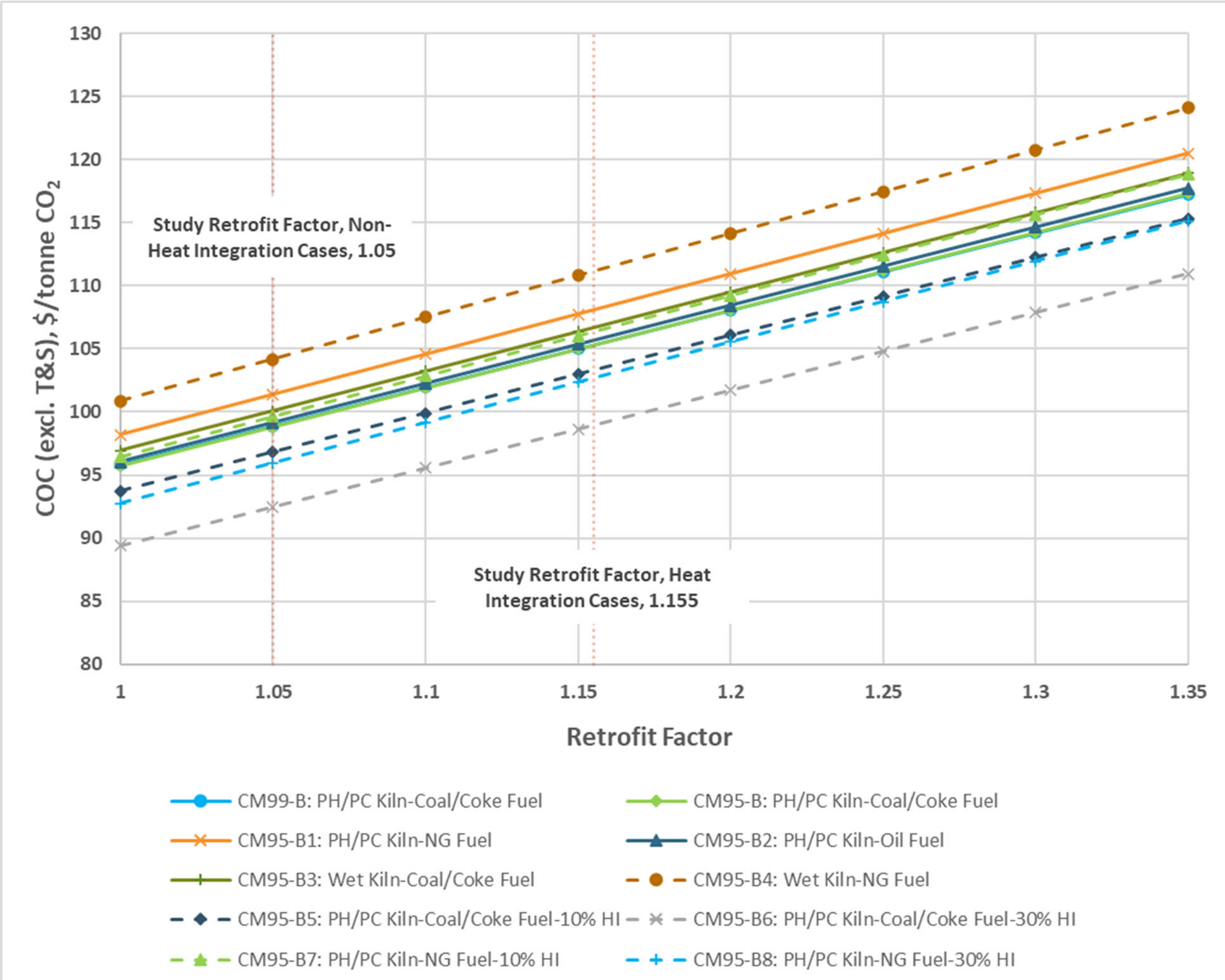
Exhibit 5-76. COC (excl. T&S) vs. WACC



5.11.3 Retrofit Factor

The retrofit factors used to estimate the COC for each base case were applied as a blanket multiplier to TPC. The basis for this methodology is detailed in Section 2.3, but such an overall retrofit factor could vary depending on installation specifics, technology considerations, existing site constraints, and other determinants. As such, the COC for each case was evaluated across a retrofit factor range of 1.00–1.35, resulting in an increase in COC of $21.4–23.2/tonne CO_2 across the sensitivity range, where the values corresponding to a 1.00 retrofit factor are indicative of essentially greenfield installations in each case (Exhibit 5-77). Because the retrofit factors in this study are applied as a blanket multiplier to TPC, the effect of varying those factors across a range of values is an increase in COC with increasing retrofit factor.

Exhibit 5-77. COC (excl. T&S) vs. retrofit factor



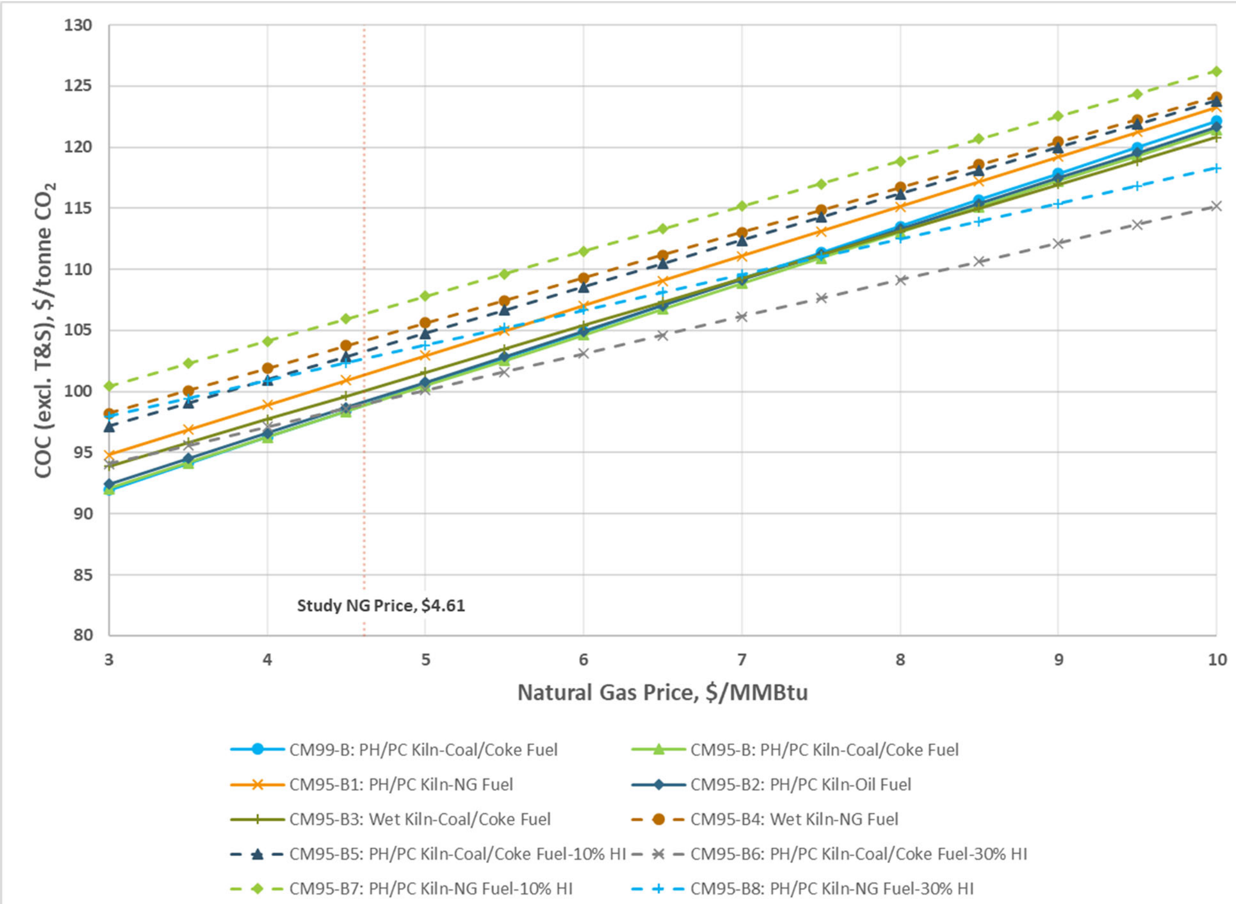
Note: HI = heat integration

Heat integration potential incurs an additional retrofit difficulty that is 10 percent higher than the base cases (i.e., 1.155 versus 1.05). Because of the additional difficulty considered, COC with 10 or 30 percent heat integration potential is higher compared to the respective non-heat integration cases. Based on the assumptions in this study, heat integration potential always results in a higher COC (i.e., higher COC with no retrofit difficulty factor), but at lower NG prices, it is possible that heat integration could reduce COC, as demonstrated in the evaluation of COC sensitivity to NG price.

5.11.4 Natural Gas Price

The fuel cost required for the industrial boiler in each case is directly dependent upon the NG price assumed. For each case, a $4.61/MMBtu price was used for the NG price but can vary widely depending upon market scenario, location, economic conditions, fuel availability, oil prices, and more. As such, the total COC for each case was estimated across a range of $3–10/MMBtu fuel price. An increase of $20.3–30.2/tonne CO_2 is observed across the sensitivity range (Exhibit 5-78). Based on this analysis, for every $1/MMBtu increase in natural gas price, the COC increases by 3.0–4.7 percent.

Exhibit 5-78. COC (excl. T&S) vs. NG price



Note: HI = heat integration

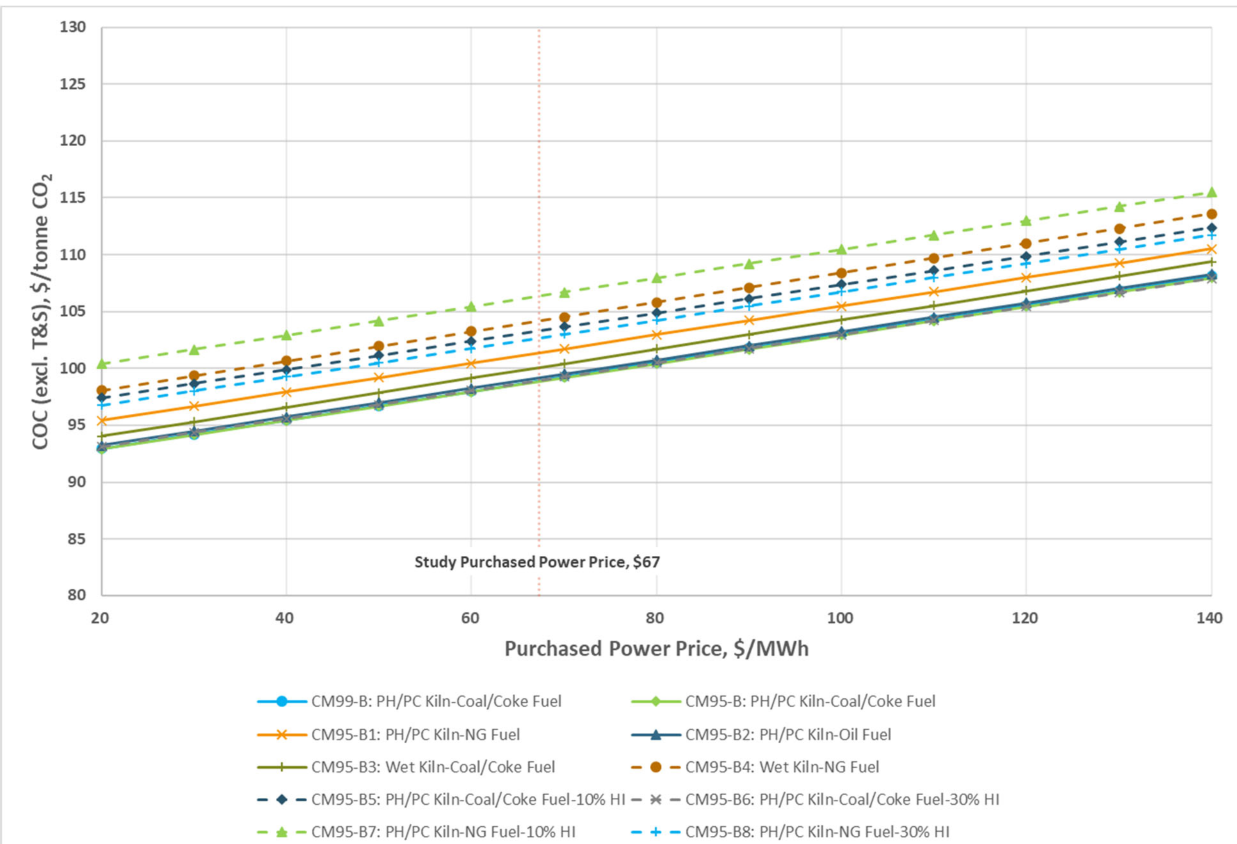
Sensitivity to NG price highlights potential benefits of heat integration when NG prices are higher than that assumed for this analysis. For the coal/coke-fueled kiln in this analysis, COC is lower with 10 percent heat integration potential when NG price is $16.16/MMBtu or higher, and with 30 percent heat integration potential, COC is lower when NG price is $4.70/MMBtu or higher. For the NG-fueled kiln in this analysis, crossover NG prices for 10 percent and 30 percent heat integration potential are $17.62/MMBtu and $5.71/MMBtu, respectively. Under alternative financial assumptions (e.g., cost of capital, NG price, purchased power price), heat integration may provide cost benefits, but requires higher fidelity of heat optimization and cost estimation to ascertain if and at what level of heat integration that benefit is realized.

5.11.5 Purchased Power Price

The auxiliary power cost for each case is directly dependent upon the purchased power price assumed. For each case, a $67.28/MWh price was used to estimate the auxiliary power costs, but purchased power price can vary widely depending upon market scenario, location, economic conditions, fuel pricing, and more. As such, the total COC for each case was estimated across a range of $20–140/MWh purchased power price, resulting in an increase in COC of $14.8–15.5/tonne CO_2 across the sensitivity range as shown in Exhibit 5-79. Based on this analysis, for every $5/MWh increase in purchased power price, the COC increases by 0.63–0.68 percent.

Although CO_2 capture system technology R&D will not impact the purchased power price, it is worth noting that due to factors such as demand for power, supply constraints, weather events, or even typical seasonal variation, the COC will fluctuate due to changes in purchased power price. This will introduce additional difficulty for cement plants, or other industrial users, when attempting to do long-term planning on the economics of carbon capture and storage, since the COC will vary in response to changing power prices. This dependency can be mitigated by decreasing the reliance on purchased power, potentially by generating auxiliary power needs internally—possibly through on-site combined heat and power deployment, or by using steam-driven mechanical equipment, where possible.

Exhibit 5-79. COC (excl. T&S) vs. purchased power price

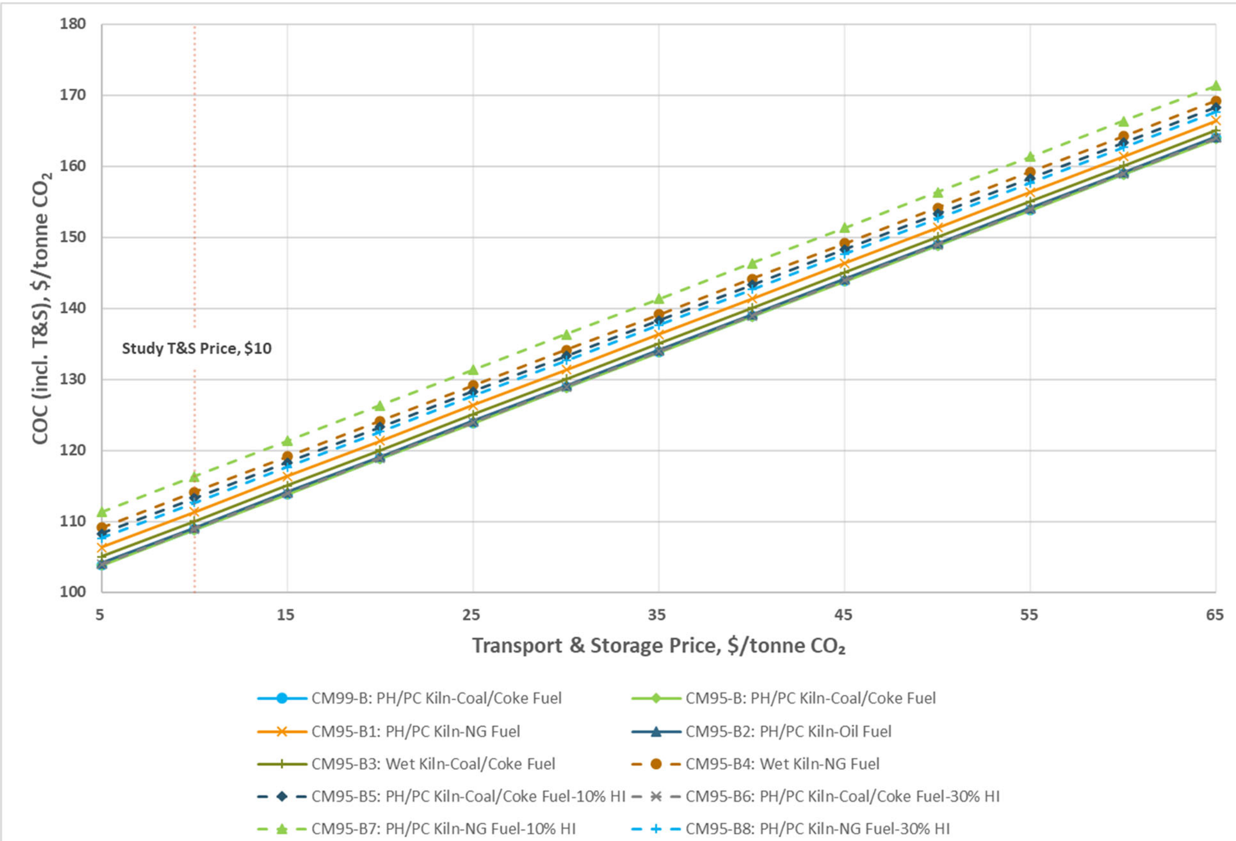


Note: HI = heat integration

5.11.6 Transport and Storage Price

The T&S cost added to the COC in each case is $10/tonne CO_2 based on guidance in NETL's "QGESS: Carbon Dioxide Transport and Storage Costs in NETL Studies," but can vary widely depending upon market scenario, location, economic conditions, storage availability, and more. [23] As such, the total COC (incl. T&S) for each case was estimated across a range of $5–65/tonne CO_2 T&S price. An increase of $60.0/tonne CO_2 is observed across the sensitivity range, as the cost is an addition to the estimated COC without T&S (Exhibit 5-81). Based on this analysis, for every $10/tonne CO_2 increase in T&S price, the COC increases by 9.0–9.6 percent.

Exhibit 5-80. COC (incl. T&S) vs. T&S price



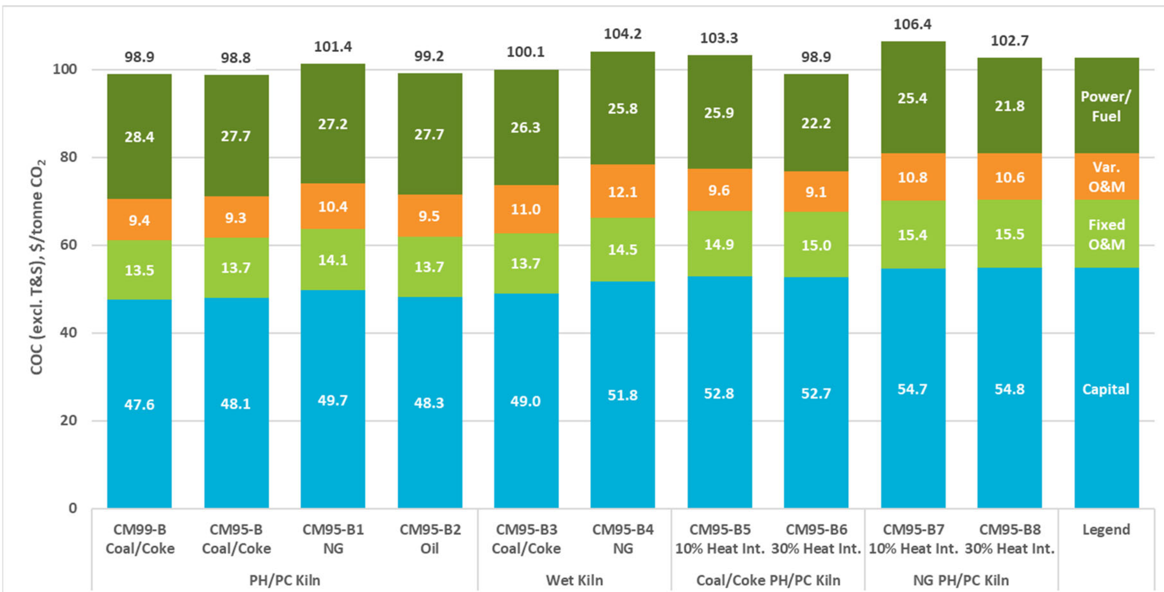
5.12 Base Cases Conclusion

The CO_2 emissions streams produced in cement plants, both by the cement production process and by the emissions from steam generation required for capture operations, represent a large quantity of CO_2 and as such, the cement industry represents an impactful opportunity for decarbonization. CO_2 capture, purification, and compression systems were modeled for representative cement plants, producing 1.5 M tonnes of finished cement annually, to estimate the cost of capturing the combined CO_2 emissions from the kiln off-gas and the industrial boiler in each case. The results showed the retrofit COC (excluding T&S) ranges $98.8–$106.4/tonne CO_2 for the base cases evaluated in this study, as shown in Exhibit 5-81.

The differences in COC for the base cases with 95 percent capture and no heat integration are easily correlated with the CO_2 concentration in the kiln off-gas stream. Lower CO_2 concentrations, with all other operating parameters and design being the same, results in a higher COC (i.e., comparing CM95-B at 31 mol% kiln off-gas CO_2 concentration to that of CM95-

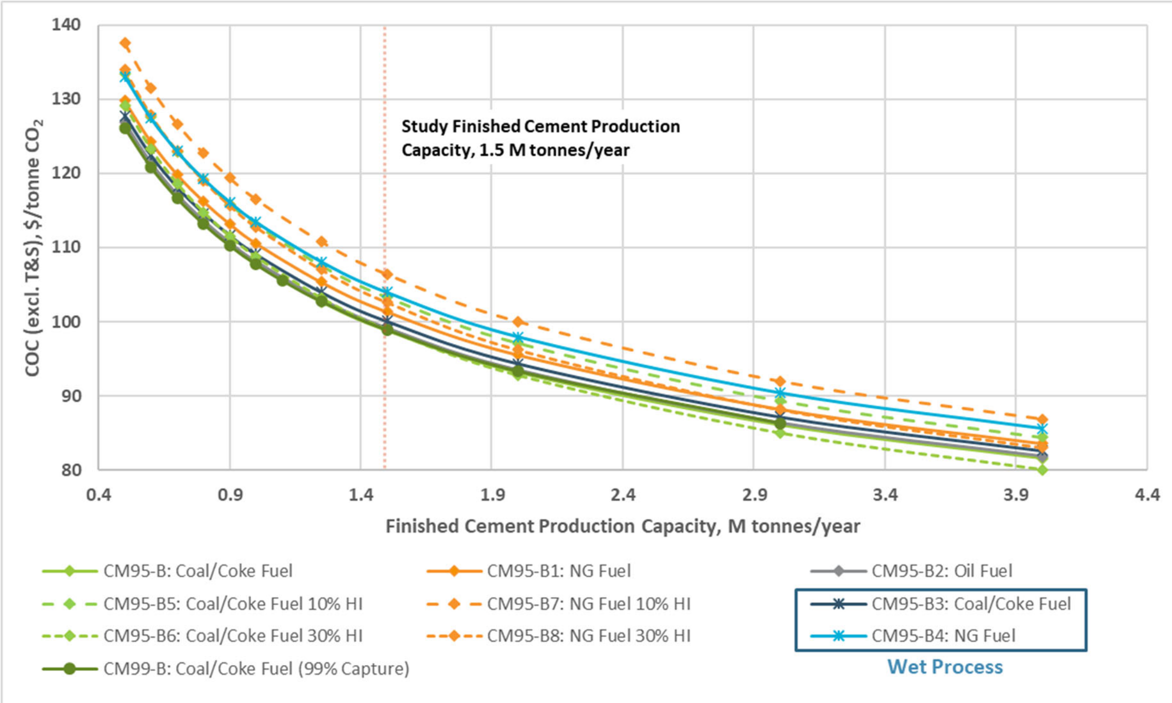
B4 at 13 mol% kiln off-gas CO_2 concentration). Heat integration cases highlight that the potential O&M savings gained by using available heat must be balanced with increased capital costs required to achieve that benefit before a COC improvement is realized. Lastly, higher capture rates equate to a marginally higher COC, based on the assumptions of this study (i.e., CM99-B versus CM95-B).

Exhibit 5-81. Summary of base cases COC (excl. T&S)



The plant size sensitivities showed that as plant size decreased from 4 M tonnes/year to 0.5 M tonnes/year of finished cement production, the COC increased by $39.8–50.9/tonne CO_2 (i.e., 46–61 percent). As the plant production capacity is decreased, less CO_2 is produced by the kiln and the NG-fired boiler. As such, economies of scale related to the capture system equipment and fixed O&M are lost, resulting in a higher normalized capture cost at lower production capacities, as demonstrated in Exhibit 5-82.

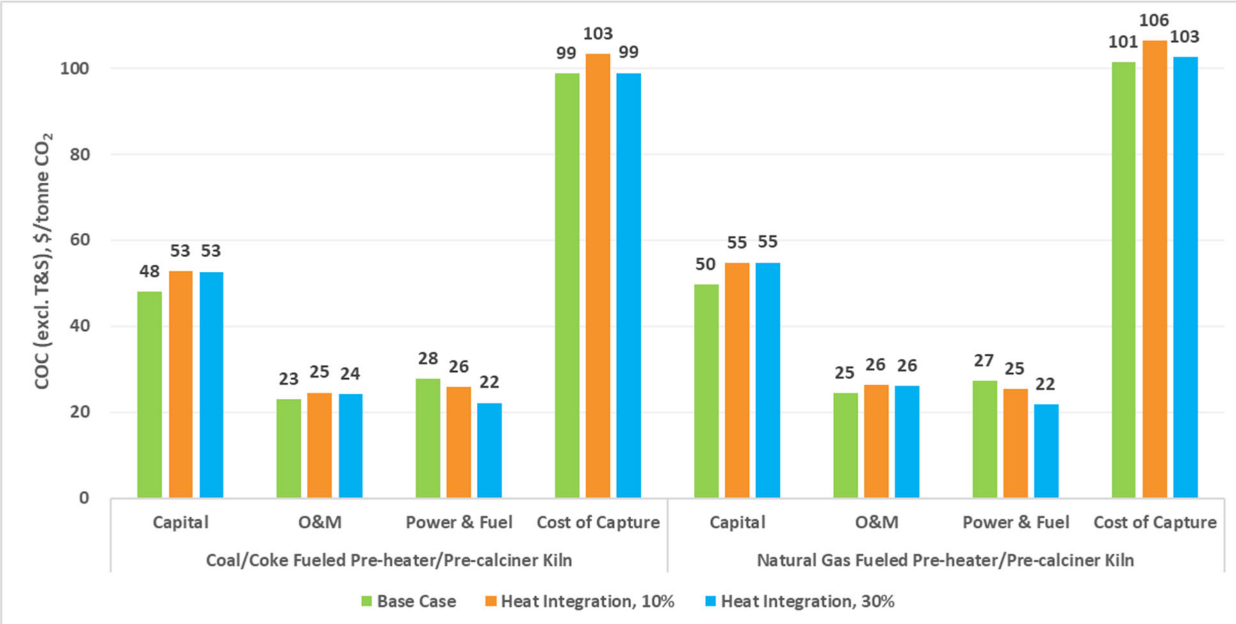
Exhibit 5-82. Summary of plant capacity sensitivity analyses for base cases



Note: HI = heat integration

When evaluating heat integration potential of the existing cement plant, a decrease in normalized power and fuel consumption is observed. However, this is partly offset by an increase in normalized capital and O&M costs, as less CO_2 is generated from steam production in the industrial boiler. In addition, a 10 percent increase in retrofit difficulty (i.e., retrofit factor of 1.155) was factored into capital calculations for the cases where 10 and 30 percent heat integration was considered. A combination of these effects on normalized costs results in a 4.5–4.9 percent higher total COC at 10 percent heat integration potential and a 0.1–1.3 percent higher total COC at 30 percent heat integration potential. These trends are demonstrated in Exhibit 5-83. Such an analysis highlights that detailed optimization and project-specific design with regards to heat integration opportunities for retrofit CO_2 capture systems is necessary to realize any potential benefits.

Exhibit 5-83. Summary of cases with potential heat integration opportunities



When considering heat integration potential, evaluating the cost of CO_2 avoided (COA) alongside the COC is valuable for highlighting how heat integration may benefit owners assuming a CO_2 emissions penalty scenario. Equation 5-1 shows how the COA is calculated to represent the cost of the CO_2 emissions captured from the cement kiln off-gas (i.e., negating emissions created by the NG-fired boiler).

$$COA\left(\frac{\$}{tonne\ CO_2}\right) = \frac{TOC*CCF+FOM+VOM+PF+PP}{tonnes\ total\ CO_2\ captured - tonnes\ CO_2\ emitted\ by\ NG\ boiler}$$

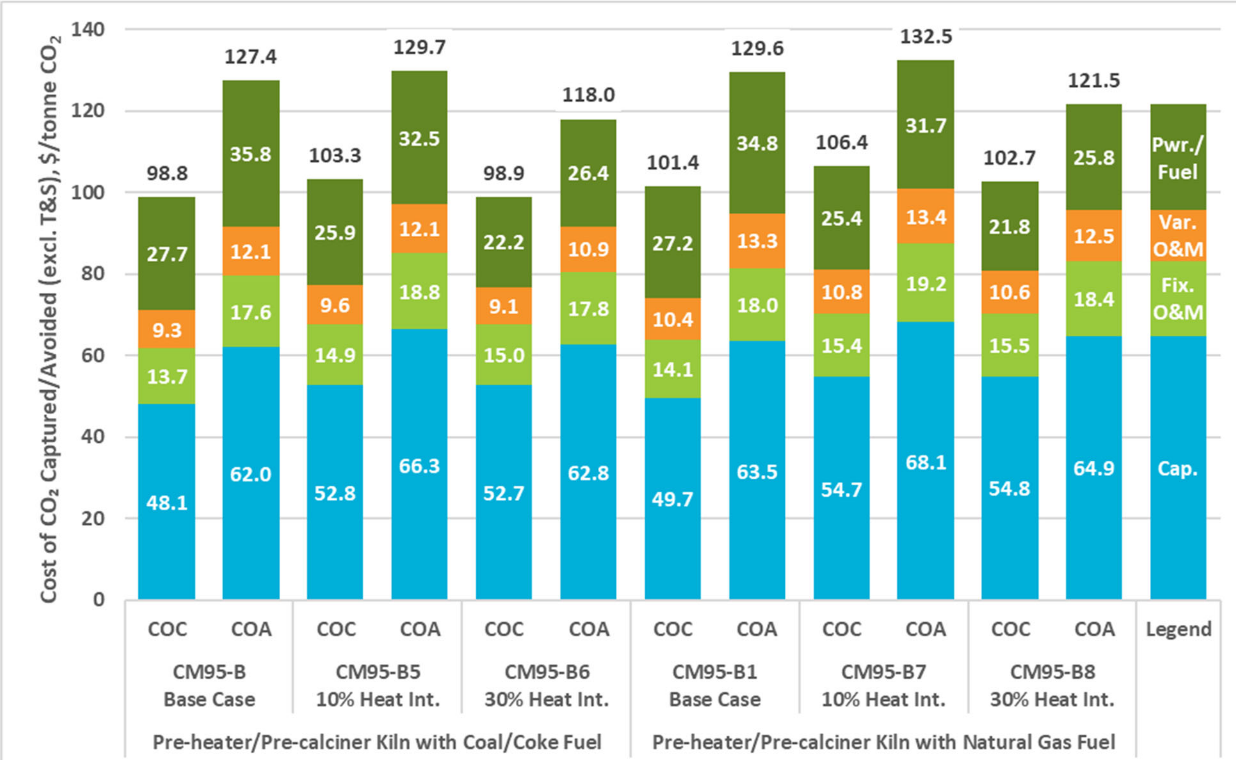
Equation 5-1: Cost of CO_2 Avoided

Where:

- TOC – Total overnight costs of CO_2 capture retrofit system
- CCF – Capital charge factor, based on industry-specific financial assumptions as detailed in Section 2.2
- FOM – Annual fixed O&M costs
- VOM – Annual variable O&M costs
- PF – Purchased fuel
- PP – Purchased power

Exhibit 5-84 shows the COA and COC for each case evaluated to consider heat integration potential, along with their respective base cases. At 10 percent heat integration potential, the COA is marginally increased (i.e., 1.8 percent when the kiln is NG fueled and 2.2 percent when the kiln is coal/coke fueled) from the base case, while at 30 percent heat integration potential, the COA is 6.2–7.4 percent lower than the base case.

Exhibit 5-84. COC and COA for cases with heat integration potential



Because heat integration decreases the need for auxiliary fuel burning in the NG-fired boiler, it is expected that COA would also decrease, as less CO_2 is emitted in the boiler flue gas. For the heat integration cases in this analysis, however, the retrofit difficulty factor is 10 percent higher than non-heat integration cases (i.e., 1.155 versus 1.05), which results in an increase in capital expenditure. As such, like the COC, the COA is higher at 10 percent heat integration when compared to the respective non-heat integration case. If additional retrofit difficulty is not added with heat integration potential (i.e., retrofit factor is 1.05 for all cases analyzed), then the COA is 2.5–2.9 percent lower at 10 percent heat-integration potential and 10.8–11.9 percent lower at 30 percent heat-integration potential, when compared to the respective non-heat integration case. This analysis highlights that optimization and project-specific design with regards to heat integration opportunities for retrofit CO_2 capture systems provides an opportunity for potential reductions of COC and COA.

6 SENSITIVITY CASES WITH FGD AND SCR: COST AND PERFORMANCE

For this study, the main point source of CO_2 available for capture is the kiln off-gas, and it is inherently assumed that the kiln off-gas requires only CO_2 capture and compression, with intercooling and TEG dehydration, and no other gas clean-up operations; however, it is possible that other treatment of the off-gas would be necessary upstream of the CO_2 capture unit. As mentioned in Section 1.1, contaminants such as SOx, NOx, and PM can negatively affect solvent-based CO_2 capture systems in terms of operability and lifespan. Abatement of these contaminants is not considered in this study's base cases found in Section 5; rather, the kiln off-gas in those cases is assumed suitable for solvent-based post-combustion capture. As such, sensitivity cases evaluate the cost impact of deeper levels of kiln off-gas pretreatment prior to the CO_2 capture island, with the addition of an SCR unit to treat NOx and an FGD unit to remove SOx (Exhibit 6-1). The kiln off-gas was assumed to have NOx and SOx concentrations of 500–1,500 ppm_v and 100–500 ppm_v, respectively, for each of the configurations shown in Exhibit 6-1. The kiln off-gas for each configuration was treated such that SOx levels were 37 ppm_v, and NOx levels were 2 ppm_v (i.e., after FGD and SCR, respectively), at the capture system inlet. These systems are described in Section 3.7 and Section 3.8, respectively. A polishing baghouse is included as part of the FGD system.

Exhibit 6-1. Description of sensitivity cases

Case Number	CM95-B-S	CM95-B1-S	CM95-B3-S	CM95-B4-S
Capture Rate	95 Percent			
Kiln Type	Pre-heater/Pre-calciner		Wet Process	
Kiln Off-Gas CO_2 Concentration, mol %	31	25	17	13
Kiln Fuel Type	Coal/Coke	NG	Coal/Coke	NG

Note: The kiln emissions for all configurations were varied across a range of 500–1,000 ppm_v NOx and 1–500 ppm_v SOx, to evaluate the cost impact of different levels of CO_2 capture island gas pretreatment

The kiln off-gas is first treated in the FGD and SCR systems for SOx and NOx removal, respectively. The post-FGD and SCR stream and boiler flue gas are combined and sent to the CANSOLV® separation unit. The high-purity CO_2 stream is then compressed, dehydrated, and cooled for pipeline transport. Water and solids recovered from the CANSOLV® and compression systems are sent to waste treatment. Exhibit 6-2 shows a simplified block flow diagram for this process, and Exhibit 6-3 shows for illustrative purposes the simplified stream table for this process for case CM95-B-S, with a kiln off-gas SOx content of 300 ppm_v and NOx content of 1,000 ppm_v. Energy and mass balance diagrams and stream tables for select sensitivity cases are provided in Appendix A: Energy and Mass Balances.

Exhibit 6-2. Simplified block flow diagram for sensitivity cases with FGD and SCR

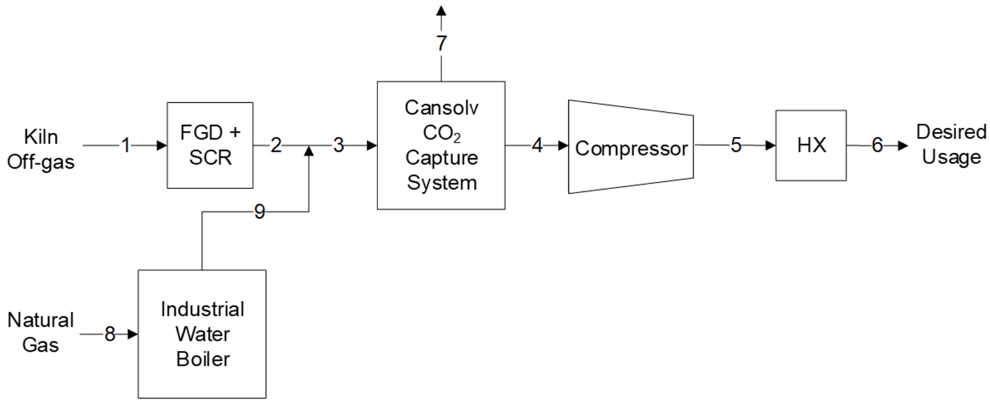


Exhibit 6-3. Simplified stream table for case CM95-B-S, with kiln off-gas SOx content: 300 ppm$_v$ and NOx content: 1,000 ppm$_v$

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0040	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3106	0.2921	0.1944	0.9821	0.9995	0.9995	0.0137	0.0100	0.0869
H_2O	0.0501	0.1070	0.1398	0.0179	0.0005	0.0005	0.0487	0.0000	0.1758
N_2	0.6109	0.5745	0.6383	0.0000	0.0000	0.0000	0.8988	0.0160	0.7083
O_2	0.0281	0.0264	0.0236	0.0000	0.0000	0.0000	0.0332	0.0000	0.0205
SO_2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,867	10,492	20,040	3,767	3,701	3,701	14,232	794	9,548
V-L Flowrate (kg/hr)	321,712	332,843	598,539	164,051	162,840	162,840	397,714	13,756	265,696
Temperature (°C)	160	70	105	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)^A	235.40	235.19	339.17	44.17	-78.54	-231.09	124.95	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)^B	-3,987.22	-4,393.77	-3,608.26	-8,971.41	-9,042.09	-9,194.65	-600.62	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	1.1	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.604	31.722	29.867	43.544	43.997	43.997	27.946	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,754	23,132	44,180	8,306	8,160	8,160	31,375	1,750	21,049
V-L Flowrate (lb/hr)	709,253	733,793	1,319,552	361,670	359,000	359,000	876,810	30,326	585,759
Temperature (°F)	320	158	220	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)^A	101.2	101.1	145.8	19.0	-33.8	-99.4	53.7	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)^B	-1,714.2	-1,889.0	-1,551.3	-3,857.0	-3,887.4	-3,953.0	-258.2	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.067	0.057	0.216	26.998	39.338	0.069	0.044	0.051

^{A}Steam table reference conditions are 32.02°F & 0.089 psia
^{B}Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

6.1 Case CM95-B-S

6.1.1 Performance Results

Case CM95-B-S represents a PH/PC kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. The plant was evaluated with kiln off-gas SOx concentrations of 100, 300, and 500 ppm_v and NOx concentrations of 500, 1,000, and 1,500 ppm_v at each SOx concentration point. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream of the industrial boiler flue gas and the cement kiln off-gas, after the FGD and SCR processes. The performance summary for sensitivity case CM95-B-S is provided in Exhibit 6-4, while the emissions summary and auxiliary load summary are shown in Exhibit 6-5 and Exhibit 6-6, respectively.

Exhibit 6-4. CM95-B-S performance summary

Performance Summary	
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	618 (586)
Natural Gas Feed Flow, kg/hr (lb/hr)	13,756 (30,326)
HHV Thermal Input, kWt	199,818
LHV Thermal Input, kWt	180,356
Raw Water Withdrawal, m^3/min (gpm)	5.6 (1,481)
Raw Water Consumption, m^3/min (gpm)	3.7 (989)

Exhibit 6-5. CM95-B-S emissions summary

Emission	tonne/yr (ton/year)[A]	kg/$tonne_{clinker}$ (lb/$ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	184 (203)	0.158 (0.316)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	64,099 (70,657)	55 (110)
CO_2[B]	–	50 (101)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis (assuming 91.4 percent clinker basis)

Exhibit 6-6. CM95-B-S auxiliary load summary

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Auxiliary Load Summary									
Ash Handling, kWe	4			13			21		
Baghouse, kWe	1			2			3		
Circulating Water Pumps, kWe	1,390								
Cooling Tower Fans, kWe	730								
CO_2 Capture Auxiliaries, kWe	6,300								
CO_2 Compression, kWe	12,480								
Feedwater Pumps, kWe	60								
Forced Draft Fans, kWe	480								
Ground Water Pumps, kWe	130								
Flue Gas Desulfurizer, kWe	40			110			190		
Miscellaneous Balance of Plant[A], kWe	430						440		
SCR, kWe	7	15	22	7	15	22	7	15	22
Transformer Losses, kWe	140								
Total Auxiliaries, MWe	**22**								

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

6.1.2 Economic Analysis Results

The economic results for case CM95-B-S with a kiln off-gas SOx content of 300 ppm$_v$ and NOx content of 1,000 ppm$_v$ are provided for illustrative purposes. Owner's costs (Exhibit 6-7), capital costs (Exhibit 6-8), and O&M costs (Exhibit 6-9) for case CM95-B-S are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 6-10 shows the resulting COC for each combination of SOx and NOx concentrations for case CM95-B-S.

Exhibit 6-7. Owners' costs for case CM95-B-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,027	$2
1-Month Maintenance Materials	$555	$0
1-Month Non-Fuel Consumables	$870	$1
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$11,800	$8
Total	**$16,258**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,596	$1
0.5% of TPC (spare parts)	$2,950	$2
Total	**$4,546**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$144	$0
Land	$0	$0
Other Owner's Costs	$88,499	$62
Financing Costs	$15,930	$11
TOC	**$715,371**	**$501**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$799,801**	**$561**

Exhibit 6-8. Capital costs for case CM95-B-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

	Case:	CM95-B-S300N1000							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3					Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,018	$1,745	$873	$0	$3,636	$636	$0	$854	$5,127	$4
3.2	Water Makeup & Pretreating	$2,726	$273	$1,545	$0	$4,544	$795	$0	$1,068	$6,407	$4
3.3	Other Feedwater Subsystems	$494	$162	$154	$0	$809	$142	$0	$190	$1,141	$1
3.4	Industrial Boiler Package w/Deaerator	$6,581	$0	$1,913	$0	$8,494	$1,486	$0	$1,996	$11,976	$8
3.5	Other Boiler Plant Systems	$119	$43	$108	$0	$271	$47	$0	$64	$382	$0
3.6	NG Pipeline and Start-Up System	$1,023	$44	$33	$0	$1,100	$192	$0	$258	$1,551	$1
3.7	Waste Water Treatment Equipment	$5,582	$0	$3,421	$0	$9,003	$1,576	$0	$2,116	$12,694	$9
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$17,684**	**$2,286**	**$8,119**	**$0**	**$28,089**	**$4,915**	**$0**	**$6,601**	**$39,605**	**$28**
	5					Flue Gas Cleanup					
5.1	CANSOLV® CO_2 Capture System	$88,864	$39,064	$82,035	$0	$209,963	$36,743	$35,694	$56,480	$338,880	$238
5.2	FGD & Accessories	$14,359	$0	$3,070	$0	$17,429	$3,050	$0	$4,096	$24,575	$17
5.3	Other FGD	$184	$0	$207	$0	$390	$68	$0	$92	$551	$0
5.4	CO_2 Compression & Drying	$25,258	$3,789	$8,445	$0	$37,492	$6,561	$0	$8,811	$52,863	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$9,187	$0	$5,246	$0	$14,433	$2,526	$0	$3,392	$20,350	$14
5.12	Gas Cleanup Foundations	$0	$101	$89	$0	$190	$33	$0	$45	$268	$0
	Subtotal	**$138,061**	**$42,987**	**$99,181**	**$0**	**$280,229**	**$49,040**	**$35,694**	**$72,993**	**$437,956**	**$307**
	7					Ductwork & Stack					
7.3	Ductwork	$0	$2,457	$1,708	$0	$4,165	$729	$0	$979	$5,873	$4
7.4	Stack	$10,396	$0	$6,041	$0	$16,438	$2,877	$0	$3,863	$23,177	$16
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,396**	**$2,690**	**$8,024**	**$0**	**$21,110**	**$3,694**	**$0**	**$4,961**	**$29,766**	**$21**
	9					Cooling Water System					
9.1	Cooling Towers	$2,355	$0	$728	$0	$3,084	$540	$0	$725	$4,348	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$266	$47	$0	$63	$375	$0
9.3	Circulating Water System Aux.	$3,006	$0	$398	$0	$3,404	$596	$0	$800	$4,800	$3
9.4	Circulating Water Piping	$0	$1,390	$1,259	$0	$2,649	$464	$0	$623	$3,735	$3
9.5	Make-up Water System	$315	$0	$404	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$151	$251	$0	$403	$71	$0	$95	$568	$0
	Subtotal	**$6,142**	**$1,542**	**$3,225**	**$0**	**$10,908**	**$1,909**	**$0**	**$2,563**	**$15,380**	**$11**
	11					Accessory Electric Plant					
11.2	Station Service Equipment	$4,051	$0	$348	$0	$4,399	$770	$0	$1,034	$6,203	$4
11.3	Switchgear & Motor Control	$6,289	$0	$1,091	$0	$7,381	$1,292	$0	$1,734	$10,407	$7
11.4	Conduit & Cable Tray	$0	$818	$2,356	$0	$3,174	$555	$0	$746	$4,475	$3
11.5	Wire & Cable	$0	$2,165	$3,870	$0	$6,036	$1,056	$0	$1,418	$8,510	$6
	Subtotal	**$10,341**	**$2,983**	**$7,665**	**$0**	**$20,989**	**$3,673**	**$0**	**$4,932**	**$29,594**	**$21**
	12					Instrumentation & Control					
12.8	Instrument Wiring & Tubing	$555	$444	$1,778	$0	$2,777	$486	$0	$653	$3,916	$3
12.9	Other I&C Equipment	$683	$0	$1,581	$0	$2,264	$396	$0	$532	$3,192	$2
	Subtotal	**$1,238**	**$444**	**$3,359**	**$0**	**$5,041**	**$882**	**$0**	**$1,185**	**$7,108**	**$5**
	13					Improvements to Site					
13.1	Site Preparation	$0	$38	$759	$0	$797	$139	$0	$187	$1,124	$1
13.2	Site Improvements	$0	$177	$235	$0	$412	$72	$0	$97	$580	$0
13.3	Site Facilities	$202	$0	$213	$0	$415	$73	$0	$98	$585	$0
	Subtotal	**$202**	**$215**	**$1,207**	**$0**	**$1,624**	**$284**	**$0**	**$382**	**$2,289**	**$2**
	14					Buildings & Structures					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$200	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$200**	**$0**
	Total	**$184,065**	**$53,225**	**$130,842**	**$0**	**$368,132**	**$64,423**	**$35,694**	**$93,650**	**$561,899**	**$394**
					Retrofit Values	**$386,539**	**$67,644**	**$37,478**	**$98,332**	**$589,994**	**$414**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 6-9. Initial & annual O&M costs for case CM95-B-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Case:	CM95-B-S300N1000				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operating (%):	85
Operating & Maintenance Labor						
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):		40.72	$/hour	Skilled Operator:		0.0
Operating Labor Burden:		30.00	% of base	Operator:		2.3
Labor O-H Charge Rate:		25.00	% of labor	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	$/(tonne CO_2/year)
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$3,775,958	$3.11
Administrative & Support Labor:					$1,210,646	$1.00
Property Taxes and Insurance:					$11,799,870	$9.73
Total:					**$17,853,099**	**$14.72**
Variable Operating Costs						
					($)	$/(tonne CO_2/year)
Maintenance Material:					$5,663,938	$4.67
Consumables						
	Initial Fill	Per Day	Per Unit	Initial Fill		
Water (/1,000 gal):	0	1,067	$2.24	$0	$739,887	$0.61
Makeup and Waste Water Treatment Chemicals (ton):	0	3.2	$647.04	$0	$638,005	$0.53
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,024	$3.30
Triethylene Glycol (gal):	w/equip.	286	$8.00	$0	$710,707	$0.59
Lime (ton):	0	6	$188.23	$0	$332,346	$0.27
Ammonia (19 wt%, ton):	0	22.2	$352.93	$0	$2,428,289	$2.00
SCR Catalyst (ft^3):	818	0.4	$176.46	$144,326	$24,535	$0.02
Subtotal:				**$144,326**	**$8,878,793**	**$7.32**
						Waste Disposal
SCR Catalyst (ft^3):		0	$2.94		$64	$0.00
Triethylene Glycol (gal):		286	$0.41		$36,581	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70		$23,426	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70		$426	$0.00
Subtotal:					**$60,497**	**$0.05**
Variable Operating Costs Total:				**$144,326**	**$14,603,228**	**$12.04**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,363	$4.61	$0	$23,409,294	$19.31
Purchased Power (MWh):	0	22	$67.28	$0	$11,161,337	$9.21
Total:				**$0**	**$34,570,631**	**$28.51**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

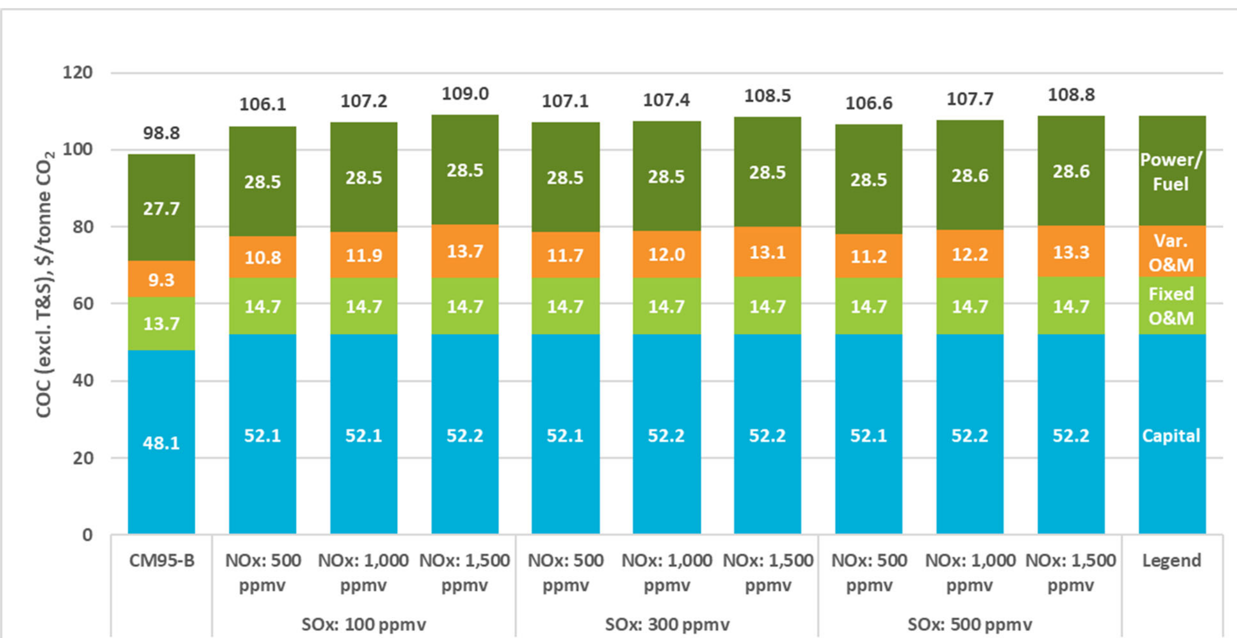
Exhibit 6-10. COC for case CM95-B-S, \$/tonne CO_2

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Capital	52.1	52.1	52.2	52.1	52.2	52.2	52.1	52.2	52.2
Fixed	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
Variable	10.8	11.9	13.7	11.7	12.0	13.1	11.2	12.2	13.3
Purchased Power and Fuel	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.6	28.6
Total COC (excl. T&S)	**106.1**	**107.2**	**109.0**	**107.1**	**107.4**	**108.5**	**106.6**	**107.7**	**108.8**
Total COC (incl. T&S)	**116.1**	**117.2**	**119.0**	**117.1**	**117.4**	**118.5**	**116.6**	**117.7**	**118.8**

Note: The SOx and NOx values shown are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

The addition of FGD and SCR results in a COC that is 7.4–10.3 percent higher than the base case CM95-B. The cost components most affected are the capital and variable O&M components, as additional equipment and consumables are required for FGD and SCR operation. The comparison of the CM95-B-S case at each combination of SOx and NOx concentrations with base case CM95-B is presented in Exhibit 6-11.

Exhibit 6-11. COC comparison of sensitivity case CM95-B-S and base case CM95-B



Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

6.2 CASE CM95-B1-S

6.2.1 Performance Results

Case CM95-B1-S represents a PH/PC kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. The plant was evaluated with kiln off-gas SOx concentrations of 100, 300, and 500 ppm_v and NOx concentrations of 500, 1,000, and 1,500 ppm_v at each SOx concentration point. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream of the industrial boiler flue gas and the cement kiln off-gas, after the FGD and SCR processes. The performance summary for sensitivity case CM95-B1-S is provided in Exhibit 6-12, while the emissions summary and auxiliary load summary are shown in Exhibit 6-13 and Exhibit 6-14, respectively.

Exhibit 6-12. CM95-B1-S performance summary

Performance Summary	
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	602 (571)
Natural Gas Feed Flow, kg/hr (lb/hr)	13,235 (29,179)
HHV Thermal Input, kWt	192,260
LHV Thermal Input, kWt	173,533
Raw Water Withdrawal, m^3/min (gpm)	5.5 (1,451)
Raw Water Consumption, m^3/min (gpm)	3.4 (888)

Exhibit 6-13. CM95-B1-S emissions summary

Emission	tonne/yr (ton/year)^A	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	202 (223)	0.174 (0.348)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	63,582 (70,088)	55 (109)
CO_2^{B}	–	50 (100)

^{A}Calculations based on an 85 percent operating basis
^{B}CO_2 emissions based on cement basis instead of clinker basis (assuming 91.4 percent clinker basis)

Exhibit 6-14. CM95-B1-S auxiliary load summary

SOx Concentration	100 ppm_v			300 ppm_v			500 ppm_v		
NOx Concentration	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v
Auxiliary Load Summary									
Ash Handling, kWe	5			15			26		
Baghouse, kWe	1			3			4		
Circulating Water Pumps, kWe	1,360								
Cooling Tower Fans, kWe	710								
CO_2 Capture Auxiliaries, kWe	6,600								
CO_2 Compression, kWe	12,380								
Feedwater Pumps, kWe	50								
Forced Draft Fans, kWe	460								
Ground Water Pumps, kWe	130								
Flue Gas Desulfurizer, kWe	50			140			230		
Miscellaneous Balance of Plant[A], kWe	440								
SCR, kWe	9	18	28	9	18	28	9	18	28
Transformer Losses, kWe	140								
Total Auxiliaries, MWe	**22**						**23**		

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

6.2.2 Economic Analysis Results

The economic results for case CM95-B1-S with a kiln off-gas SOx content of 300 ppm_v and NOx content of 1,000 ppm_v are provided for illustrative purposes. Owner's costs (Exhibit 6-15), capital costs (Exhibit 6-16), and O&M costs (Exhibit 6-17) for case CM95-B1-S are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 6-18 shows the resulting COC for each combination of SOx and NOx concentrations for case CM95-B1-S.

Exhibit 6-15. Owners' costs for case CM95-B1-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,108	$2
1-Month Maintenance Materials	$574	$0
1-Month Non-Fuel Consumables	$1,041	$1
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$12,205	$9
Total	**$16,935**	**$12**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$1,940	$1
0.5% of TPC (spare parts)	$3,051	$2
Total	**$4,991**	**$4**
Other Costs		
Initial Cost for Catalyst and Chemicals	$159	$0
Land	$0	$0
Other Owner's Costs	$91,541	$65
Financing Costs	$16,477	$12
TOC	**$740,374**	**$523**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$827,755**	**$585**

Exhibit 6-16. Capital costs for case CM95-B1-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/(tonne CO_2/year)
	Case:	CM95-B1-S300N1000							Estimate Type:	Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$991	$1,699	$850	$0	$3,540	$620	$0	$832	$4,992	$4
3.2	Water Makeup & Pretreating	$2,686	$269	$1,522	$0	$4,476	$783	$0	$1,052	$6,311	$4
3.3	Other Feedwater Subsystems	$477	$156	$149	$0	$782	$137	$0	$184	$1,103	$1
3.4	Industrial Boiler Package w/Deaerator	$6,359	$0	$1,849	$0	$8,207	$1,436	$0	$1,929	$11,572	$8
3.5	Other Boiler Plant Systems	$115	$42	$105	$0	$262	$46	$0	$62	$369	$0
3.6	NG Pipeline and Start-Up System	$1,004	$43	$32	$0	$1,079	$189	$0	$254	$1,522	$1
3.7	Waste Water Treatment Equipment	$6,138	$0	$3,762	$0	$9,900	$1,733	$0	$2,327	$13,960	$10
3.9	Miscellaneous Plant Equipment	$140	$18	$71	$0	$229	$40	$0	$54	$324	$0
	Subtotal	**$17,910**	**$2,228**	**$8,339**	**$0**	**$28,477**	**$4,983**	**$0**	**$6,692**	**$40,153**	**$28**
5	Flue Gas Cleanup										
5.1	CANSOLV® CO_2 Capture System	$92,256	$40,555	$85,166	$0	$217,978	$38,146	$37,056	$58,636	$351,816	$249
5.2	FGD & Accessories	$16,774	$0	$3,586	$0	$20,360	$3,563	$0	$4,785	$28,707	$20
5.3	Other FGD	$215	$0	$242	$0	$456	$80	$0	$107	$643	$0
5.4	CO_2 Compression & Drying	$25,134	$3,770	$8,404	$0	$37,308	$6,529	$0	$8,767	$52,604	$37
5.5	CO_2 Compressor Aftercooler	$208	$33	$89	$0	$331	$58	$0	$78	$466	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$9,848	$0	$5,623	$0	$15,471	$2,707	$0	$3,636	$21,814	$15
5.12	Gas Cleanup Foundations	$0	$107	$94	$0	$202	$35	$0	$47	$284	$0
	Subtotal	**$144,434**	**$44,466**	**$103,205**	**$0**	**$292,105**	**$51,118**	**$37,056**	**$76,056**	**$456,336**	**$323**
7	Ductwork & Stack										
7.3	Ductwork	$0	$2,637	$1,832	$0	$4,469	$782	$0	$1,050	$6,302	$4
7.4	Stack	$10,442	$0	$6,068	$0	$16,510	$2,889	$0	$3,880	$23,279	$16
7.5	Duct & Stack Foundations	$0	$232	$275	$0	$506	$89	$0	$119	$714	$1
	Subtotal	**$10,442**	**$2,868**	**$8,175**	**$0**	**$21,486**	**$3,760**	**$0**	**$5,049**	**$30,295**	**$21**
9	Cooling Water System										
9.1	Cooling Towers	$2,311	$0	$715	$0	$3,026	$530	$0	$711	$4,267	$3
9.2	Circulating Water Pumps	$244	$0	$17	$0	$261	$46	$0	$61	$368	$0
9.3	Circulating Water System Aux.	$2,960	$0	$392	$0	$3,352	$587	$0	$788	$4,726	$3
9.4	Circulating Water Piping	$0	$1,369	$1,240	$0	$2,609	$457	$0	$613	$3,678	$3
9.5	Make-up Water System	$311	$0	$400	$0	$711	$124	$0	$167	$1,002	$1
9.6	Component Cooling Water System	$213	$0	$164	$0	$377	$66	$0	$89	$532	$0
9.7	Circulating Water System Foundations	$0	$149	$248	$0	$397	$70	$0	$93	$560	$0
	Subtotal	**$6,040**	**$1,518**	**$3,175**	**$0**	**$10,732**	**$1,878**	**$0**	**$2,522**	**$15,133**	**$11**
11	Accessory Electric Plant										
11.2	Station Service Equipment	$4,064	$0	$349	$0	$4,413	$772	$0	$1,037	$6,222	$4
11.3	Switchgear & Motor Control	$6,310	$0	$1,095	$0	$7,404	$1,296	$0	$1,740	$10,440	$7
11.4	Conduit & Cable Tray	$0	$820	$2,364	$0	$3,184	$557	$0	$748	$4,489	$3
11.5	Wire & Cable	$0	$2,172	$3,883	$0	$6,055	$1,060	$0	$1,423	$8,537	$6
	Subtotal	**$10,374**	**$2,992**	**$7,690**	**$0**	**$21,056**	**$3,685**	**$0**	**$4,948**	**$29,689**	**$21**
12	Instrumentation & Control										
12.8	Instrument Wiring & Tubing	$556	$445	$1,779	$0	$2,780	$487	$0	$653	$3,920	$3
12.9	Other I&C Equipment	$683	$0	$1,583	$0	$2,266	$397	$0	$533	$3,195	$2
	Subtotal	**$1,239**	**$445**	**$3,362**	**$0**	**$5,046**	**$883**	**$0**	**$1,186**	**$7,115**	**$5**
13	Improvements to Site										
13.1	Site Preparation	$0	$38	$761	$0	$798	$140	$0	$188	$1,126	$1
13.2	Site Improvements	$0	$177	$235	$0	$412	$72	$0	$97	$581	$0
13.3	Site Facilities	$203	$0	$213	$0	$416	$73	$0	$98	$586	$0
	Subtotal	**$203**	**$215**	**$1,208**	**$0**	**$1,626**	**$285**	**$0**	**$382**	**$2,293**	**$2**
14	Buildings & Structures										
14.5	Circulation Water Pumphouse	$0	$78	$62	$0	$140	$25	$0	$33	$198	$0
	Subtotal	**$0**	**$78**	**$62**	**$0**	**$140**	**$25**	**$0**	**$33**	**$198**	**$0**
	Total	**$190,642**	**$54,811**	**$135,215**	**$0**	**$380,669**	**$66,617**	**$37,056**	**$96,868**	**$581,210**	**$411**
					Retrofit Values	**$399,702**	**$69,948**	**$38,909**	**$101,712**	**$610,271**	**$431**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 6-17. Initial & annual O&M costs for case CM95-B1-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Case:	CM95-B1-S300N1000				Cost Base:	Nov 2022
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
			Operating & Maintenance Labor			
	Operating Labor			**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
			Fixed Operating Costs			
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.89
Maintenance Labor:					$3,905,732	$3.25
Administrative & Support Labor:					$1,243,089	$1.03
Property Taxes and Insurance:					$12,205,414	$10.15
Total:					**$18,420,860**	**$15.32**
			Variable Operating Costs			
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,858,599	$4.87
			Consumables			
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,045	$2.24	$0	$724,851	$0.60
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$625,040	$0.52
CO_2 Capture System Chemicals[A]:			Proprietary		$5,113,132	$4.25
Triethylene Glycol (gal):	w/equip.	284	$8.00	$0	$704,977	$0.59
Lime (ton):	0	7	$188.23	$0	$411,268	$0.34
Ammonia (19 wt%, ton):	0	27.5	$352.93	$0	$3,012,723	$2.50
SCR Catalyst (ft^3):	901	0.5	$176.46	$158,998	$27,030	$0.02
Subtotal:				**$158,998**	**$10,619,022**	**$8.83**
			Waste Disposal			
SCR Catalyst (ft^3):		0	$2.94		$450	$0.00
Triethylene Glycol (gal):		284	$0.41		$36,286	$0.03
Thermal Reclaimer Unit Waste (ton):		1.68	$44.70		$23,237	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70		$457	$0.00
Subtotal:					**$60,430**	**$0.05**
Variable Operating Costs Total:				**$158,998**	**$16,538,051**	**$13.75**
			Fuel and Purchased Power Costs			
Natural Gas (MMBTU):	0	15,744	$4.61	$0	$22,523,790	$18.73
Purchased Power (MWh):	0	22	$67.28	$0	$11,244,499	$9.35
Total:				**$0**	**$33,768,289**	**$28.08**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

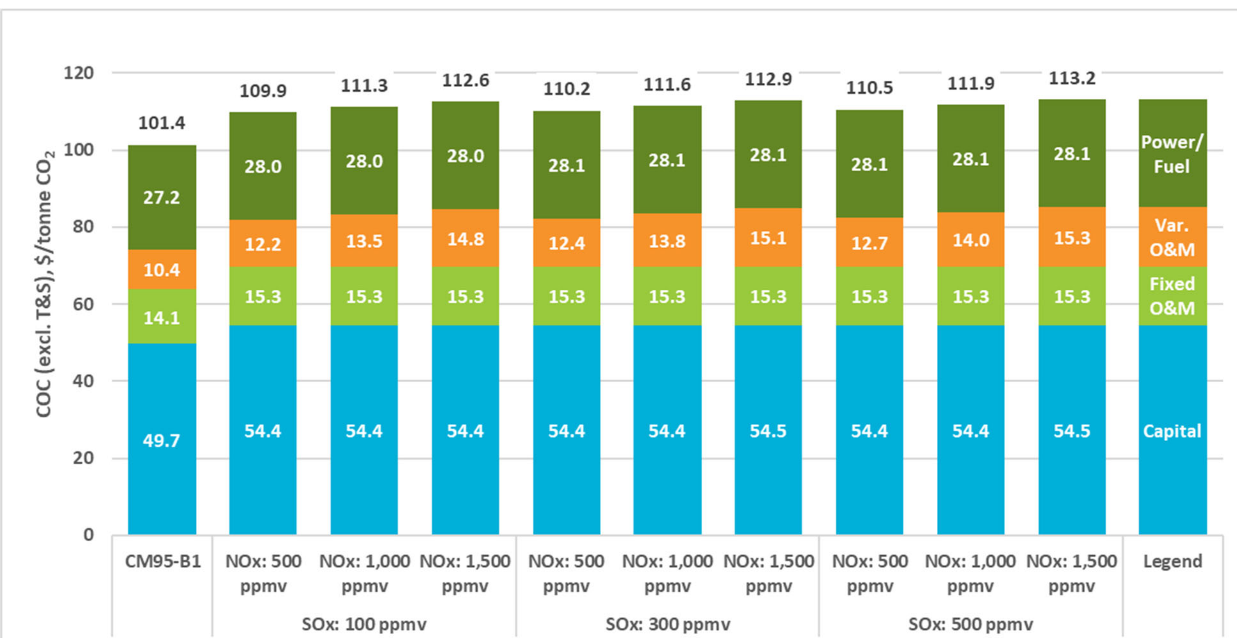
Exhibit 6-18. COC for case CM95-B1-S, $/tonne CO_2

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Capital	54.4	54.4	54.4	54.4	54.4	54.5	54.4	54.4	54.5
Fixed	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Variable	12.2	13.5	14.8	12.4	13.8	15.1	12.7	14.0	15.3
Purchased Power and Fuel	28.0	28.0	28.0	28.1	28.1	28.1	28.1	28.1	28.1
Total COC (excl. T&S)	**109.9**	**111.3**	**112.6**	**110.2**	**111.6**	**112.9**	**110.5**	**111.9**	**113.2**
Total COC (incl. T&S)	**119.9**	**121.3**	**122.6**	**120.2**	**121.6**	**122.9**	**120.5**	**121.9**	**123.2**

Note: The SOx and NOx values shown are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

The addition of FGD and SCR results in a COC that is 8.4–11.7 percent higher than the base case CM95-B1. The cost components most affected are the capital and variable O&M components, as additional equipment and consumables are required for FGD and SCR operation. The comparison of the CM95-B1-S case at each combination of SOx and NOx concentrations with base case CM95-B1 is presented in Exhibit 6-19.

Exhibit 6-19. COC comparison of sensitivity case CM95-B1-S and base case CM95-B1



Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

6.3 Case CM95-B3-S

6.3.1 Performance Results

Case CM95-B3-S represents a wet process kiln that burns coal/coke fuel to produce 1.5 M tonnes of finished cement per year. The plant was evaluated with kiln off-gas SOx concentrations of 100, 300, and 500 ppm_v and NOx concentrations of 500, 1,000, and 1,500 ppm_v at each SOx concentration point. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream of the industrial boiler flue gas and the cement kiln off-gas, after the FGD and SCR processes. The performance summary for sensitivity case CM95-B3-S is provided in Exhibit 6-20, while the emissions summary and the auxiliary load summary are shown in Exhibit 6-21 and Exhibit 6-22, respectively.

Exhibit 6-20. CM95-B3-S performance summary

Performance Summary	
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	696 (659)
Natural Gas Feed Flow, kg/hr (lb/hr)	14,932 (32,919)
HHV Thermal Input, kWt	216,904
LHV Thermal Input, kWt	195,777
Raw Water Withdrawal, m^3/min (gpm)	6.4 (1,694)
Raw Water Consumption, m^3/min (gpm)	1.9 (508)

Exhibit 6-21. CM95-B3-S emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	302 (333)	0.259 (0.519)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	75,855 (83,615)	65 (130)
CO_2[B]	–	59 (119)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis (assuming 91.4 percent clinker basis)

Exhibit 6-22. CM95-B3-S auxiliary load summary

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Auxiliary Load Summary									
Ash Handling, kWe	9			27			46		
Baghouse, kWe	2			4			7		
Circulating Water Pumps, kWe	1,570								
Cooling Tower Fans, kWe	830								
CO_2 Capture Auxiliaries, kWe	8,900								
CO_2 Compression, kWe	14,770								
Feedwater Pumps, kWe	60								
Forced Draft Fans, kWe	520								
Ground Water Pumps, kWe	150								
Flue Gas Desulfurizer, kWe	80			250			410		
Miscellaneous Balance of Plant[A], kWe	540						550		
SCR, kWe	15	32	49	15	32	49	15	32	49
Transformer Losses, kWe	170								
Total Auxiliaries, MWe	**28**								

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

6.3.2 Economic Analysis Results

The economic results for case CM95-B3-S with a kiln off-gas SOx content of 300 ppm$_v$ and NOx content of 1,000 ppm$_v$ are provided for illustrative purposes. Owner's costs (Exhibit 6-23), capital costs (Exhibit 6-24), and O&M costs (Exhibit 6-25) for case CM95-B3-S are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 6-26 shows the resulting COC for each combination of SOx and NOx concentrations for case CM95-B3-S.

Exhibit 6-23. Owners' costs for case CM95-B3-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,601	$2
1-Month Maintenance Materials	$690	$0
1-Month Non-Fuel Consumables	$1,530	$1
1-Month Waste Disposal	$7	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$14,671	$9
Total	**$20,499**	**$12**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$2,893	$2
0.5% of TPC (spare parts)	$3,668	$2
Total	**$6,561**	**$4**
Other Costs		
Initial Cost for Catalyst and Chemicals	$237	$0
Land	$0	$0
Other Owner's Costs	$110,030	$65
Financing Costs	$19,805	$12
TOC	**$890,669**	**$528**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$995,789**	**$590**

Exhibit 6-24. Capital costs for case CM95-B3-S, with kiln off-gas SOx content: 300 ppm_v & NOx content: 1,000 ppm_v

	Case:	CM95-B3-S300N1000							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3	Feedwater & Miscellaneous BOP Systems									
3.1	Feedwater System	$1,077	$1,847	$923	$0	$3,848	$673	$0	$904	$5,425	$3
3.2	Water Makeup & Pretreating	$3,008	$301	$1,705	$0	$5,014	$877	$0	$1,178	$7,069	$4
3.3	Other Feedwater Subsystems	$531	$174	$165	$0	$871	$152	$0	$205	$1,228	$1
3.4	Industrial Boiler Package w/Deaerator	$7,079	$0	$2,058	$0	$9,137	$1,599	$0	$2,147	$12,884	$8
3.5	Other Boiler Plant Systems	$128	$47	$117	$0	$292	$51	$0	$69	$412	$0
3.6	NG Pipeline and Start-Up System	$1,065	$46	$34	$0	$1,145	$200	$0	$269	$1,614	$1
3.7	Waste Water Treatment Equipment	$10,436	$0	$6,396	$0	$16,833	$2,946	$0	$3,956	$23,734	$14
3.9	Miscellaneous Plant Equipment	$144	$19	$73	$0	$236	$41	$0	$56	$333	$0
	Subtotal	**$23,470**	**$2,433**	**$11,473**	**$0**	**$37,375**	**$6,541**	**$0**	**$8,783**	**$52,699**	**$31**
	5	Flue Gas Cleanup									
5.1	CANSOLV® CO_2 Capture System	$110,385	$48,525	$101,902	$0	$260,811	$45,642	$44,338	$70,158	$420,949	$249
5.2	FGD & Accessories	$25,453	$0	$5,442	$0	$30,895	$5,407	$0	$7,260	$43,562	$26
5.3	Other FGD	$326	$0	$366	$0	$692	$121	$0	$163	$976	$1
5.4	CO_2 Compression & Drying	$27,992	$4,199	$9,359	$0	$41,549	$7,271	$0	$9,764	$58,585	$35
5.5	CO_2 Compressor Aftercooler	$241	$38	$103	$0	$383	$67	$0	$90	$540	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$13,121	$0	$7,492	$0	$20,613	$3,607	$0	$4,844	$29,064	$17
5.12	Gas Cleanup Foundations	$0	$138	$121	$0	$259	$45	$0	$61	$365	$0
	Subtotal	**$177,516**	**$52,900**	**$124,786**	**$0**	**$355,202**	**$62,160**	**$44,338**	**$92,340**	**$554,040**	**$328**
	7	Ductwork & Stack									
7.3	Ductwork	$0	$3,528	$2,452	$0	$5,980	$1,046	$0	$1,405	$8,431	$5
7.4	Stack	$10,552	$0	$6,132	$0	$16,684	$2,920	$0	$3,921	$23,525	$14
7.5	Duct & Stack Foundations	$0	$233	$277	$0	$510	$89	$0	$120	$719	$0
	Subtotal	**$10,552**	**$3,761**	**$8,860**	**$0**	**$23,174**	**$4,055**	**$0**	**$5,446**	**$32,675**	**$19**
	9	Cooling Water System									
9.1	Cooling Towers	$2,592	$0	$802	$0	$3,393	$594	$0	$797	$4,784	$3
9.2	Circulating Water Pumps	$277	$0	$20	$0	$296	$52	$0	$70	$418	$0
9.3	Circulating Water System Aux.	$3,251	$0	$430	$0	$3,681	$644	$0	$865	$5,190	$3
9.4	Circulating Water Piping	$0	$1,503	$1,361	$0	$2,865	$501	$0	$673	$4,039	$2
9.5	Make-up Water System	$335	$0	$430	$0	$764	$134	$0	$180	$1,078	$1
9.6	Component Cooling Water System	$234	$0	$180	$0	$414	$72	$0	$97	$584	$0
9.7	Circulating Water System Foundations	$0	$163	$270	$0	$433	$76	$0	$102	$611	$0
	Subtotal	**$6,688**	**$1,666**	**$3,492**	**$0**	**$11,847**	**$2,073**	**$0**	**$2,784**	**$16,704**	**$10**
	11	Accessory Electric Plant									
11.2	Station Service Equipment	$4,458	$0	$382	$0	$4,840	$847	$0	$1,137	$6,825	$4
11.3	Switchgear & Motor Control	$6,920	$0	$1,201	$0	$8,121	$1,421	$0	$1,908	$11,450	$7
11.4	Conduit & Cable Tray	$0	$900	$2,592	$0	$3,492	$611	$0	$821	$4,924	$3
11.5	Wire & Cable	$0	$2,382	$4,258	$0	$6,641	$1,162	$0	$1,561	$9,363	$6
	Subtotal	**$11,378**	**$3,282**	**$8,434**	**$0**	**$23,093**	**$4,041**	**$0**	**$5,427**	**$32,562**	**$19**
	12	Instrumentation & Control									
12.8	Instrument Wiring & Tubing	$572	$457	$1,830	$0	$2,859	$500	$0	$672	$4,031	$2
12.9	Other I&C Equipment	$703	$0	$1,627	$0	$2,330	$408	$0	$548	$3,286	$2
	Subtotal	**$1,275**	**$457**	**$3,457**	**$0**	**$5,189**	**$908**	**$0**	**$1,219**	**$7,316**	**$4**
	13	Improvements to Site									
13.1	Site Preparation	$0	$39	$794	$0	$833	$146	$0	$196	$1,175	$1
13.2	Site Improvements	$0	$185	$245	$0	$430	$75	$0	$101	$607	$0
13.3	Site Facilities	$212	$0	$222	$0	$434	$76	$0	$102	$612	$0
	Subtotal	**$212**	**$224**	**$1,261**	**$0**	**$1,697**	**$297**	**$0**	**$399**	**$2,393**	**$1**
	14	Buildings & Structures									
14.5	Circulation Water Pumphouse	$0	$85	$68	$0	$153	$27	$0	$36	$216	$0
	Subtotal	**$0**	**$85**	**$68**	**$0**	**$153**	**$27**	**$0**	**$36**	**$216**	**$0**
	Total	**$231,091**	**$64,809**	**$161,831**	**$0**	**$457,731**	**$80,103**	**$44,338**	**$116,434**	**$698,606**	**$414**
					Retrofit Values	$480,617	$84,108	$46,555	$122,256	$733,536	$435

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 6-25. Initial & annual O&M costs for case CM95-B3-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Case:	**CM95-B3-S300N1000**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operating (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.74
Maintenance Labor:					$4,694,630	$3.27
Administrative & Support Labor:					$1,440,314	$1.00
Property Taxes and Insurance:					$14,670,720	$10.22
Total:					**$21,872,289**	**$15.24**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$7,041,946	$4.91
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,221	$2.24	$0	$846,673	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.6	$647.04	$0	$730,087	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary				$7,058,813	$4.92
Triethylene Glycol (gal):	w/equip.	339	$8.00	$0	$841,045	$0.59
Lime (ton):	0	12	$188.23	$0	$728,821	$0.51
Ammonia (19 wt%, ton):	0	48.9	$352.93	$0	$5,357,160	$3.73
SCR Catalyst (ft^3):	1,344	0.7	$176.46	$237,174	$40,320	$0.03
Subtotal:				**$237,174**	**$15,602,918**	**$10.87**
Waste Disposal						
SCR Catalyst (ft^3):		1	$2.94		$672	$0.00
Triethylene Glycol (gal):		339	$0.41		$43,289	$0.03
Thermal Reclaimer Unit Waste (ton):		2.00	$44.70		$27,723	$0.02
Pre-scrubber Blowdown Waste (ton):		0.04	$44.70		$593	$0.00
Subtotal:					**$72,277**	**$0.05**
Variable Operating Costs Total:				**$237,174**	**$22,717,140**	**$15.83**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	17,763	$4.61	$0	$25,410,932	$17.71
Purchased Power (MWh):	0	28	$67.28	$0	$13,938,720	$9.71
Total:				**$0**	**$39,349,652**	**$27.42**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

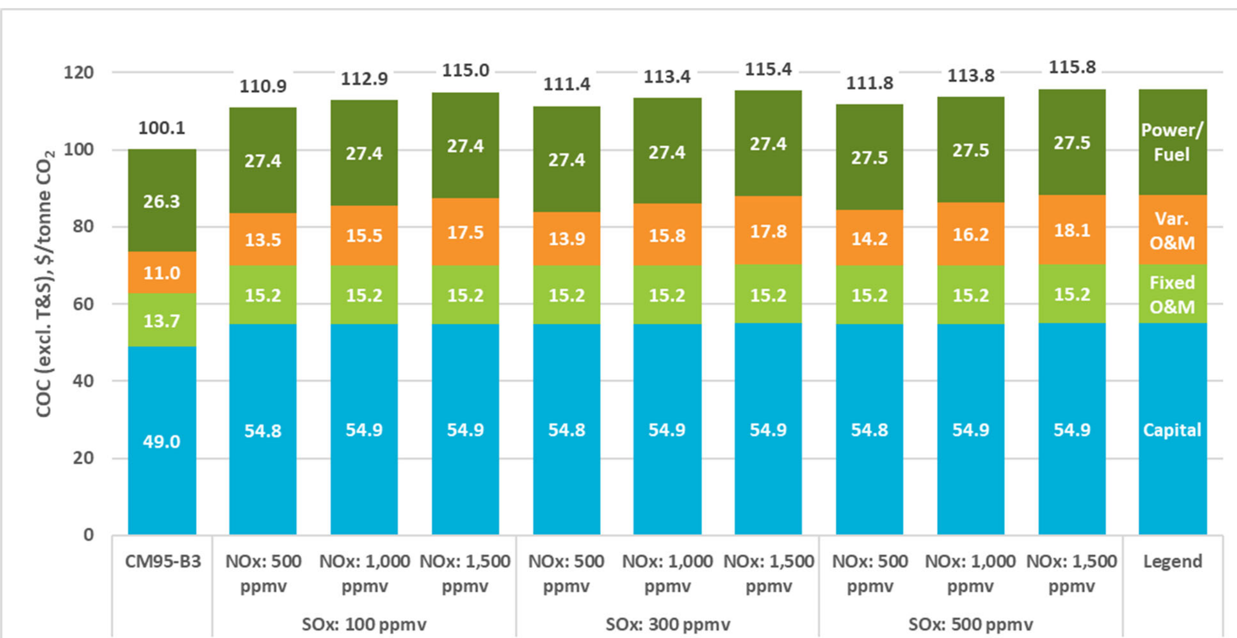
Exhibit 6-26. COC for case CM95-B3-S, $/tonne CO_2

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Capital	54.8	54.9	54.9	54.8	54.9	54.9	54.8	54.9	54.9
Fixed	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
Variable	13.5	15.5	17.5	13.9	15.8	17.8	14.2	16.2	18.1
Purchased Power and Fuel	27.4	27.4	27.4	27.4	27.4	27.4	27.5	27.5	27.5
Total COC (excl. T&S)	**110.9**	**112.9**	**115.0**	**111.4**	**113.4**	**115.4**	**111.8**	**113.8**	**115.8**
Total COC (incl. T&S)	**120.9**	**122.9**	**125.0**	**121.4**	**123.4**	**125.4**	**121.8**	**123.8**	**125.8**

Note: The SOx and NOx values shown are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

The addition of FGD and SCR results in a COC that is 10.8–15.7 percent higher than the base case CM95-B3. The cost components most affected are the capital and variable O&M components, as additional equipment and consumables are required for FGD and SCR operation. The comparison of the CM95-B3-S case at each combination of SOx and NOx concentrations with base case CM95-B3 is presented in Exhibit 6-27.

Exhibit 6-27. COC comparison of sensitivity case CM95-B3-S and base case CM95-B3



Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

6.4 Case CM95-B4-S

6.4.1 Performance Results

Case CM95-B4-S represents a wet process kiln that burns NG fuel to produce 1.5 M tonnes of finished cement per year. The plant was evaluated with kiln off-gas SOx concentrations of 100, 300, and 500 ppm_v and NOx concentrations of 500, 1,000, and 1,500 ppm_v at each SOx concentration point. The CANSOLV® unit captures and purifies 95 percent of the CO_2 in the combined emissions stream of the industrial boiler flue gas and the cement kiln off-gas, after the FGD and SCR processes. The performance summary for sensitivity case CM95-B4-S is provided in Exhibit 6-28, while the emissions summary and the auxiliary load summary are shown in Exhibit 6-29 and Exhibit 6-30, respectively.

Exhibit 6-28. CM95-B4-S performance summary

Performance Summary	
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	672 (637)
Natural Gas Feed Flow, kg/hr (lb/hr)	14,252 (31,420)
HHV Thermal Input, kWt	207,029
LHV Thermal Input, kWt	186,864
Raw Water Withdrawal, m^3/min (gpm)	6.3 (1,661)
Raw Water Consumption, m^3/min (gpm)	0.6 (164)

Exhibit 6-29. CM95-B4-S emissions summary

Emission	tonne/yr (ton/year)[A]	$kg/tonne_{clinker}$ ($lb/ton_{clinker}$)
SO_2	0 (0)	0.000 (0.000)
NOx	302 (333)	0.259 (0.518)
PM	<49 (<54)	<0.035 (<0.070)
CO_2	75,855 (83,615)	65 (130)
CO_2[B]	–	59 (119)

[A]Calculations based on an 85 percent operating basis
[B]CO_2 emissions based on cement basis instead of clinker basis (assuming 91.4 percent clinker basis)

Exhibit 6-30. CM95-B4-S auxiliary load summary

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Auxiliary Load Summary									
Ash Handling, kWe	12			36			59		
Baghouse, kWe	2			6			10		
Circulating Water Pumps, kWe	1,520								
Cooling Tower Fans, kWe	800								
CO_2 Capture Auxiliaries, kWe	9,600								
CO_2 Compression, kWe	14,640								
Feedwater Pumps, kWe	60								
Forced Draft Fans, kWe	500								
Ground Water Pumps, kWe	150								
Flue Gas Desulfurizer, kWe	110			320			540		
Miscellaneous Balance of Plant[A], kWe	550								560
SCR, kWe	20	42	64	20	42	64	20	42	64
Transformer Losses, kWe	180								
Total Auxiliaries, MWe	**28**								**29**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

6.4.2 Economic Analysis Results

The economic results for case CM95-B4-S with a kiln off-gas SOx content of 300 ppm$_v$ and NOx content of 1,000 ppm$_v$ are provided for illustrative purposes. Owner's costs (Exhibit 6-31), capital costs (Exhibit 6-32), and O&M costs (Exhibit 6-33) for case CM95-B4-S are calculated as discussed in Section 2.1. Retrofit costs are estimated by applying a retrofit factor to TPC, discussed in Section 2.3. Exhibit 6-34 shows the resulting COC for each combination of SOx and NOx concentrations for case CM95-B4-S.

Exhibit 6-31. Owners' costs for case CM95-B4-S, with kiln off-gas SOx content: 300 ppm_v & NOx content: 1,000 ppm_v

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,778	$2
1-Month Maintenance Materials	$732	$0
1-Month Non-Fuel Consumables	$1,833	$1
1-Month Waste Disposal	$7	$0
25% of 1-Month Fuel Cost at 100% Operating Basis	$0	$0
2% of TPC	$15,559	$9
Total	**$21,909**	**$13**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% Operating Basis	$3,504	$2
0.5% of TPC (spare parts)	$3,890	$2
Total	**$7,393**	**$4**
Other Costs		
Initial Cost for Catalyst and Chemicals	$283	$0
Land	$0	$0
Other Owner's Costs	$116,689	$70
Financing Costs	$21,004	$13
TOC	**$945,209**	**$565**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$1,056,765**	**$632**

Exhibit 6-32. Capital costs for case CM95-B4-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

	Case:	CM95-B4-S300N1000							Estimate Type:	Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
	3						Feedwater & Miscellaneous BOP Systems				
3.1	Feedwater System	$1,043	$1,788	$894	$0	$3,726	$652	$0	$876	$5,254	$3
3.2	Water Makeup & Pretreating	$2,966	$297	$1,681	$0	$4,943	$865	$0	$1,162	$6,970	$4
3.3	Other Feedwater Subsystems	$510	$167	$159	$0	$835	$146	$0	$196	$1,178	$1
3.4	Industrial Boiler Package w/Deaerator	$6,792	$0	$1,975	$0	$8,766	$1,534	$0	$2,060	$12,360	$7
3.5	Other Boiler Plant Systems	$123	$45	$112	$0	$280	$49	$0	$66	$395	$0
3.6	NG Pipeline and Start-Up System	$1,041	$45	$34	$0	$1,119	$196	$0	$263	$1,578	$1
3.7	Waste Water Treatment Equipment	$12,317	$0	$7,549	$0	$19,866	$3,476	$0	$4,668	$28,010	$17
3.9	Miscellaneous Plant Equipment	$143	$19	$72	$0	$234	$41	$0	$55	$330	$0
	Subtotal	**$24,934**	**$2,360**	**$12,475**	**$0**	**$39,769**	**$6,960**	**$0**	**$9,346**	**$56,074**	**$34**
	5						Flue Gas Cleanup				
5.1	CANSOLV® CO_2 Capture System	$116,846	$51,365	$107,867	$0	$276,077	$48,314	$46,933	$74,265	$445,589	$266
5.2	FGD & Accessories	$30,932	$0	$6,614	$0	$37,546	$6,571	$0	$8,823	$52,939	$32
5.3	Other FGD	$396	$0	$445	$0	$841	$147	$0	$198	$1,186	$1
5.4	CO_2 Compression & Drying	$27,841	$4,176	$9,309	$0	$41,326	$7,232	$0	$9,712	$58,270	$35
5.5	CO_2 Compressor Aftercooler	$239	$38	$103	$0	$380	$67	$0	$89	$536	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$14,801	$0	$8,452	$0	$23,253	$4,069	$0	$5,464	$32,786	$20
5.12	Gas Cleanup Foundations	$0	$153	$134	$0	$287	$50	$0	$68	$405	$0
	Subtotal	**$191,055**	**$55,732**	**$132,923**	**$0**	**$379,710**	**$66,449**	**$46,933**	**$98,619**	**$591,711**	**$354**
	7						Ductwork & Stack				
7.3	Ductwork	$0	$3,987	$2,770	$0	$6,757	$1,182	$0	$1,588	$9,527	$6
7.4	Stack	$10,630	$0	$6,177	$0	$16,806	$2,941	$0	$3,949	$23,697	$14
7.5	Duct & Stack Foundations	$0	$233	$276	$0	$509	$89	$0	$120	$717	$0
	Subtotal	**$10,630**	**$4,219**	**$9,223**	**$0**	**$24,072**	**$4,213**	**$0**	**$5,657**	**$33,942**	**$20**
	9						Cooling Water System				
9.1	Cooling Towers	$2,529	$0	$782	$0	$3,311	$579	$0	$778	$4,669	$3
9.2	Circulating Water Pumps	$269	$0	$19	$0	$288	$50	$0	$68	$407	$0
9.3	Circulating Water System Aux.	$3,187	$0	$422	$0	$3,608	$631	$0	$848	$5,087	$3
9.4	Circulating Water Piping	$0	$1,474	$1,334	$0	$2,808	$491	$0	$660	$3,959	$2
9.5	Make-up Water System	$329	$0	$423	$0	$752	$132	$0	$177	$1,061	$1
9.6	Component Cooling Water System	$230	$0	$176	$0	$406	$71	$0	$95	$572	$0
9.7	Circulating Water System Foundations	$0	$160	$265	$0	$425	$74	$0	$100	$599	$0
	Subtotal	**$6,544**	**$1,633**	**$3,422**	**$0**	**$11,599**	**$2,030**	**$0**	**$2,726**	**$16,354**	**$10**
	11						Accessory Electric Plant				
11.2	Station Service Equipment	$4,497	$0	$386	$0	$4,883	$855	$0	$1,148	$6,885	$4
11.3	Switchgear & Motor Control	$6,982	$0	$1,211	$0	$8,193	$1,434	$0	$1,925	$11,552	$7
11.4	Conduit & Cable Tray	$0	$908	$2,616	$0	$3,523	$617	$0	$828	$4,968	$3
11.5	Wire & Cable	$0	$2,404	$4,296	$0	$6,700	$1,172	$0	$1,574	$9,447	$6
	Subtotal	**$11,479**	**$3,311**	**$8,509**	**$0**	**$23,299**	**$4,077**	**$0**	**$5,475**	**$32,852**	**$20**
	12						Instrumentation & Control				
12.8	Instrument Wiring & Tubing	$573	$459	$1,835	$0	$2,866	$502	$0	$674	$4,042	$2
12.9	Other I&C Equipment	$705	$0	$1,632	$0	$2,336	$409	$0	$549	$3,294	$2
	Subtotal	**$1,278**	**$459**	**$3,466**	**$0**	**$5,203**	**$911**	**$0**	**$1,223**	**$7,336**	**$4**
	13						Improvements to Site				
13.1	Site Preparation	$0	$39	$797	$0	$837	$146	$0	$197	$1,180	$1
13.2	Site Improvements	$0	$186	$246	$0	$432	$76	$0	$102	$609	$0
13.3	Site Facilities	$213	$0	$223	$0	$436	$76	$0	$102	$614	$0
	Subtotal	**$213**	**$225**	**$1,267**	**$0**	**$1,704**	**$298**	**$0**	**$401**	**$2,403**	**$1**
	14						Buildings & Structures				
14.5	Circulation Water Pumphouse	$0	$84	$66	$0	$150	$26	$0	$35	$212	$0
	Subtotal	**$0**	**$84**	**$66**	**$0**	**$150**	**$26**	**$0**	**$35**	**$212**	**$0**
	Total	**$246,132**	**$68,024**	**$171,351**	**$0**	**$485,507**	**$84,964**	**$46,933**	**$123,481**	**$740,885**	**$443**
					Retrofit Values	**$509,783**	**$89,212**	**$49,280**	**$129,655**	**$777,929**	**$465**

Note: Account line-item costs are calculated on a greenfield basis. Retrofit costs, shown at the bottom of the table, are calculated by applying a retrofit factor, as discussed in Section 2.3, to the TPC (and consequently to the BEC, Eng'g CM H.O. & Fee, and contingencies)

Exhibit 6-33. Initial & annual O&M costs for case CM95-B4-S, with kiln off-gas SOx content: 300 ppm$_v$ & NOx content: 1,000 ppm$_v$

Case:	CM95-B4-S300N1000				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operating (%):	85
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.75
Maintenance Labor:					$4,978,748	$3.50
Administrative & Support Labor:					$1,511,343	$1.06
Property Taxes and Insurance:					$15,558,589	$10.94
Total:					**$23,115,305**	**$16.25**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$7,468,123	$5.25
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1,000 gal):	0	1,197	$2.24	$0	$830,426	$0.58
Makeup and Waste Water Treatment Chemicals (ton):	0	3.6	$647.04	$0	$716,077	$0.50
CO_2 Capture System Chemicals[A]:	Proprietary				$8,309,404	$5.84
Triethylene Glycol (gal):	w/equip.	336	$8.00	$0	$833,559	$0.59
Lime (ton):	0	16	$188.23	$0	$952,302	$0.67
Ammonia (19 wt%, ton):	0	61.0	$352.93	$0	$7,008,532	$4.93
SCR Catalyst (ft^3):	1,605	0.9	$176.46	$283,150	$48,136	$0.03
Subtotal:				**$283,150**	**$18,698,435**	**$13.15**
Waste Disposal						
SCR Catalyst (ft^3):		1	$2.94		$802	$0.00
Triethylene Glycol (gal):		336	$0.41		$42,904	$0.03
Thermal Reclaimer Unit Waste (ton):		1.98	$44.70		$27,476	$0.02
Pre-scrubber Blowdown Waste (ton):		0.05	$44.70		$676	$0.00
Subtotal:					**$71,858**	**$0.05**
Variable Operating Costs Total:				**$283,150**	**$26,238,416**	**$18.45**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,954	$4.61		$24,254,096	$17.06
Purchased Power (MWh):	0	28	$67.28	$0	$14,229,438	$10.01
Total:				**$0**	**$38,483,534**	**$27.06

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

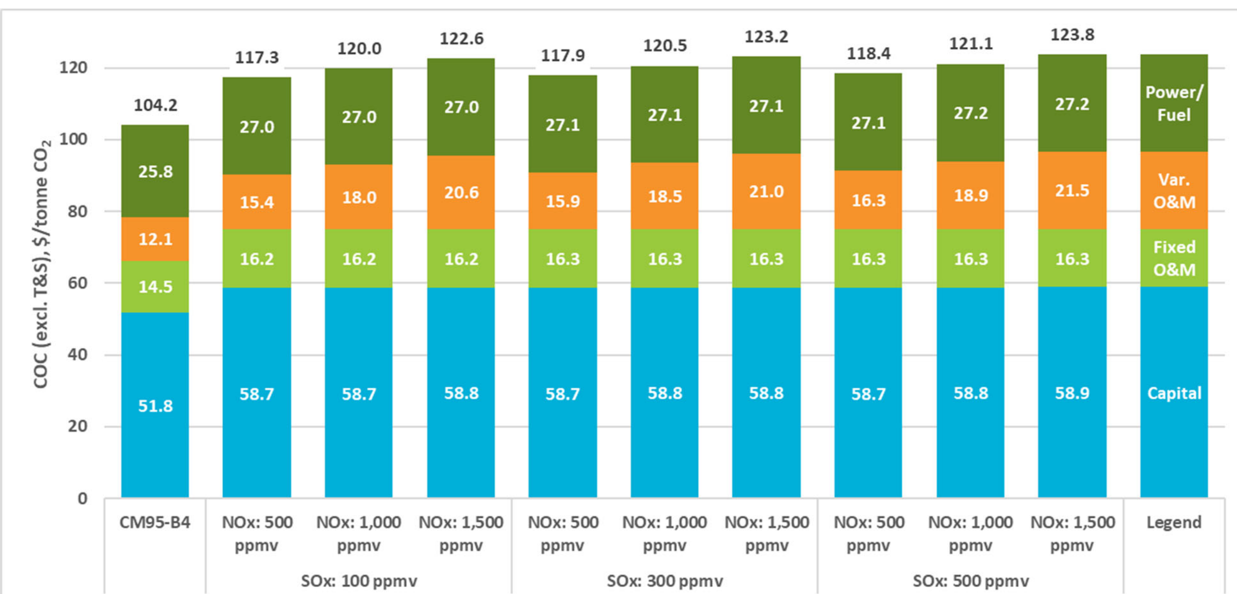
Exhibit 6-34. COC for case CM95-B4-S, \$/tonne CO_2

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
Capital	58.7	58.7	58.8	58.7	58.8	58.8	58.7	58.8	58.9
Fixed	16.2	16.2	16.2	16.3	16.3	16.3	16.3	16.3	16.3
Variable	15.4	18.0	20.6	15.9	18.5	21.0	16.3	18.9	21.5
Purchased Power and Fuel	27.0	27.0	27.0	27.1	27.1	27.1	27.1	27.2	27.2
Total COC (excl. T&S)	**117.3**	**120.0**	**122.6**	**117.9**	**120.5**	**123.2**	**118.4**	**121.1**	**123.8**
Total COC (incl. T&S)	**127.3**	**130.0**	**132.6**	**127.9**	**130.5**	**133.2**	**128.4**	**131.1**	**133.8**

Note: The SOx and NOx values shown are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

The addition of FGD and SCR results in a COC that is 12.6–18.8 percent higher than the base case CM95-B4. The cost components most affected are the capital and variable O&M components, as additional equipment and consumables are required for FGD and SCR operation. The comparison of the CM95-B4-S case at each combination of SOx and NOx concentrations with base case CM95-B4 is presented in Exhibit 6-35.

Exhibit 6-35. COC comparison of sensitivity case CM95-B4-S and base case CM95-B4

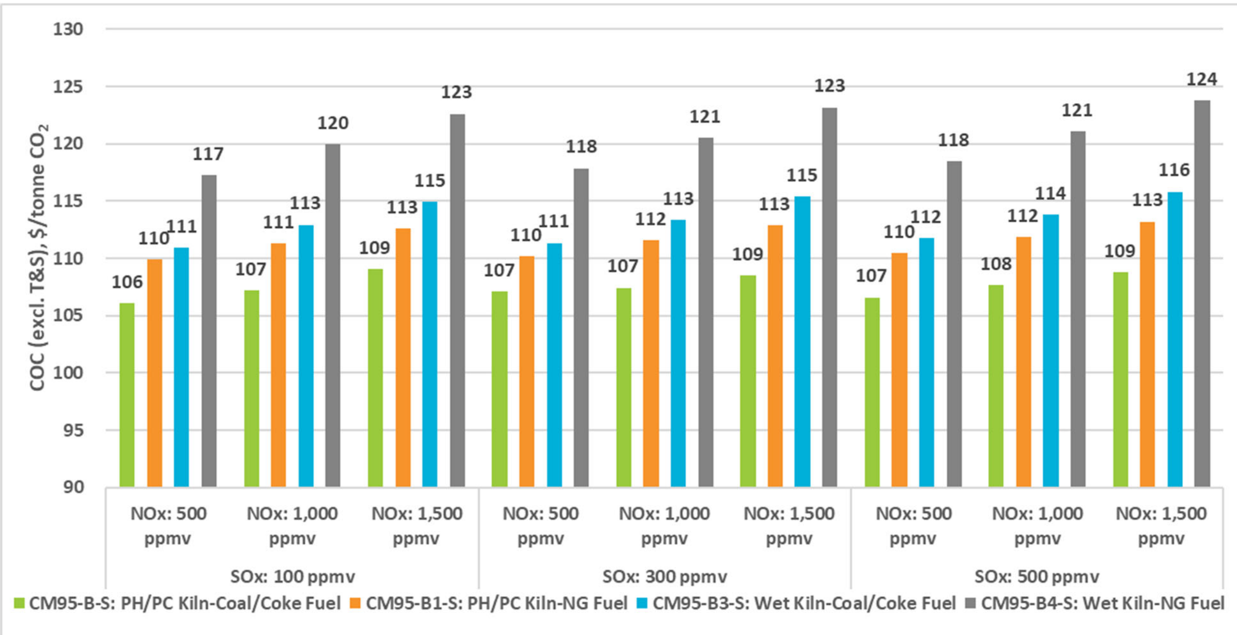


Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

6.5 Sensitivity Cases with FGD and SCR Conclusion

Cases CM95-B, CM95-B1, CM95-B3, and CM95-B4 were evaluated to address the cost implications of adding equipment for removing NOx and SOx from the kiln off-gas stream prior to CO_2 capture, purification, and compression. The results of these additional case analyses showed an increase in COC that is 7.4–18.8 percent over the respective base case. The effect of adding FGD and SCR processes increased the capital costs for the sensitivity cases by 8.4–13.7 percent over the base cases. O&M costs increased by 6.4–23.9 percent over the base cases. Exhibit 6-36 provides a summary of the COC for the sensitivity cases considering advanced SOx and NOx control.

Exhibit 6-36. Summary of COC for sensitivity cases with FGD and SCR



Note: The SO_x and NO_x values shown on the abscissa of are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

7 Sensitivity Cases with Air In-Leakage: Cost and Performance

The kiln off-gas in a cement plant is often used for heating and drying the raw meal solids in the first steps of the cement production process. As a result, the kiln off-gas stream moisture content and volumetric flowrate increase, as air leaks into the stream when passing through raw mill units and water is absorbed from the raw meal solids. In addition to air in-leakage, the kiln off-gas stream is cooler leaving the raw mill unit operations. Three scenarios of air in-leakage and off-gas cooling are considered for Case CM95-B and for Case CM95-B-S100N500 (i.e., the base case PH/PC kiln with coal/coke fuel and the same case including FGD and SCR operations). For each case, a scenario where the kiln off-gas arrives at the capture system inlet at 121°C (250°F) without air in-leakage is considered. Two scenarios with air in-leakage, increased moisture, and precooling through the raw mill are evaluated: for both scenarios, the moisture content is increased to 12 mol% and due to air in-leakage, the volume of the kiln off-gas stream increases to 400,000 actual cubic feet per minute (ACFM) for one scenario and 700,000 ACFM for the second scenario. Exhibit 7-1 details the air in-leakage scenarios, alongside the base case conditions, and the resulting characteristics of the stream entering the CO_2 capture system.

Exhibit 7-1. Air in-leakage scenarios

Base Case Number	CM95-B				CM95-B-S100N500			
Air In-leakage Scenario	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F
Kiln Type	Pre-heater/Pre-calciner							
Fuel Type	Coal/Coke							
Treated Stream Temperature, °F	320	250			320	250		
Treated Stream H_2O Concentration, mol %	5.95		12		5.95		12	
Treated Stream CO_2 Concentration, mol %	30.8		14.5	8.35	30.8		14.5	8.35
Treated Stream Volumetric Flowrate, 1,000 ACFM	208	200	400	700	206	200	400	700

7.1 Performance Results

The performance results for each of the air in-leakage scenarios are presented alongside the respective base cases in Exhibit 7-2. The impact of air in-leakage is noted in the increasing CO_2 capture auxiliary load–largely due to increased volumetric flowrate and moisture content at the capture system inlet. Note that it was assumed that the specific reboiler duty and specific cooling duty are equivalent between cases.

Exhibit 7-2. Auxiliary load summary of air in-leakage scenarios

Base Case Number	CM95-B				CM95-B-S100N500			
Air In-leakage Scenario	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F
Performance Summary								
CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	619 (587)	619 (587)	619 (587)	620 (588)	618 (586)	618 (586)	619 (587)	620 (588)
NG Feed Flow, kg/hr (lb/hr)	13,765 (30,346)	13,765 (30,346)	13,778 (30,376)	13,799 (30,421)	13,756 (30,326)	13,756 (30,326)	13,768 (30,354)	13,789 (30,399)
HHV Thermal Input, kWt	199,949	199,949	200,146	200,446	199,818	199,818	200,001	200,299
LHV Thermal Input, kWt	180,474	180,474	180,652	180,922	180,356	180,356	180,521	180,790
Raw Water Withdrawal, m^3/min (gpm)	5.4 (1,433)	5.4 (1,433)	5.4 (1,435)	5.4 (1,437)	5.6 (1,481)	5.5 (1,462)	5.6 (1,483)	5.8 (1,521)
Raw Water Consumption[A], m^3/min (gpm)	3.7 (970)	3.7 (970)	3.3 (861)	2.9 (755)	3.7 (989)	3.7 (983)	3.3 (873)	2.9 (778)
Auxiliary Load Summary								
Ash Handling, kWe	–				4		9	16
Baghouse, kWe	–				1			3
Circulating Water Pumps, kWe	1,390							
Cooling Tower Fans, kWe	730	720	730					
CO_2 Capture Auxiliaries, kWe	4,600	4,600	5,000	5,600	6,300		7,300	8,700
CO_2 Compression, kWe	12,490		12,500	12,520	12,480		12,490	12,510
Feedwater Pumps, kWe	60							
Forced Draft Fans, kWe	480							
Ground Water Pumps, kWe	130							140
Flue Gas Desulfurizer, kWe	–				40		80	140
Miscellaneous Balance of Plant[B], kWe	400		410	420	430		450	480
SCR, kWe	–				7		15	26
Transformer Losses, kWe	130			140			150	
Total Auxiliaries, MWe	**20**	**20**	**21**		**22**		**23**	**25**

[A]Raw water consumption is defined as the difference of raw water withdrawal and process water discharged
[B]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

7.2 Economic Analysis Results

The capital and O&M costs for the air in-leakage scenarios were estimated based on methodology in Section 2.1. The resulting COC for each scenario is summarized in Exhibit 7-3 and Exhibit 7-4.

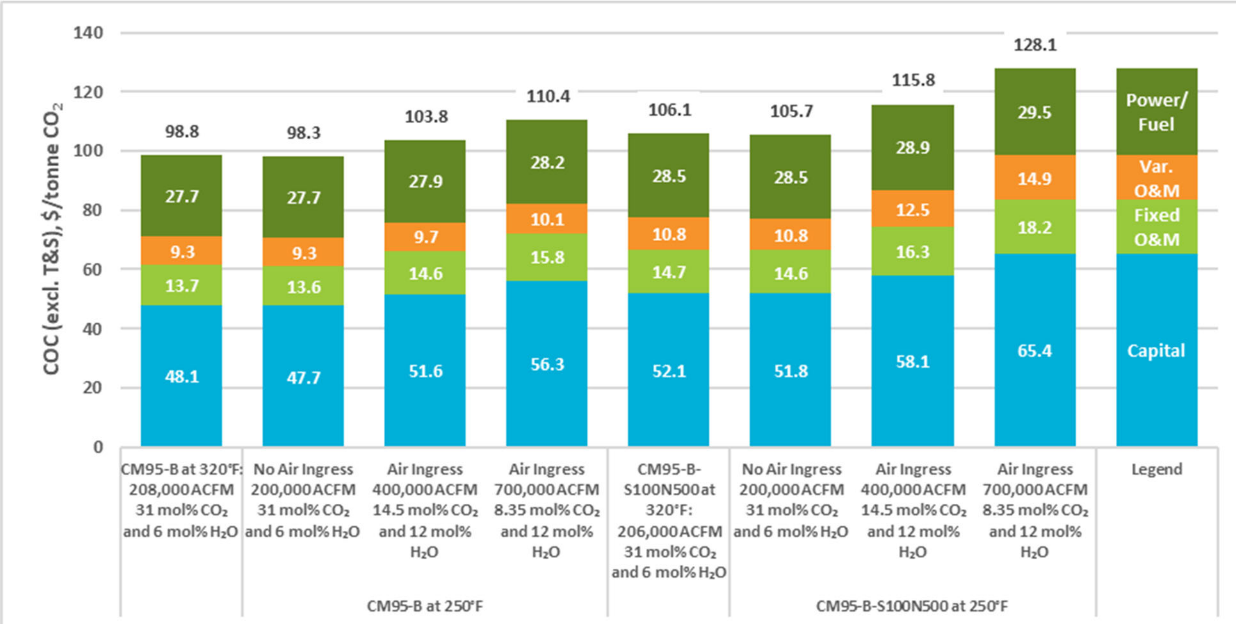
The cases in Exhibit 7-3 show the impacts of both kiln off-gas cooling from 160°C (320°F) (in the base case) to 121°C (250°F) due to raw meal drying, and of air ingress. These sensitivity cases were applied to configurations that assumed additional FGD/SCR cleanup trains as described in Section 6, and to those without additional cleanup. The temperature reduction associated with raw meal drying results in a decreased emissions stream volumetric flowrate; therefore, all downstream equipment becomes slightly smaller and less expensive. This is observed in the slight capital cost decrease in Exhibit 7-3 for the "Base Case at 250°F" scenario. The other cases (i.e., "400,000 ACFM at 250°F" and "700,000 ACFM at 250°F") introduce false air ingress into the system, which increases the volumetric flowrate to 400,000 and 700,000 ACFM, respectively. Exhibit 7-3 shows the effects of these competing phenomena: when the kiln off gas is cooled to 250°F due to raw meal drying without false air ingress, capital costs fall as expected (i.e., due to the reduction in volumetric flowrate). However, when false air is introduced into the system, the additional air volume overcomes the reduction in volume due to gas cooling (i.e., from 320°F to 250°F), and the net effect is an overall increase in costs. This trend was observed for the configurations that included FGD and SCR, and those that did not.

False air ingress via raw mill processing can result in a COC that is 5–22 percent higher than the respective base case. In some cases, the COC is essentially equivalent to the base case. The impacts of air in-leakage are seen in the capital costs associated with larger equipment required to accommodate higher volumetric flowrates and with increased O&M costs associated with larger operating units. The deviation from base case costs is most evident in the cases that include FGD and SCR units, where the FGD and SCR will need to process large volumes of gas leading the capital and O&M costs to rise more significantly.

Exhibit 7-3. COC summary of air in-leakage scenarios

Base Case Number	CM95-B				CM95-B-S100N500			
Air In-leakage Scenario	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F	Base Case	Base Case at 250°F	400,000 ACFM at 250°F	700,000 ACFM at 250°F
Capital	48.1	47.7	51.6	56.3	52.1	51.8	58.1	65.4
Fixed	13.7	13.6	14.6	15.8	14.7	14.6	16.3	18.2
Variable	9.3	9.3	9.7	10.1	10.8	10.8	12.5	14.9
Purchased Power and Fuel	27.7	27.7	27.9	28.2	28.5	28.5	28.9	29.5
Total COC (excl. T&S)	**98.8**	**98.3**	**103.8**	**110.4**	**106.1**	**105.7**	**115.8**	**128.1**
Total COC (incl. T&S)	**108.8**	**108.3**	**113.8**	**120.4**	**116.1**	**115.7**	**125.8**	**138.1**

Exhibit 7-4. COC comparison of air in-leakage scenarios

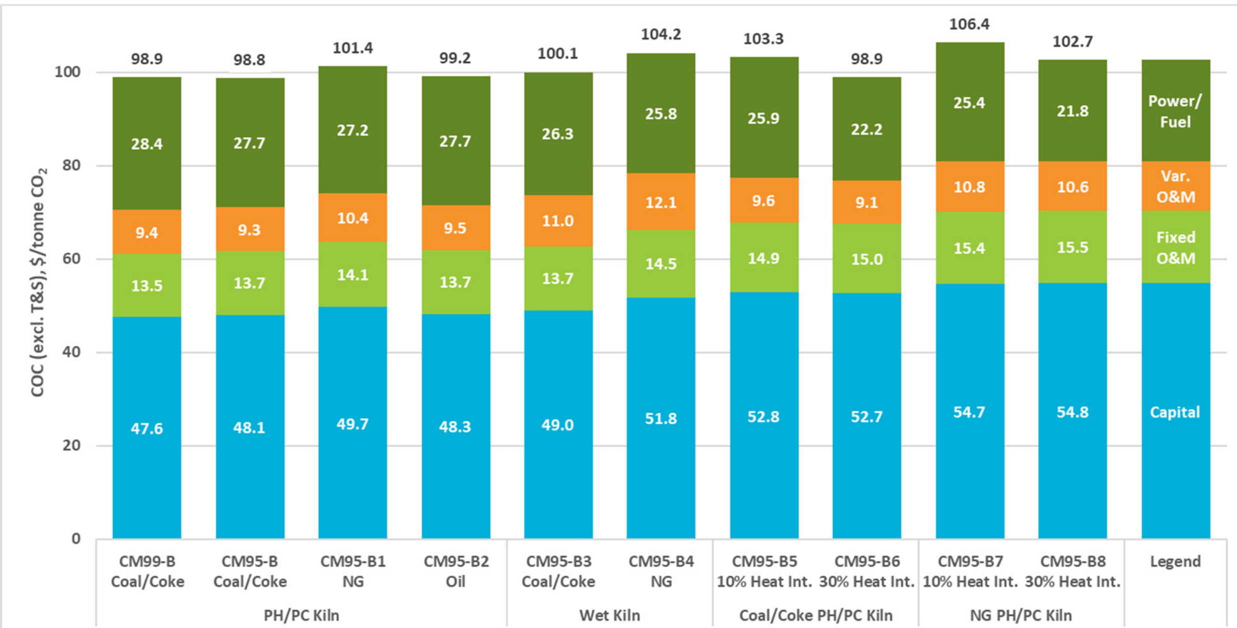


Line-item capital costs, owner's costs, and O&M costs are summarized in Appendix F: Cost Details for Air In-Leakage Scenarios for each air in-leakage scenario. Energy and mass balance diagrams and stream tables for select sensitivity cases are provided in Appendix A: Energy and Mass Balances.

8 RESULTS ANALYSIS

Exhibit 8-1 shows the COC results of each of the base cases considered in this study, which are described in Exhibit 5-1. When comparing kiln off-gas streams and their associated COCs, it is evident that lower COC correlates with higher CO_2 concentrations in the kiln off-gas (e.g., comparing the coal/coke-fired PH/PC kiln case CM95-B at 31 mole percent CO_2 and the NG-fired wet kiln case CM95-B4 at 13 mole percent CO_2). This result is expected, as it is generally observed that separation of a component in a mixed gas stream is more easily achieved at higher concentrations of that component.

Exhibit 8-1. COC summary for base cases



Another observation regarding capital intensity and CO_2 availability is demonstrated by comparing the heat integration cases (i.e., CM95-B5, CM95-B6, CM95-B7, and CM95-B8) to the corresponding non-heat integration cases. The total normalized COC is higher for the 10 percent heat integration cases and lower for the 30 percent heat integration cases, when comparing to their respective base cases. This trend underscores the tradeoffs that exist with respect to heat integration and process economics. Recovery and reuse of excess heat can provide economic benefits, but any process improvement must be great enough to overcome the cost increases (i.e., capital and O&M) necessary to realize any benefit. At only 10 percent heat integration, that benefit wasn't significant enough to offset the increase in capital and operating costs, and a slight COC increase was observed.

Although heat integration requires capital equipment and therefore increases total plant cost, the recovered heat is used to raise steam needed for solvent regeneration, reducing the amount of NG burned in the industrial boiler. Exhibit 8-1 shows that approximately one-third of the total COC is attributable to purchase of NG and supplemental electricity; any steps taken to alleviate this burden, such as the heat integration cases evaluated in this study, could reduce capture costs. However, a crossover point exists whereby the process improvement benefit is too small to justify the additional capital expense associated with retrofitting heat integration. With lower amounts of CO_2 available for capture due to heat integration (i.e., less CO_2 generated by the NG-fired boiler, relative to the non-heat integration cases) and higher retrofit difficulty, normalized capital costs increase at low levels of heat integration. At higher levels of heat integration (i.e., 30 percent), recovery and reuse of excess heat result in lower purchased power and NG costs, therefore making the project economically viable and justifying the expense.

This analysis supports the notion that heat integration opportunities at the base plant would require precise evaluation to determine optimal heat use, or to determine whether heat integration is economically prudent at all. This study only quantifies heat integration based on potential to offset the heating needs of the CO_2 capture systems (i.e., 10 or 30 percent potential). Part of a more in-depth optimization of heat integration potential would include considerations of heat source quality (i.e., temperature pinch analysis), specific retrofit difficulty, and other processing implications of heat integration.

8.1 Cost and Performance Summaries

The cost and performance results presented in this study are summarized in Exhibit 8-2 through Exhibit 8-7. Of all cases examined in this study, the lowest COC of $98.8/tonne CO_2 is shown for a representative PH/PC kiln that fires coal/coke fuel (i.e., CM95-B). The COC for all cases, including all of those examined to include FGD and SCR processes and for air in-leakage impacts, ranges $98.8–128.1/tonne CO_2, excluding T&S costs. The most likely scenario for capture retrofits to existing cement plants is illustrated by the cases that include false air ingress from the raw mill circuit as well as FGD and SCR unit operations to preclean the resulting emissions stream prior to the Shell CANSOLV® island.

All else being equal, the cost results observed in Exhibit 8-2 are consistent with the conclusion that, in general, the economics of CO_2 separation from a mixed gas stream improve with increasing CO_2 concentration. Total flow into the capture island is also a significant factor for capture costs: for all cases shown in Exhibit 8-2, capital cost and purchased fuel/power costs represent approximately 75–77 percent of the total COC. Both cost components are influenced largely by the flowrate and conditions of the gas stream entering the capture island (i.e., capital cost as a function of the volumetric flow rate and CO_2 mass flow rate; purchased fuel and power costs for solvent regeneration and CO_2 compression are functions of the CO_2 mass flowrate). Therefore, the lower-cost base case configurations shown in Exhibit 8-2 tend to be those with lower mass flowrates—to keep equipment size and the need for auxiliary power and natural gas to a minimum—but highest CO_2 concentrations for ease of separation from a mixed flue gas stream.

Exhibit 8-2. Cost and performance summary comparison – base cases

Case Number	CM99-B	CM95-B	CM95-B1	CM95-B2	CM95-B3	CM95-B4	CM95-B5	CM95-B6	CM95-B7	CM95-B8
PERFORMANCE										
Capture Rate	99 percent	95 percent								
Kiln Type	Pre-heater/Pre-calciner				Wet Process		Pre-heater/Pre-calciner			
Kiln Fuel	Coal/Coke		Nat. Gas	Oil	Coal/Coke	Nat. Gas	Coal/Coke		Natural Gas	
Kiln Off-gas CO_2 Concentration, mol%	31	31	25	30	17	13	31	25	31	31
Heat Integration Potential, %	N/A						10	30	10	30
Combined Stream CO_2 Conc., mol%	21	21	19	21	15	12	22	23	19	20
CO_2 Captured, tonnes/year	1,516,106	1,426,677	1,415,169	1,424,904	1,688,297	1,673,262	1,391,847	1,325,543	1,381,155	1,316,892
CO_2 Captured, tonnes/hour	173	163	162	163	193	191	159	151	158	150
CO_2 Compressor Load, kW	13,270	12,490	12,390	12,470	14,780	14,650	12,180	11,600	12,090	11,530
Cooling Water Flowrate, gpm	72,800	67,058	65,439	66,974	75,927	73,552	65,774	63,216	64,217	61,563
Cooling Tower Duty, MMBtu/hour	728	671	654	670	759	736	658	632	642	616
COST										
TPC, $/1,000	573,135	544,376	557,714	545,922	656,587	687,283	583,992	554,481	599,812	572,780
BEC, $/1,000	372,272	353,837	362,108	354,793	425,737	445,120	379,614	360,505	389,444	371,893
Home Office Expenses	65,148	61,921	63,369	62,089	74,504	77,896	66,432	63,088	68,153	65,081
Project Contingency	95,522	90,729	92,952	90,987	109,431	114,547	97,332	92,414	99,969	95,463
Process Contingency	40,192	37,888	39,284	38,053	46,914	49,720	40,613	38,474	42,247	40,342
TOC, $M	694	659	676	661	796	833	707	671	726	694
TOC, $/1,000	694,192	659,341	675,757	661,257	795,743	833,149	707,054	671,212	726,493	693,706
Owner's Costs	121,057	114,965	118,043	115,334	139,157	145,866	123,062	116,731	126,681	120,926
TASC, $/1,000	776,123	737,159	755,513	739,301	889,660	931,480	790,503	750,431	812,237	775,580
Capital Costs, $/tonne CO_2	47.6	48.1	49.7	48.3	49.0	51.8	52.8	52.7	54.7	54.8
Fixed Costs, $/tonne CO_2	13.5	13.7	14.1	13.7	13.7	14.5	14.9	15.0	15.4	15.5
Variable Costs, $/tonne CO_2	9.4	9.3	10.4	9.5	11.0	12.1	9.6	9.1	10.8	10.6
Purchased Power and Fuel, $/tonne CO_2	28.4	27.7	27.2	27.7	26.3	25.8	25.9	22.2	25.4	21.8
COC (excl. T&S), $/tonne CO_2	**98.9**	**98.8**	**101.4**	**99.2**	**100.1**	**104.2**	**103.3**	**98.9**	**106.4**	**102.7**
COC (incl. T&S), $/tonne CO_2	**108.9**	**108.8**	**111.4**	**109.2**	**110.1**	**114.2**	**113.3**	**108.9**	**116.4**	**112.7**

Exhibit 8-3. Cost and performance summary comparison – CM95-B-S sensitivity cases

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Pre-heater/Pre-calciner								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,426,477								
CO_2 Captured, tonnes/hour	163								
CO_2 Compressor Load, kW	12,480								
Cooling Water Flowrate, gpm	66,994								
Cooling Tower Duty, MMBtu/hour	670								
COST									
TPC, $/1,000	544,376	589,878	589,883	589,888	589,988	589,994	589,999	590,111	590,116
BEC, $/1,000	353,837	386,460	386,464	386,467	386,535	386,539	386,542	386,619	386,622
Home Office Expenses	61,921	67,631	67,631	67,632	67,644	67,644	67,645	67,658	67,659
Project Contingency	90,729	98,313	98,314	98,315	98,331	98,332	98,333	98,352	98,353
Process Contingency	37,888	37,474	37,474	37,474	37,478	37,478	37,478	37,482	37,482
TOC, $M	659	715	715	716	715	715	716	715	716
TOC, $/1,000	659,341	714,789	715,172	715,644	715,076	715,371	715,754	715,202	715,585
Owner's Costs	114,965	124,911	125,289	125,755	125,088	125,377	125,755	125,091	125,469
TASC, $/1,000	737,159	799,151	799,580	800,107	799,472	799,801	800,229	799,613	800,041
Capital Costs, $/tonne CO_2	48.1	52.1	52.1	52.2	52.1	52.2	52.2	52.1	52.2
Fixed Costs, $/tonne CO_2	13.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
Variable Costs, $/tonne CO_2	9.3	10.8	11.9	13.7	11.7	12.0	13.1	11.2	12.2
Purchased Power and Fuel, $/tonne CO_2	27.7	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.6
COC (excl. T&S), $/tonne CO_2	**98.8**	**106.1**	**107.2**	**109.0**	**107.1**	**107.4**	**108.5**	**106.6**	**107.7**
COC (incl. T&S), $/tonne CO_2	**108.8**	**116.1**	**117.2**	**119.0**	**117.1**	**117.4**	**118.5**	**116.6**	**117.7**

Exhibit 8-4. Cost and performance summary comparison – CM95-B1-S sensitivity cases

SOx Concentration	100 ppm_v			300 ppm_v			500 ppm_v		
NOx Concentration	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Pre-heater/Pre-calciner								
Kiln Fuel	Natural Gas								
CO_2 Captured, tonnes/year	1,414,977								
CO_2 Captured, tonnes/hour	162								
CO_2 Compressor Load, kW	12,380								
Cooling Water Flowrate, gpm	65,377								
Cooling Tower Duty, MMBtu/hour	654								
COST									
TPC, $/1,000	557,714	610,130	610,137	610,143	610,264	610,271	610,277	610,399	610,405
BEC, $/1,000	362,108	399,606	399,610	399,615	399,698	399,702	399,706	399,790	399,794
Home Office Expenses	63,369	69,931	69,932	69,933	69,947	69,948	69,949	69,963	69,964
Project Contingency	92,952	101,688	101,689	101,690	101,711	101,712	101,713	101,733	101,734
Process Contingency	39,284	38,905	38,905	38,905	38,909	38,909	38,909	38,913	38,913
TOC, $M	676	740	740	741	740	740	741	740	741
TOC, $/1,000	675,757	739,657	740,131	740,605	739,900	740,374	740,847	740,143	740,617
Owner's Costs	118,043	129,527	129,994	130,462	129,635	130,103	130,570	129,744	130,212
TASC, $/1,000	755,513	826,954	827,484	828,014	827,225	827,755	828,285	827,497	828,027
Capital Costs, $/tonne CO_2	49.7	54.4	54.4	54.4	54.4	54.4	54.5	54.4	54.4
Fixed Costs, $/tonne CO_2	14.1	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Variable Costs, $/tonne CO_2	10.4	12.2	13.5	14.8	12.4	13.8	15.1	12.7	14.0
Purchased Power and Fuel, $/tonne CO_2	27.2	28.0	28.0	28.0	28.1	28.1	28.1	28.1	28.1
COC (excl. T&S), $/tonne CO_2	**101.4**	**109.9**	**111.3**	**112.6**	**110.2**	**111.6**	**112.9**	**110.5**	**111.9**
COC (incl. T&S), $/tonne CO_2	**111.4**	**119.9**	**121.3**	**122.6**	**120.2**	**121.6**	**122.9**	**120.5**	**121.9**

Exhibit 8-5. Cost and performance summary comparison – CM95-B3-S sensitivity cases

SOx Concentration	100 ppmv			300 ppmv			500 ppmv		
NOx Concentration	500 ppmv	1,000 ppmv	1,500 ppmv	500 ppmv	1,000 ppmv	1,500 ppmv	500 ppmv	1,000 ppmv	1,500 ppmv
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Wet Process								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,688,081								
CO_2 Captured, tonnes/hour	193								
CO_2 Compressor Load, kW	14,770								
Cooling Water Flowrate, gpm	75,855								
Cooling Tower Duty, MMBtu/hour	759								
COST									
TPC, $/1,000	656,587	733,323	733,333	733,343	733,526	733,536	733,546	733,731	733,740
BEC, $/1,000	425,737	480,471	480,478	480,485	480,610	480,617	480,624	480,751	480,758
Home Office Expenses	74,504	84,082	84,084	84,085	84,107	84,108	84,109	84,131	84,133
Project Contingency	109,431	122,220	122,222	122,224	122,254	122,256	122,258	122,288	122,290
Process Contingency	46,914	46,549	46,549	46,549	46,555	46,555	46,555	46,560	46,560
TOC, $M	796	889	890	891	890	891	892	890	891
TOC, $/1,000	795,743	889,442	890,281	891,119	889,831	890,669	891,507	890,221	891,059
Owner's Costs	139,157	156,120	156,948	157,776	156,304	157,133	157,961	156,490	157,318
TASC, $/1,000	889,660	994,418	995,355	996,292	994,852	995,789	996,726	995,288	996,225
Capital Costs, $/tonne CO_2	49.0	54.8	54.9	54.9	54.8	54.9	54.9	54.8	54.9
Fixed Costs, $/tonne CO_2	13.7	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
Variable Costs, $/tonne CO_2	11.0	13.5	15.5	17.5	13.9	15.8	17.8	14.2	16.2
Purchased Power and Fuel, $/tonne CO_2	26.3	27.4	27.4	27.4	27.4	27.4	27.4	27.5	27.5
COC (excl. T&S), $/tonne CO_2	**100.1**	**110.9**	**112.9**	**115.0**	**111.4**	**113.4**	**115.4**	**111.8**	**113.8**
COC (incl. T&S), $/tonne CO_2	**110.1**	**120.9**	**122.9**	**125.0**	**121.4**	**123.4**	**125.4**	**121.8**	**123.8**

Exhibit 8-6. Cost and performance summary comparison – CM95-B4-S sensitivity cases

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Wet Process								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,673,056								
CO_2 Captured, tonnes/hour	191								
CO_2 Compressor Load, kW	14,640								
Cooling Water Flowrate, gpm	73,482								
Cooling Tower Duty, MMBtu/hour	735								
COST									
TPC, $/1,000	687,283	777,668	777,680	777,693	777,917	777,929	777,942	778,178	778,191
BEC, $/1,000	445,120	509,603	509,612	509,621	509,774	509,783	509,792	509,954	509,962
Home Office Expenses	77,896	89,180	89,182	89,184	89,210	89,212	89,214	89,242	89,243
Project Contingency	114,547	129,611	129,613	129,616	129,653	129,655	129,657	129,696	129,699
Process Contingency	49,720	49,273	49,273	49,273	49,280	49,280	49,280	49,287	49,287
TOC, $M	833	944	945	946	944	945	946	945	946
TOC, $/1,000	833,149	943,627	944,722	945,816	944,114	945,209	946,303	944,617	945,711
Owner's Costs	145,866	165,959	167,041	168,123	166,197	167,279	168,361	166,438	167,520
TASC, $/1,000	931,480	1,054,997	1,056,221	1,057,445	1,055,542	1,056,765	1,057,989	1,056,104	1,057,328
Capital Costs, $/tonne CO_2	51.8	58.7	58.7	58.8	58.7	58.8	58.8	58.7	58.8
Fixed Costs, $/tonne CO_2	14.5	16.2	16.2	16.2	16.3	16.3	16.3	16.3	16.3
Variable Costs, $/tonne CO_2	12.1	15.4	18.0	20.6	15.9	18.5	21.0	16.3	18.9
Purchased Power and Fuel, $/tonne CO_2	25.8	27.0	27.0	27.0	27.1	27.1	27.1	27.1	27.2
COC (excl. T&S), $/tonne CO_2	**104.2**	**117.3**	**120.0**	**122.6**	**117.9**	**120.5**	**123.2**	**118.4**	**121.1**
COC (incl. T&S), $/tonne CO_2	**114.2**	**127.3**	**130.0**	**132.6**	**127.9**	**130.5**	**133.2**	**128.4**	**131.1**

Exhibit 8-7. Cost and performance summary comparison – air in-leakage cases

	CM95-B				CM95-B-S100N500			
	Base Case at 320°F	Emissions Stream at 250 °F			Base Case at 320°F	Emissions Stream at 250 °F		
		No Air In-leakage	Air In-leakage 400,000 ACFM	Air In-leakage 700,000 ACFM		No Air In-leakage	Air In-leakage 400,000 ACFM	Air In-leakage 700,000 ACFM
PERFORMANCE								
Capture Rate	95 percent							
Kiln Type	Pre-heater/Pre-calciner							
Kiln Fuel	Coal/Coke							
CO_2 Captured, tonnes/year	1,426,677	1,426,677	1,428,082	1,430,220	1,426,477	1,426,477	1,427,786	1,429,911
CO_2 Captured, tonnes/hour	163	163	163	163	163	163	163	163
CO_2 Compressor Load, kW	12,490	12,490	12,500	12,520	12,480	12,480	12,490	12,510
Cooling Water Flowrate, gpm	67,058	67,058	67,124	67,224	66,994	66,994	67,056	67,155
Cooling Tower Duty, MMBtu/hour	671	671	671	672	670	670	671	672
COST								
TPC, $/1,000	544,376	540,164	585,671	639,911	589,878	586,173	657,756	741,791
BEC	353,837	351,207	379,897	414,050	386,460	383,949	431,169	486,615
Home Office Expenses	61,921	61,461	66,482	72,459	67,631	67,191	75,455	85,158
Project Contingency	90,729	90,027	97,612	106,652	98,313	97,696	109,626	123,632
Process Contingency	37,888	37,469	41,680	46,750	37,474	37,337	41,506	46,387
TOC, $M	659	654	709	775	715	710	797	899
TOC, $/1,000	659,341	654,258	709,182	774,647	714,789	710,313	797,228	899,387
Owner's Costs	114,965	114,094	123,511	134,737	124,911	124,140	139,472	157,597
TASC, $/1,000	737,159	731,476	792,882	866,074	799,151	794,147	891,319	1,005,536
Capital Costs, $/tonne CO_2	48.1	47.7	51.6	56.3	52.1	51.8	58.1	65.4
Fixed Costs, $/tonne CO_2	13.7	13.6	14.6	15.8	14.7	14.6	16.3	18.2
Variable Costs, $/tonne CO_2	9.3	9.3	9.7	10.1	10.8	10.8	12.5	14.9
Purchased Power and Fuel, $/tonne CO_2	27.7	27.7	27.9	28.2	28.5	28.5	28.9	29.5
COC (excl. T&S), $/tonne CO_2	**98.8**	**98.3**	**103.8**	**110.4**	**106.1**	**105.7**	**115.8**	**128.1**
COC (incl. T&S), $/tonne CO_2	**108.8**	**108.3**	**113.8**	**120.4**	**116.1**	**115.7**	**125.8**	**138.1**

8.2 Potential Cost Improvement Analysis

As a supplemental analysis, the COC is broken down into the following five categories: CO_2 capture system, compression, steam generation and purchased power, water, and miscellaneous shared costs. Such an analysis provides insight into the potential influence of capture system improvements on the overall cost of capture, highlights the cost categories that are not influenced by improvements to the capture system, and allows isolation of the cost contributions of different systems to quantify the impact of potential cost improvements.

8.2.1 Description of Capital Cost Breakdown

The capital costs that comprise the COC were broken down into the five categories as follows:

- CO_2 Capture System
  - Account 5.1: CO_2 Capture System
  - Account 5.12: Gas Cleanup Foundations
  - Account 7: Ductwork & Stack (Ductwork, Stack, Duct & Stack Foundations)
- Compression
  - Account 5.4: Compression & Drying
  - Account 5.5: Compression Aftercooling
- Steam Generation and Purchased Power
  - Account 3: Feedwater and Miscellaneous BOP Systems (excluding Account 3.2: Water Makeup & Pretreating and Account 3.7: Waste Water Treatment Equipment)
  - Account 11: Accessory Electric Plant
- Water
  - Account 3.2: Water Makeup & Pretreating
  - Account 3.7: Waste Water Treatment Equipment
  - Account 9: Cooling Water System
  - Account 14.5: Circulation Water Pumphouse
- Miscellaneous Shared Costs
  - Account 12: Instrumentation & Control
  - Account 13: Improvements to Site

8.2.2 Description of O&M Cost Breakdown

The fixed and variable O&M costs (i.e., those detailed in Exhibit 5-8 and Exhibit 5-15) were categorized similarly to the capital costs, but since some O&M costs (i.e., 'Maintenance Material') are calculated based on the TPC, the five cost categories account for those costs proportionate to the respective category's contribution to the TPC. In the same fashion, the fixed O&M costs of 'Maintenance Labor,' 'Administrative & Support Labor,' and 'Property Taxes and Insurance' are distributed to each category proportionate to the category's contribution to TPC.

In addition to those partial O&M costs allocated to each cost category, the consumable, waste, and fuel costs are categorized to the five cost groups as follows:

- CO_2 Capture System
  - CO_2 Capture System Chemicals
  - Thermal Reclaimer Unit Waste
  - Pre-scrubber Blowdown Waste
- Compression
  - Triethylene Glycol (both consumption and waste disposal)
- Steam Generation and Purchased Power
  - Fuel (i.e., NG)
  - Purchased power
- Water
  - Water
  - Makeup and Waste Water Treatment Chemicals
- Miscellaneous Shared Costs
  - Annual Operating Labor

8.2.3 Cost Breakdown Results

Exhibit 8-8 shows the cost breakdown for COC excluding T&S, while Exhibit 8-9 shows the cost breakdown for COC including T&S. This analysis shows that the costs attributed to the CO_2 capture system and purchased power/steam generation make up 85 percent of the overall COC, excluding T&S, and 77 percent of the COC when T&S is included. Since the compression, water, CO_2 T&S, and miscellaneous shared costs contribute relatively little to the COC, improvements to those categories are not as impactful as cost improvements to the CO_2 capture or purchased power/steam generation categories.

Exhibit 8-8. COC breakdown (excl. T&S)

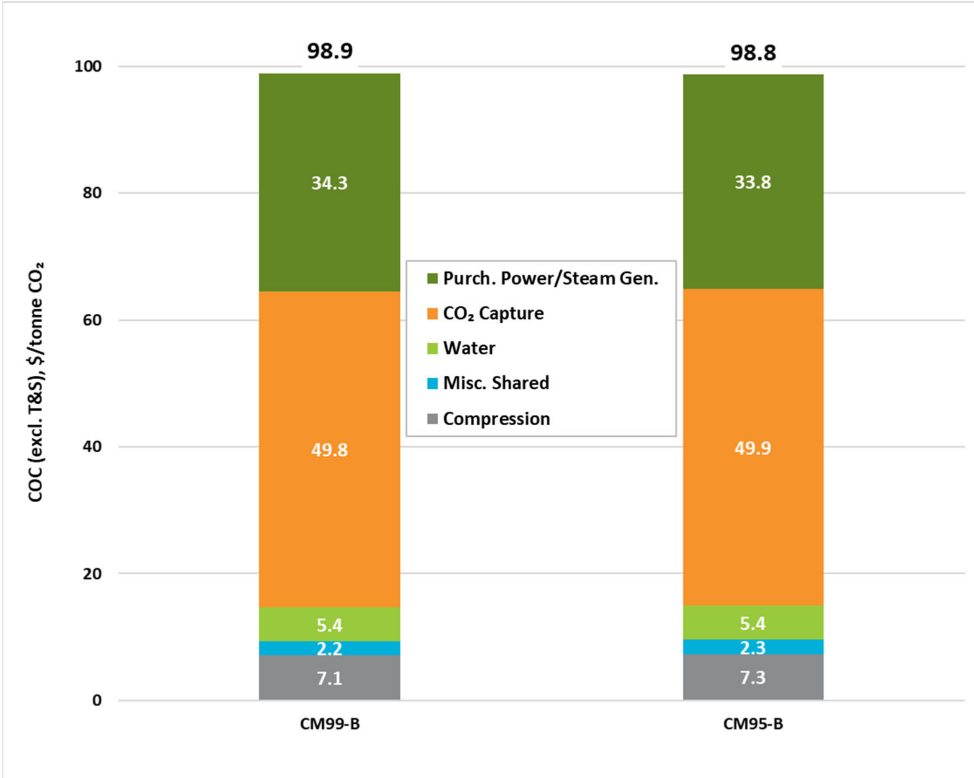
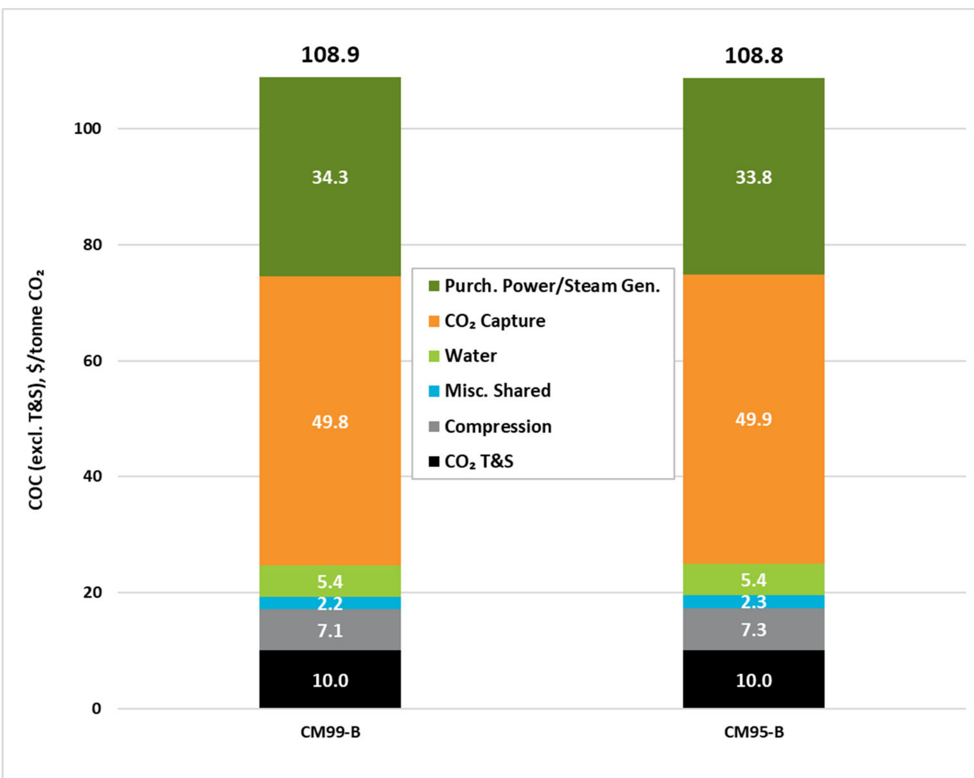


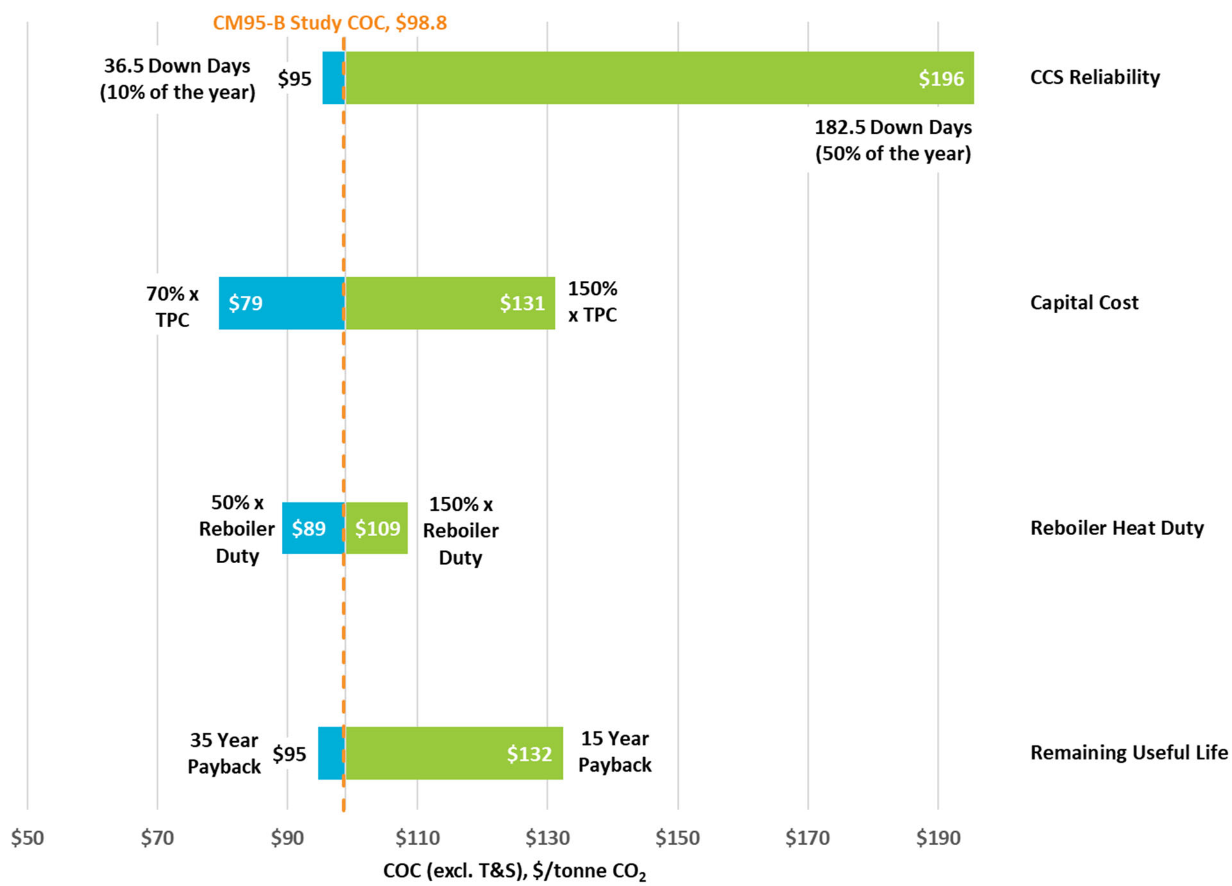
Exhibit 8-9. COC breakdown (incl. T&S)



8.3 Impacts of Select Study Assumptions

Exhibit 8-10 shows the relative impact of four key study assumptions: CO_2 capture system reliability (i.e., down days), capital cost (i.e., TPC), capture system reboiler heat duty, and remaining useful life of the cement plant. The case considered to generate Exhibit 8-10 is CM95-B, the pre-heater/pre-calciner kiln with coal/coke fuel and 95 percent CO_2 capture. Each parameter was varied individually across a range of values, to observe which has the most significant impact on and could, therefore, yield the greatest improvement in COC. The analysis suggests that improvements to the capture system reboiler duty and capital cost reduction have the greatest potential to reduce capture costs.

Exhibit 8-10. COC vs. select study assumptions



Although there are currently no federal requirements for carbon capture at cement plants, historically in the electric power sector when pollution control processes fail, the entire plant comes offline to avoid violating flue gas emission limits. Improvements in system reliability will minimize the extent to which these unplanned outages occur, and this could be achieved through research on improved tolerance to air pollutants, or robust response to transient operation. These improvements are shown in Exhibit 8-10 as variations in down days, and illustrate how significantly the capture cost can change with improvements (or deteriorations) in capture system reliability. Of all variables shown in Exhibit 8-10, capture system reliability has the most significant negative impact on cost, with COC rising to $196 at 50 percent operation.

Capital cost improvements were also shown to have a large range effect on capture cost. In the base case used for this example, capital accounts for approximately one third of the total COC. Improvements in those areas having such significance would be expected to also show meaningful reductions in the cost of capture. First-of-a-kind installations would be expected to have costs toward the higher end of the range selected (i.e., $131/tonne CO_2 at 150 percent of the TPC estimated for the base case), but as learning improves and the number of demonstrations increases, costs will inevitably decrease, as has been observed with other air pollution control technologies. Capital cost improvements could be achieved with modular system design, improved unit operation reliability (eliminating redundancies), or through process improvements that would allow for smaller equipment design (such as enhancements in solvent carrying capacity).

The CO_2 capture solvent assumed for this analysis requires the use of stripping steam for regeneration, and this steam is raised in a supplemental NG-fired boiler. In Exhibit 8-10, changes in stripping steam requirement are indicated by reboiler duty. At the NG price assumed ($4.61/MMBtu), a 50 percent reduction in reboiler duty brings the COC down to $89/tonne CO_2; however the extent of the impact is still dependent upon NG price. At higher NG prices, the impact is expected to be greater than is demonstrated in this evaluation. Improvements in reboiler duty could be achieved via increasing solvent carrying capacity, for example

The final variable that was considered in Exhibit 8-10 was the financial payback period, which was considered the remaining useful life of the cement plant prior to retrofit. Older facilities would need to recover retrofit costs sooner, since the plant has fewer remaining operating years over which to recover its costs. This would be reflected in less favorable financial terms, and, therefore, increase the COC, as demonstated by the increase to $132/tonne CO_2 with a 15-year payback period. Although the remaining useful life is not likely to be a parameter that can be improved through R&D, this could provide a better understanding regarding which facilities are the best candidates for retrofit, from an economic standpoint.

8.4 Point-Source CO_2 Avoidance

The CO_2 capture processes evaluated in this study remove 95 and 99 percent of the total CO_2 emissions produced by a combination of the base cement plant operations and the fuel burning required for steam generation provided by the NG-fired boiler described in Section 3.3. On average, the industrial boilers modeled in the base cases each emit 0.20–0.35 M tonnes CO_2 per year, based on the design basis assumptions in this study. Subtracting this CO_2 flow from the total CO_2 captured in each case allows for the approximation of the point-source emissions avoided by adding retrofit capture in representative cement plants, described in Exhibit 8-11 as the 'Point-Source CO_2 Avoidance.' The rate of CO_2 avoidance is a valuable metric when CO_2 tax penalties are in place.

Exhibit 8-11. Analysis of decarbonization impact for base cases

Case Number	Total CO_2 Captured, tonnes/year	CO_2 Emitted by Boiler Flue Gas, tonnes/year	CO_2 Emitted by Kiln Off-gas, tonnes/year	CO_2 Captured from Kiln Off-gas, tonnes/year	Point-Source CO_2 Avoidance, %
CM99-B	1,516,106	350,133	1,181,523	1,165,973	98.7%
CM95-B	1,426,677	320,081	1,181,467	1,106,596	93.7%
CM95-B1	1,415,169	307,954	1,181,627	1,107,215	93.7%
CM95-B2	1,424,904	318,205	1,181,610	1,106,699	93.7%
CM95-B3	1,689,106	347,831	1,430,594	1,341,275	93.8%
CM95-B4	1,674,063	331,995	1,430,594	1,342,068	93.8%
CM95-B5	1,391,847	283,430	1,181,467	1,108,417	93.8%
CM95-B6	1,325,543	213,678	1,181,467	1,111,865	94.1%
CM95-B7	1,381,155	272,173	1,181,627	1,108,982	93.9%
CM95-B8	1,316,892	204,565	1,181,627	1,112,327	94.1%
Average	**1,456,146**	**295,005**	**1,231,360**	**1,161,142**	**94.3%**

On average, the capture systems described in this study reduce the point-source CO_2 emissions (i.e., CO_2 avoidance) from representative cement plants by 94.3 percent. If only considering the cases that employ capture systems designed for a total CO_2 capture rate of 95 percent (i.e., excluding CM99-B), the average point-source CO_2 avoidance is 93.8 percent. Applying the more conservative reduction to average point-source emissions associated with the processing capacity of 89.3 M tonnes of finished cement reported by the cement industry in 2020 would equate to a point-source emissions avoidance of approximately 77.2 M tonnes CO_2 per year. [3] [2] This analysis does not consider lifecycle emissions (e.g., the CO_2 emissions associated with producing purchased natural gas and/or power, capture equipment manufacturing operations, etc.) and thus is not representative of lifecycle decarbonization.

9 CONCLUSION

The cement industry represents an impactful opportunity for industrial decarbonization, with nearly 69 M tonnes per year of CO_2 emissions in 2020, representing approximately 1.5 percent of total domestic CO_2 emissions based on reporting to the Environmental Protection Agency. [1] [2] Representative cement plant configurations were examined as part of this study to evaluate the effects of cement kiln off-gas characteristics on the cost of retrofit CO_2 capture. Based on the kiln fuel used, the type of kiln in the base cement plant, and heat integration potential, the off-gas stream created from calcination and kiln heating can range in CO_2 concentration from 13–31 mole percent, on average, if no additional air ingress is considered. The addition of solvent-based CO_2 capture and purification operations requires steam for solvent regeneration, which is provided by an NG-fired boiler in this study. Comingling the flue gas of the industrial boiler with the kiln off-gas stream results in a CO_2 emissions stream that is 12–23 mole percent CO_2, on average, if no additional air ingress is considered.

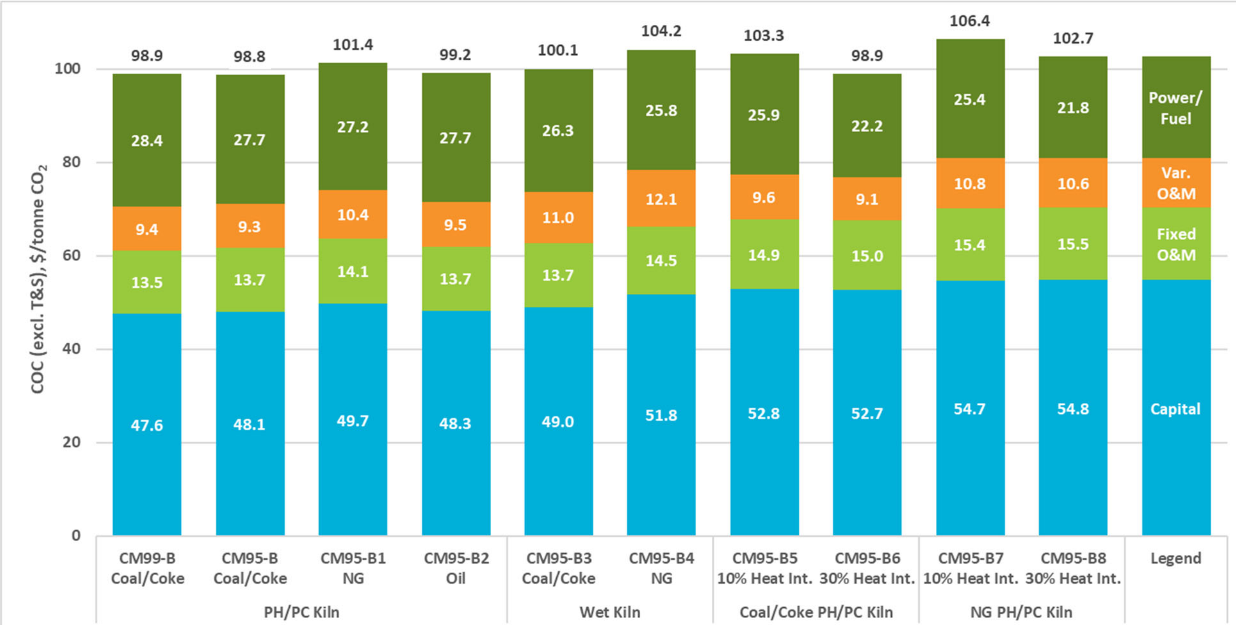
Capturing the CO_2 from the comingled emissions stream is achieved using a solvent-based CO_2 absorption process, TEG dehydration, and compression of the high-purity CO_2 product, along with the auxiliary heating and cooling systems required to support the addition of the capture processes. A retrofit difficulty factor was applied to the TPC in each case, as detailed in Section 2. The resulting retrofit COCs, excluding T&S costs, ranging $98.8–128.1/tonne CO_2 represent the levelized cost to remove approximately 1.4 M tonnes of CO_2 emissions at the representative cement plants, each producing 1.5 M tonnes of finished cement per year.

The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher than the presented estimates. Absent demonstrated first-of-a-kind plant costs, it is difficult to explicitly project fully mature, Nth-of-a-kind values. Consequently, the cost estimates provided herein represent neither first-of-a-kind nor Nth-of-a-kind costs but could be considered next-of-a-kind.

Applying a consistent methodology and presenting detailed equipment specifications and costs based on contemporary sources facilitates comparison between cases. Sensitivity analyses performed on a similar basis can be used to guide R&D, and generally improve upon publicly available estimates. Anticipated actual costs for projects based upon any of the cases presented herein are expected to deviate from the cost estimates in this report due to project- and site-specific considerations (e.g., contracting strategy, local labor costs and availability, seismic conditions, water quality, financing parameters, local environmental concerns, weather delays, market forces) that may make construction more costly. Such variations are not captured by the reported cost uncertainty.

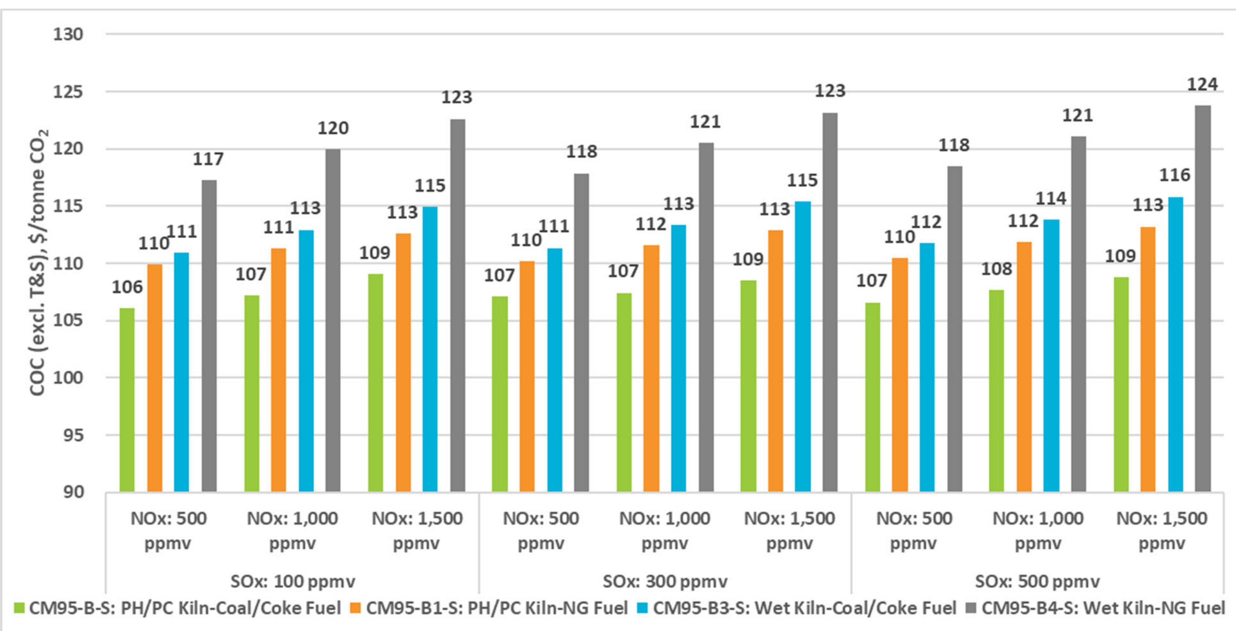
The base cases considered in this study evaluated kiln off-gas streams that were immediately suitable for treatment in the CO_2 capture system (i.e., do not require treatment to remove SOx, NOx, or PM). For the base cases, retrofit COC falls between $98.8/tonne CO_2 and $106.4/tonne CO_2, PH/PC kiln firing coal/coke fuel showing the lowest cost opportunity for retrofit capture application. The base case results are summarized in Exhibit 9-1.

Exhibit 9-1. Summary of base cases COC (excl. T&S)



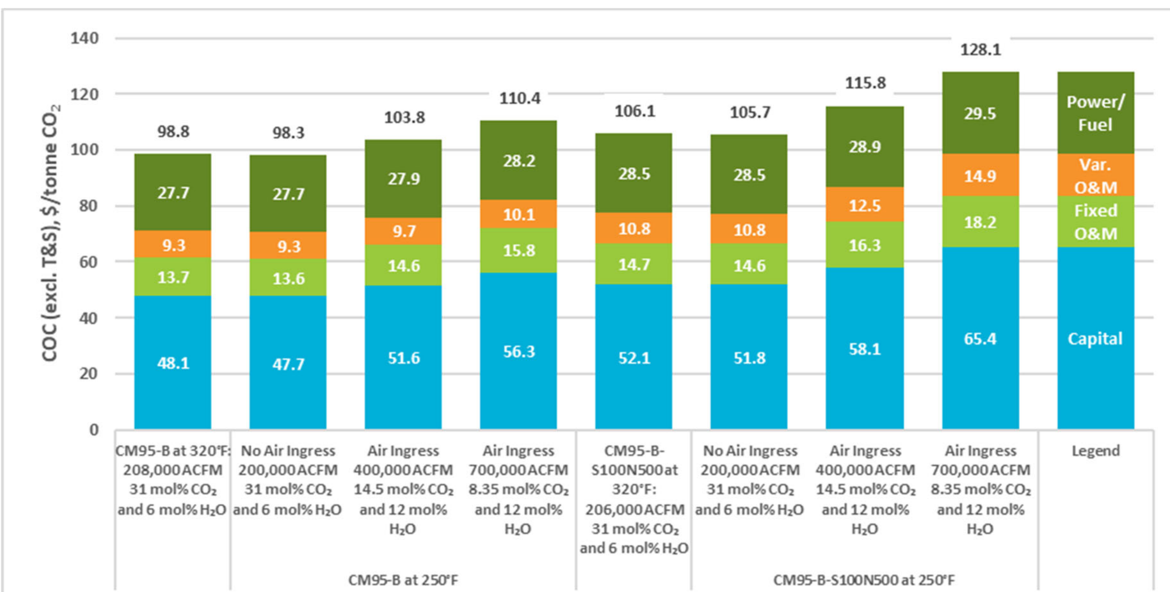
At the high end of the COC range in this study are the cases evaluated to include abatement of SOx and NOx from the kiln off-gas stream via FGD and SCR operations, respectively. In addition, inherent to the FGD process is removal of PM from the emissions stream. Addition of these treatment processes increased the total COC by 7.4–18.8 percent over the respective base case. The effect of adding FGD and SCR processes increased the capital costs for the sensitivity cases by 8.4–13.7 percent over the base cases. O&M costs increased by 6.4–23.9 percent over the base cases. Exhibit 9-2 shows a summary of the COC for the sensitivity cases with FGD and SCR.

Exhibit 9-2. Summary of COC for sensitivity cases with FGD and SCR



The kiln off-gas stream is often used for heating and drying raw meal solids, which increases the moisture and volumetric flowrate and decreases the CO_2 concentration entering the capture system due to additional air in-leakage via the raw mill units. Three additional scenarios were considered to evaluate the impacts of such air in-leakage on the COC for case CM95-B (i.e., PH/PC kiln burning coal/coke fuel) and for case CM95-B-S100N500 (i.e., PH/PC kiln burning coal/coke fuel with FGD and SCR abatement of SOx and NOx). The results of these analyses are that with additional air ingress, COC can increase by as much as 11.7 percent for cases without FGD and SCR, and 20.7 percent for cases with SCR and FGD. The impacts of increasing air in-leakage are seen in the capital costs associated with larger equipment required to accommodate higher volumetric flowrates and with increased O&M costs associated with larger operating units. The deviation from base case costs is most evident in the cases that include FGD and SCR units, where costs rise at a faster rate due to additional unit operations. The most likely scenario for capture retrofits to existing cement plants is illustrated by the two right-side cases of Exhibit 9-3 (i.e., total COCs of \$115.8 and \$128.1/tonne CO_2), which include false air ingress from the raw mill circuit as well as FGD and SCR unit operations to preclean the resulting emissions stream prior to the Shell CANSOLV® island.

Exhibit 9-3. Summary of COC for sensitivity cases with air in-leakage

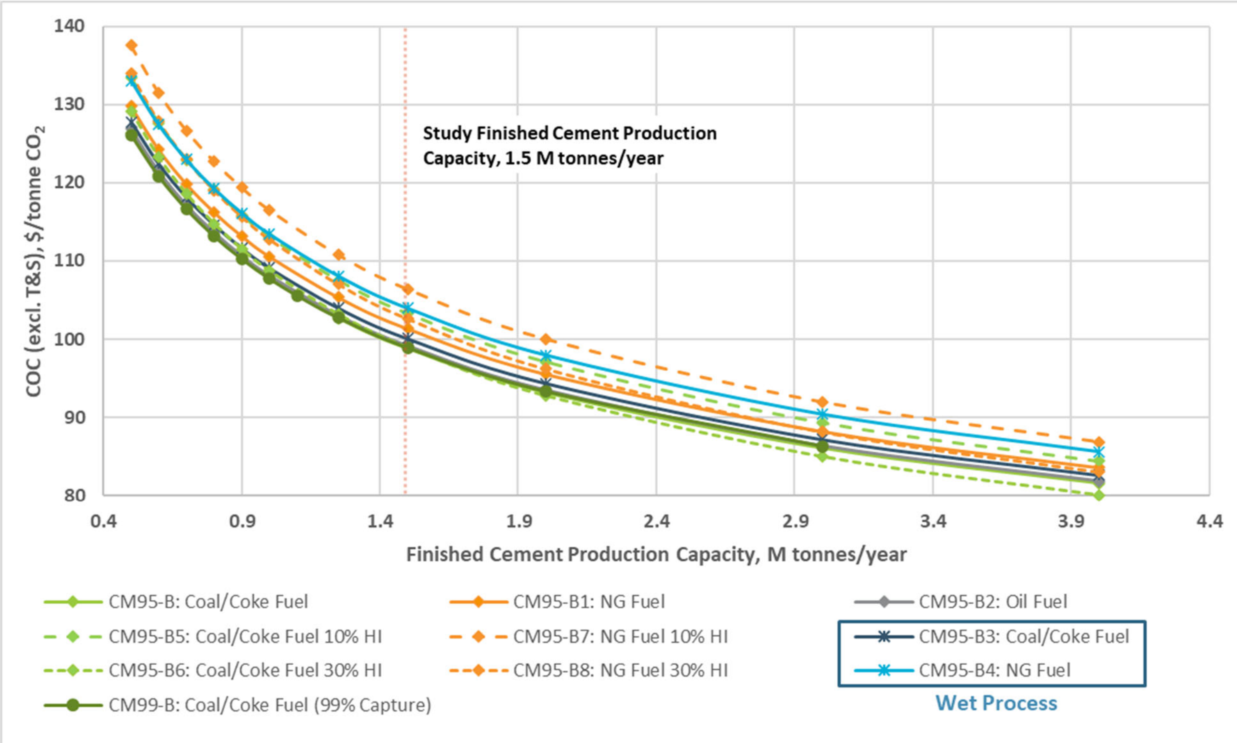


Sensitivity analyses of operating basis, CCF, WACC, retrofit factor, purchased power price, NG price, and T&S price were evaluated for the base cases (i.e., those presented in Section 5) to demonstrate the effects of changing financial or design assumptions on the COC as calculated in this study. All sensitivity analyses were evaluated in isolation, and it is possible that if individual design assumption changes were considered in combination, impacts on the COCs would potentially differ from the additive values of each change in design assumption. Operating basis can also be influenced by the reliability of the electrical power grid, as the capture systems in this study rely on purchased electricity. As an illustrative example, this analysis suggests that, to add CO_2 capture to the cement kiln considered in case CM99-B, a 22 MW auxiliary power load is incurred. It could be inferred that deployment of similar CO_2 capture processes across the domestic cement fleet would require a significant increase of additional power consumption. Although grid impact and reliability was not considered as part of this analysis, ensuring the necessary generation and transmission capacity exists to meet this demand will be an important issue to assess when considering decarbonization of the U.S. cement industry.

Another important highlight of the single-parameter sensitivity analyses performed is the comparison of purchased power price and NG price impacts to the COC. Exhibit 5-79 (purchased power price sensitivity) and Exhibit 5-78 (NG price sensitivity) demonstrated that the impact of increasing NG price is 23–34 times higher than increasing purchased power price. Taking case CM95-B1 for example, the capture system elicites a 20 MW auxiliary power load and burns roughly 29,000 lb/hr of NG. On an energy basis, this equates to roughly 10 times more natural gas than power required in support of the capture process. Although the auxiliary load for the CO_2 capture process is relatively high, it is likely more impactful to COC to focus improvements on solvent performance and reduction of the associated solvent regeneration heating demands. As an alternative, alternate heating methods for solvent regeneration, such as electric heating, or better still, a combined heat and power system, could greatly improve the COCs estimated in this study.

In addition to those sensitivity analyses related to design and financial assumptions, a sensitivity analysis related to the cement plant production capacity was evaluated for each base case. By estimating the COC across a range of cement plant sizes, the effects of economies of scale are demonstrated, as normalized COC increases with decreasing plant size (i.e., decreasing amount of CO_2 available for capture). This analysis assumed continuous equipment sizing and availability for estimating purposes. In real applications, equipment is often manufactured in discrete sizing and may require installation of several units in parallel to achieve higher-end throughput capacity, or conversely, the use of oversized/underutilized (i.e., economically non-optimal) equipment to support lower-end throughput capacity. Such factors, along with the additive effects of financial and design assumptions, would impact the outcome of the plant size sensitivities presented throughout Section 5, but the sensitivity estimates are considered appropriate within the accuracy of this study (AACE Class 4). A cumulative graph of the plant size sensitivity analyses is presented in Exhibit 9-4, where the COC increases by $39.8–50.9/tonne CO_2 (i.e., 46–61 percent) as the plant production capacity decreases from 4 M tonnes of finished cement per year to 0.5 M tonnes of finished cement per year (i.e., production capacity decreases by 87.5 percent).

Exhibit 9-4. Summary of plant capacity sensitivity analyses for base cases



Note: HI = heat integration

10 LIMITATIONS

The results produced by this technoeconomic analysis are limited to the financial and design assumptions presented in Section 1 through Section 4. Fluctuations in financial assumptions (e.g., purchased power price, natural gas price, debt and equity costs) may occur over the assumed operational and capital expenditure periods that are not accounted for when using constant economic assumptions. In addition, the models used to predict capture costs in this report are steady-state representations of the capture process. Physical challenges may also exist when retrofitting capture systems. As such, it is important to note challenges in real applications that would likely impact the results presented in this report. Limitations associated with construction would have consequences to capital expenditures, and resource availability would impact both construction costs and ongoing O&M costs. Process upsets and project-specific unit operations and operating philosophies would influence design considerations and have ramifications on the O&M costs projected in this study. Some of these limitations are detailed for qualitative consideration, but the cost of retrofitting CO_2 capture at any specific cement plant is heavily dependent upon site and operating conditions and should be thoroughly evaluated with detailed engineering design to more accurately project COC.

10.1 CONSTRUCTION CHALLENGES

10.1.1 Site Availability and Conditions

The cost of land (10 acres) for the retrofit capture equipment is estimated based on land costs in other NETL analyses, but in real applications, land availability may be scarce, requiring increased expenditure for purchasing the land or for covering the costs of more complex site development. This is especially true for the cement industry, where adjacent land for the footprint of capture facilities is scarce. In some cases, it may be necessary to construct the capture system "off-site" and include additional piping to route the kiln off-gas from the cement plant to the capture facility. These types of site-specific costs are not included in the COCs of this study. Site location could also change the ambient conditions assumed in the design basis, which would impact cooling and heating operations as well as emissions and process stream conditions. The cement industry is vast, with facilities in almost every state of the continuous United States, and site and ambient conditions vary greatly from one plant to the next, meaning that construction costs will likely differ from site to site.

Moreover, complications associated with air permitting and emissions control stipulations can vary by state and must be individually assessed. The air permitting process can often result in significant variation to a project's schedule and cost, and such real-world time and budget constraints are not accounted for in the projected COCs in this analysis. The three-year construction period for the retrofit capture systems in the cases evaluated herein may be optimistic if hurdles related to permitting were to arise.

10.1.2 Fuel Availability and Quality

The boiler used to raise steam for capture system solvent regeneration requires NG fuel. In cement plants that utilize NG fuel for kiln heating, this is likely not a limitation. However, many cement plants use coal/coke, oil, or alternative fuels for kiln heating, and NG may not be readily available at the plant or economically viable as a heating fuel due to lack of nearby distribution systems. In addition, the quality of an NG stream may be suboptimal for the boiler, requiring additional treatment steps, such as sulfur removal. Alternate steam generation technologies, such as electric heating or furnaces that utilize fuel sources that already exist at the cement plant, would change the COCs predicted in this analysis. The NG fuel costs and purchased power in each case are approximately one third of the COC, and changes to the design assumptions, equipment, and resulting power requirements would likely have an impact on capture costs.

10.1.3 Water Availability and Quality

Water availability and quality at cement plants can range from ideal to unusable based on location. This analysis assumes that 50 percent of water needs are sourced from groundwater, and, in many cement plants, that may be an optimistic estimate of water availability. In other locations, availability may not be constrained, but groundwater quality is not acceptable and would require treatment beyond what is accounted for in this analysis. These considerations would have implications for the COC and should be considered on a case-by-case basis when considering real-world applications of CO_2 capture operations.

10.2 Process Challenges

10.2.1 Air In-Leakage

As indicated in Section 7, air in-leakage, or false air ingress, can impact the conditions of the emissions stream treated by the CO_2 capture island. The air in-leakage analysis included herein is meant to show trends associated with a range of scenarios, but it is not comprehensive to the operational conditions seen across the cement industry. After passing through the raw mill, the resulting emissions stream that would enter the capture system can vary with regards to pressure, temperature, mass and volumetric flowrates, composition, and contaminants. In addition, pre-processing raw mill operations are not always a continuous unit operation in a cement plant, meaning that the kiln off-gas could potentially have two or more operating profiles dependent upon plant status. All these factors may be a stark deviation from the design bases of the cases in this analysis and would likely have significant impact on the calculated COCs.

10.2.2 Process Upsets

The models developed for this analysis represent steady-state, ideal conditions at the cement kiln exit. Of course, many deviations in kiln conditions were considered to attempt to project the changes in COC under different operating scenarios but, in real applications, process upsets would impact many aspects of the capture system O&M. Contingencies for process upsets might also necessitate the inclusion of additional processing units, bypass equipment, and more, which would cause increased capital expenditures compared to those projected in this analysis. Lastly, process upsets could dramatically impact the utilization rate (i.e., operating basis) that was assumed in this study. The sensitivity to operating basis is included to serve as a standalone analysis of how constant, average operation impacts the cost of the steady-state operation of the unit, but utilization varies from year to year based on processing conditions and market trends, which would ultimately change the COCs presented herein.

10.2.3 Process Contaminants

The base cases in this study consider an ideal kiln off-gas stream, while the sensitivity cases in Section 6 and Section 7 quantify the deviations in stream quality and conditions as they relate to SOx and NOx contaminants and to air in-leakage. However, the quality of the ambient air, kiln fuel quality, and processing operations can influence the resulting emissions stream that enters the capture system. SOx and NOx contaminants vary widely from one cement plant to the next; this analysis includes consideration of FGD and SCR operations to reduce those contaminants to the design basis limits. As increasing levels of contaminants may have a range of effects on solvents depending on the technology deployed, capture system-specific limitations should be addressed by individual technology providers in real applications.

The FGD and SCR systems employed in this analysis follow the design of a similar unit applied to the flue gas stream at a pulverized coal-fired power plant, and performance and costs are scaled from those of the same reference plant. The impact of higher amounts of particulate matter in cement plant kiln off-gas when compared to power generation flue gas streams, and the impact of cement industry-specific unburned hydrocarbons on the performance and cost of FGD and SCR steps were not considered in this analysis. More complex and costly particulate matter controls than those in this study are likely required to meet emissions standards of the cement industry and to avoid negative impacts in the solvent system.

Moreover, in the presence of cement industry-specific unburned hydrocarbons, SCR can potentially create more undesirable co-contaminants, such as hydrogen cyanide (HCN), formaldehyde, styrene, CO, and toluene. HCN is often produced in cement kilns during combustion, and in the presence of trace hydrocarbons from incomplete combustion in the kiln and ammonia used in the SCR, more HCN can form across the catalyst unit, which can be detrimental to amine systems. [24] [25]

To prevent HCN ingress into the capture system, changing the order or type of unit operations and/or adding additional control technologies may be necessary, which would add to capital and O&M costs as they are presented in this study. HCN removal can be achieved with water wash systems, but the amount removed is dependent upon its solubility in water, which is a function of temperature, and can demand a large water usage rate to achieve high removal efficiencies. If the HCN passes through to the CO_2 capture system, very little will be removed by the inlet direct contact cooler due to its temperature (i.e., the corresponding solubility of HCN in water is low at direct contact cooler operating conditions). The remaining HCN in the stream will ionize and be absorbed by the amine solvent, which will cause the formation of formic acid and ammonia in the solvent. Ammonia will be released along with the treated flue gas. Formic acid can be removed via reclamation (i.e., ion exchange or thermal reclamation), but a portion of the formic acid can react with the amine to form formamides, which can only be removed by thermal reclamation. For this reason, it is preferable to control the formic acid concentration relatively low and minimize this side reaction and associated reclamation costs. Considering the cost, performance, and emissions control impacts of increased contaminants of the kiln-off gas stream, adequately characterizing the base cement plant with regards to its location, emissions profile, and operating conditions is paramount when retrofitting CO_2 capture operations.

11 Future Work

11.1 In-Depth Process Analysis

There are several opportunities where the results herein could be used as a starting point for a more in-depth analysis of the representative cement plants evaluated in this study. For example, the heat integration potential as defined in this study might increase retrofit difficulty over that of the base 1.155 retrofit factor applied in cases CM95-B5 through CM95-B8, affecting capital expenditures. In-depth analysis of the existing cement plant layout, the availability and quality of heat sources, and operating impacts of heat integration would better demonstrate optimums of implementing heat integration opportunities.

Secondly, the heat requirements of the capture systems employed in the cases analyzed in this study elicit the need for a standalone boiler, as discussed in Section 3.2. The flue gas from this NG-fired boiler contains additional CO_2 emissions over that of the base process, which were co-mingled with the kiln off-gas stream prior to CO_2 capture based on the assumptions made in this study. As discussed, the impact of increasing NG price is 23-34 times higher than increasing purchased power price. Although the auxiliary load for the CO_2 capture process is relatively high, the NG demand in some cases 10 times higher than the power demand on an energy basis. As such, alternate heating methods for solvent regeneration, such as electric heating, or better still, a combined heat and power system, could greatly improve the COCs estimated in this study.

Lastly, much of the base cement plant is not characterized, which requires assumptions regarding utility availability (e.g., fuel gas systems, instrument air). A more in-depth process analysis might evaluate the additional capacities required for such utilities and how those additions would affect the existing plant's utility systems.

11.2 Other CO_2 Capture Technologies

Novel CO_2 capture technologies, such as membrane-based capture or cryogenic CO_2 capture systems, could be evaluated in place of the amine-based post-combustion CO_2 capture system described in this analysis. Employing other types of CO_2 capture systems would have effects on O&M costs (e.g., fuel and power needs, consumable and waste disposal costs) and on capital costs. The cost premiums associated with novel technologies could be evaluated as a sensitivity parameter to determine impactful cost improvement opportunities for researchers. Such analysis would highlight technology advancement goals for alternate, novel CO_2 capture systems that may eventually make them comparable to more mature capture technologies used in industry today.

11.3 Analysis of CO_2 Distribution to Enhanced Oil Recovery Fields

The economics of CO_2 T&S in this study were based on guidance in the QGESS "Carbon Dioxide Transport and Storage Costs in NETL Studies" but would ultimately be affected by plant location, proximity to existing CO_2 pipeline(s) and enhanced oil recovery field(s), etc. [4] For example, pressures as low as 1,200 psig may be acceptable for EOR field usage and reducing the pressure to which the CO_2 product needs to be compressed would reduce the COC, as a reduction in pressure would result in a lower compressor capital cost, as well as reduced power consumption. Considering such cost implications on a more detailed or project-specific basis would expand upon the cost implications of retrofit CO_2 capture, transmission, and storage opportunities in the cement industry.

11.4 Life Extension Costs for Existing Facilities

The implicit assumption for the cases presented in this study is that the plants that have been retrofitted (i.e., the existing cement plants and/or lime quarries) have sufficient remaining life, such that the base plant remaining life will match the expected life of the retrofit capture equipment, assumed to be 30 years. This study does not consider, or include any costs to represent, life extension projects that a plant may consider if adding CO_2 capture (i.e., improvements to the existing cement plants). Future work might include an analysis to identify the average age of the cement fleet or remaining life of the lime quarries, characterize the expected remaining life for the fleet, and characterize the cost of typical life extension projects that would be considered as part of a capture retrofit.

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APPENDIX A: ENERGY AND MASS BALANCES

Exhibit A-1. Energy and mass balance diagram for case CM99-B

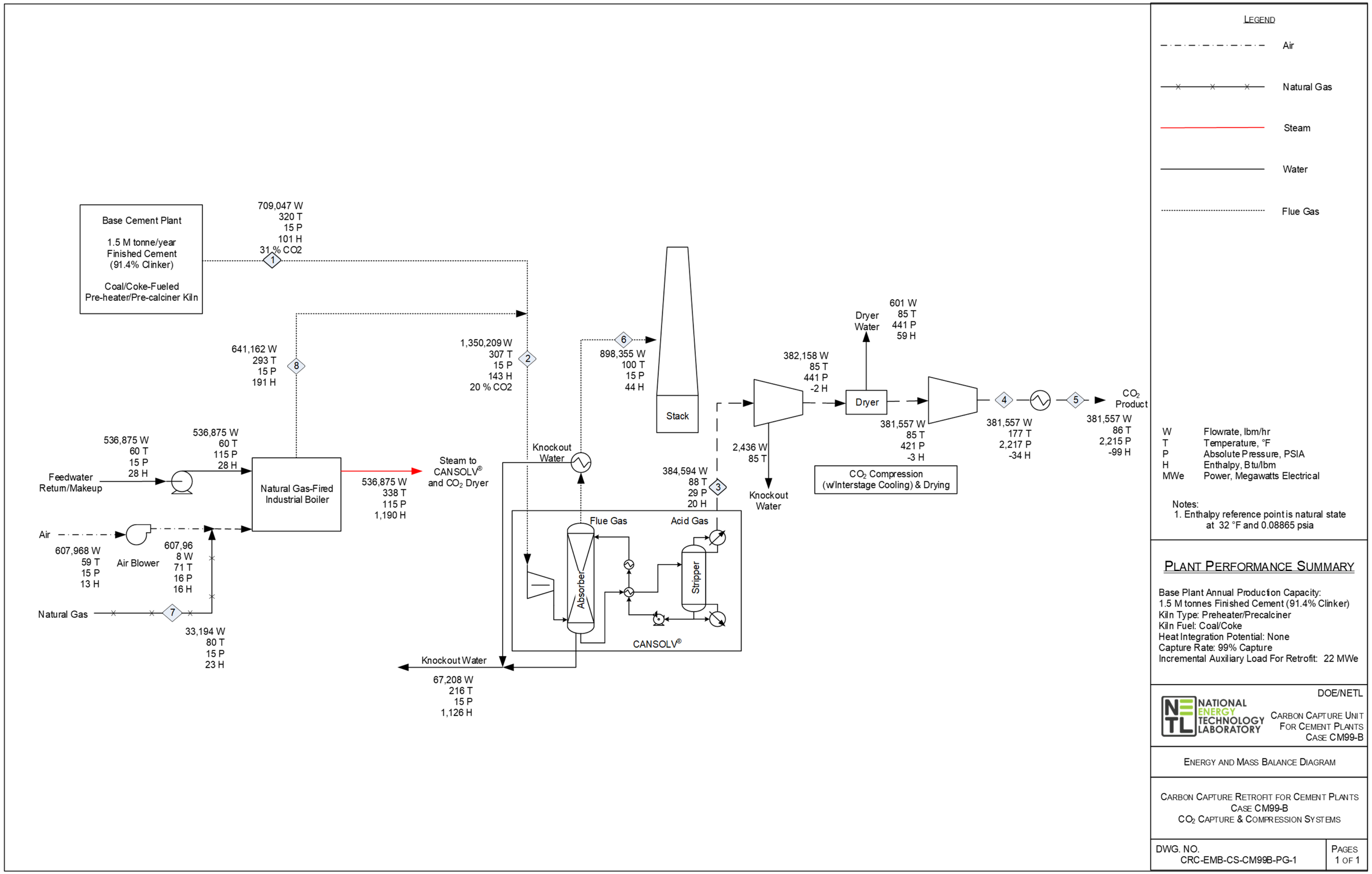

Exhibit A-2. Stream table for case CM99-B

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0043	0.0000	0.0000	0.0000	0.0060	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3106	0.1956	0.9809	0.9995	0.9995	0.0028	0.0100	0.0869
H_2O	0.0501	0.1148	0.0191	0.0005	0.0005	0.0385	0.0000	0.1758
N_2	0.6112	0.6612	0.0000	0.0000	0.0000	0.9191	0.0160	0.7083
O_2	0.0281	0.0241	0.0000	0.0000	0.0000	0.0336	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,867	20,318	4,009	3,934	3,934	14,616	869	10,451
V-L Flowrate (kg/hr)	321,618	612,445	174,449	173,071	173,071	407,487	15,057	290,826
Temperature (°C)	160	153	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	229.49	331.83	44.08	-78.54	-231.09	101.83	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-3,986.06	-3,339.39	-8,973.63	-9,042.09	-9,194.65	-360.24	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.594	30.143	43.513	43.997	43.997	27.879	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,754	44,793	8,839	8,672	8,672	32,223	1,916	23,040
V-L Flowrate (lb/hr)	709,047	1,350,209	384,594	381,557	381,557	898,355	33,194	641,162
Temperature (°F)	320	307	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	98.7	142.7	18.9	-33.8	-99.4	43.8	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,713.7	-1,435.7	-3,858.0	-3,887.4	-3,953.0	-154.9	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.054	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-3. Energy and mass balance diagram for case CM95-B

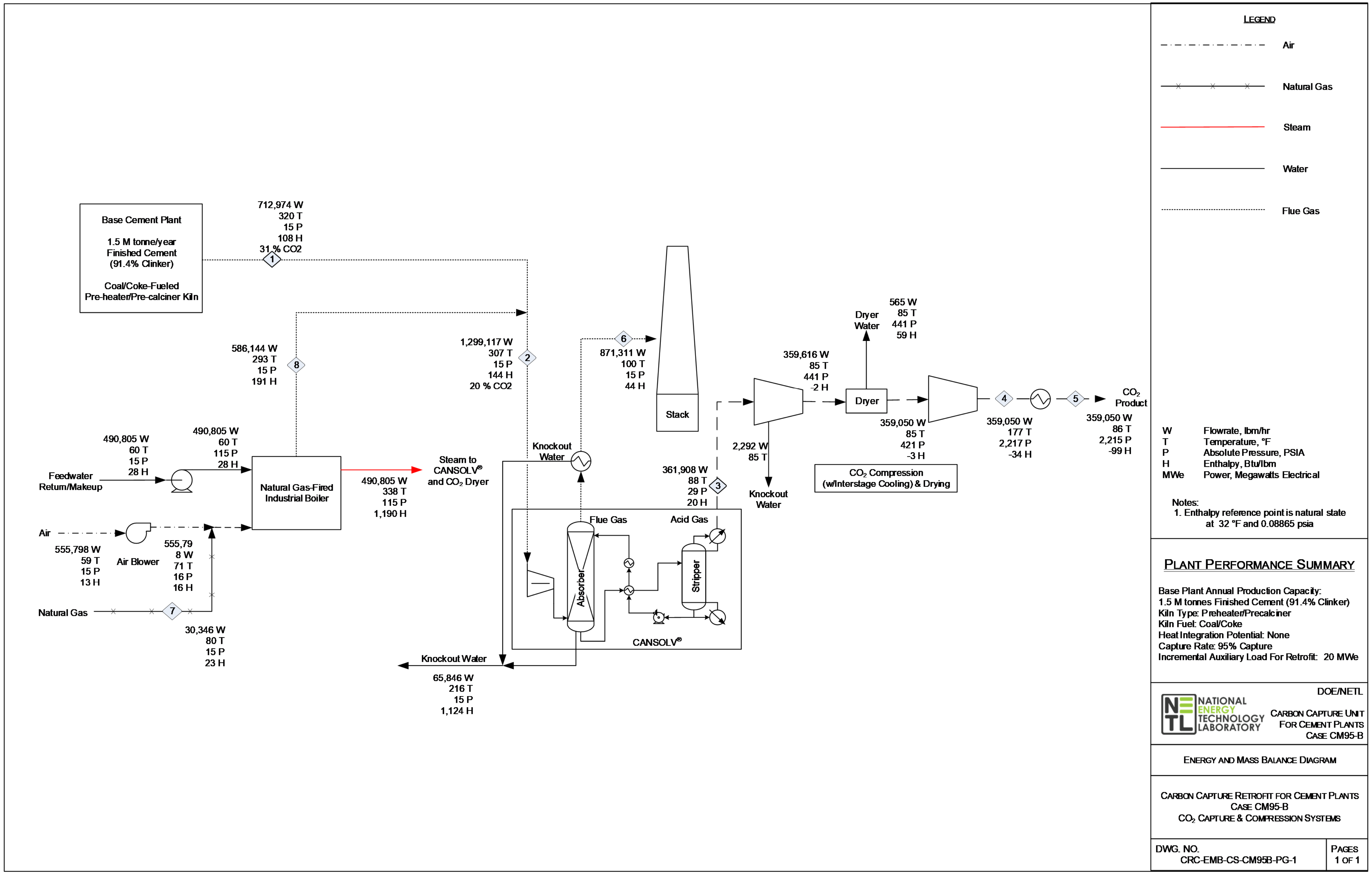

Exhibit A-4. Stream table for case CM95-B

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0041	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3075	0.1996	0.9809	0.9995	0.9995	0.0138	0.0100	0.0869
H_2O	0.0595	0.1164	0.0191	0.0005	0.0005	0.0385	0.0000	0.1758
N_2	0.6051	0.6556	0.0000	0.0000	0.0000	0.9084	0.0160	0.7083
O_2	0.0278	0.0242	0.0000	0.0000	0.0000	0.0335	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,966	19,520	3,773	3,702	3,702	14,089	794	9,554
V-L Flowrate (kg/hr)	323,399	589,270	164,159	162,862	162,862	395,220	13,765	265,870
Temperature (°C)	160	153	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	243.66	334.50	44.08	-78.54	-231.09	101.35	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,036.64	-3,399.39	-8,973.63	-9,042.09	-9,194.65	-512.99	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.450	30.188	43.513	43.997	43.997	28.052	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,972	43,034	8,317	8,161	8,161	31,061	1,751	21,063
V-L Flowrate (lb/hr)	712,974	1,299,117	361,908	359,050	359,050	871,311	30,346	586,144
Temperature (°F)	320	307	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	104.8	143.8	18.9	-33.8	-99.4	43.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,735.4	-1,461.5	-3,858.0	-3,887.4	-3,953.0	-220.5	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.054	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-5. Energy and mass balance diagram for case CM95-B1

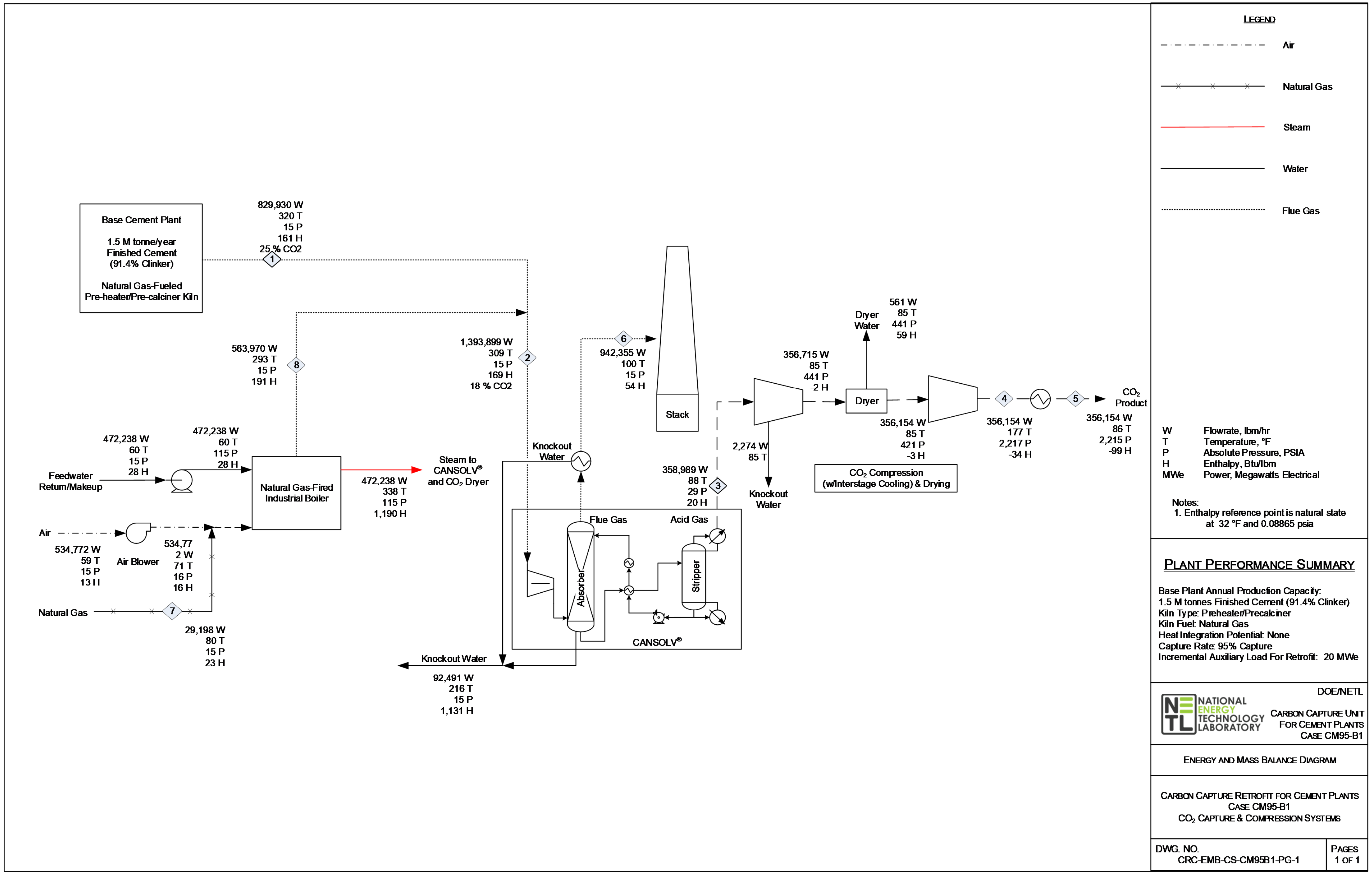

Exhibit A-6. Stream table for case CM95-B1

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0036	0.0000	0.0000	0.0000	0.0051	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.2510	0.1805	0.9809	0.9995	0.9995	0.0126	0.0100	0.0869
H_2O	0.1305	0.1500	0.0191	0.0005	0.0005	0.0528	0.0000	0.1758
N_2	0.5923	0.6422	0.0000	0.0000	0.0000	0.8965	0.0160	0.7083
O_2	0.0261	0.0237	0.0000	0.0000	0.0000	0.0331	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	12,211	21,403	3,742	3,672	3,672	15,332	764	9,192
V-L Flowrate (kg/hr)	376,450	632,262	162,835	161,549	161,549	427,445	13,244	255,812
Temperature (°C)	160	154	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	358.88	393.72	44.08	-78.54	-231.09	125.11	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,085.43	-3,494.24	-8,973.63	-9,042.09	-9,194.65	-622.66	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	30.829	29.540	43.513	43.997	43.997	27.880	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	26,921	47,186	8,250	8,095	8,095	33,801	1,685	20,266
V-L Flowrate (lb/hr)	829,930	1,393,899	358,989	356,154	356,154	942,355	29,198	563,970
Temperature (°F)	320	309	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	154.3	169.3	18.9	-33.8	-99.4	53.8	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,756.4	-1,502.3	-3,858.0	-3,887.4	-3,953.0	-267.7	-1,915.2	-1,128.2
Density (lb/ft^3)	0.054	0.053	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-7. Energy and mass balance diagram for case CM95-B2

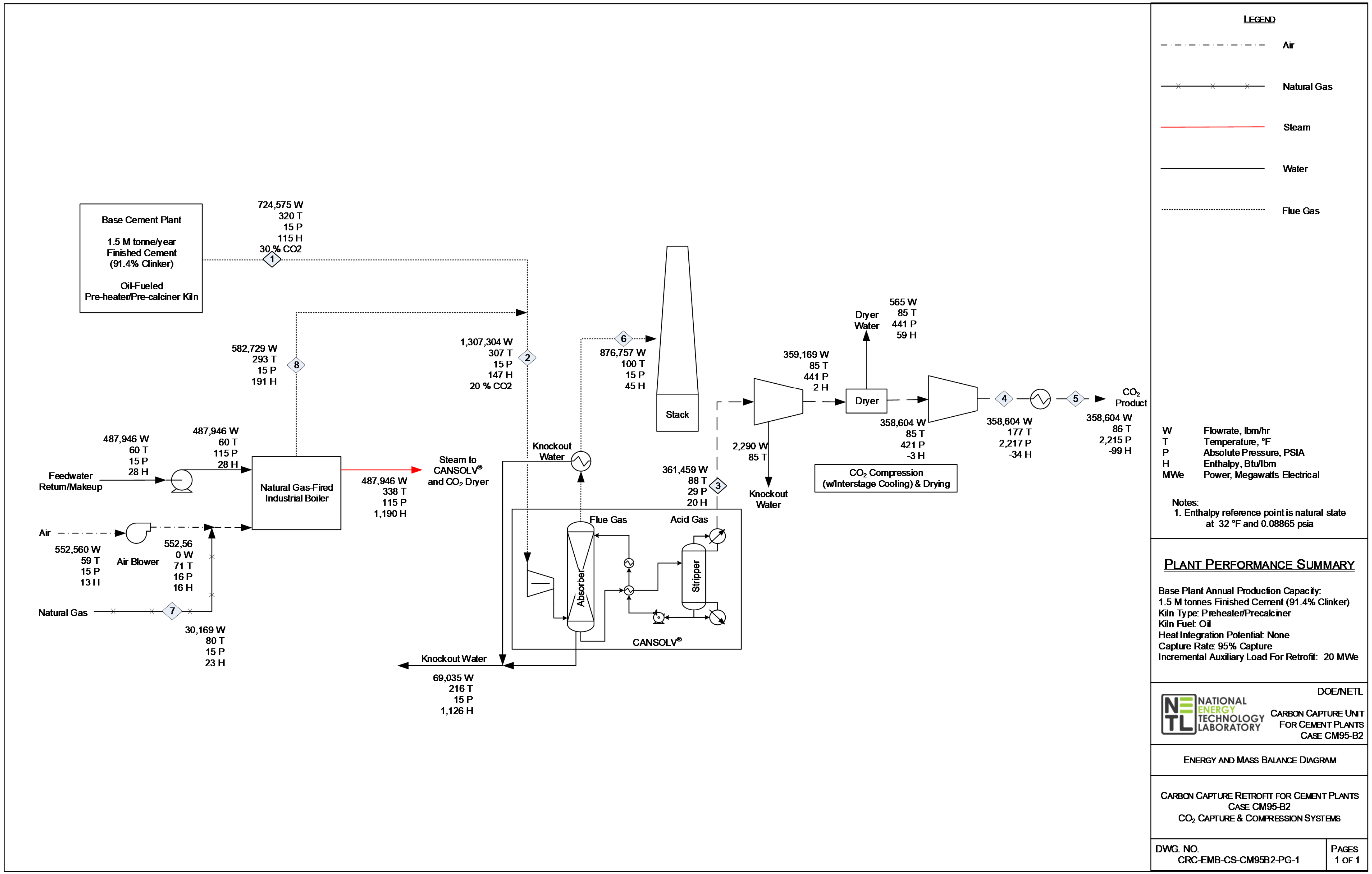

Exhibit A-8. Stream table for case CM95-B2

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0041	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3006	0.1976	0.9809	0.9995	0.9995	0.0137	0.0100	0.0869
H_2O	0.0701	0.1211	0.0191	0.0005	0.0005	0.0405	0.0000	0.1758
N_2	0.6012	0.6529	0.0000	0.0000	0.0000	0.9062	0.0160	0.7083
O_2	0.0281	0.0244	0.0000	0.0000	0.0000	0.0339	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	10,196	19,694	3,768	3,697	3,697	14,188	790	9,498
V-L Flowrate (kg/hr)	328,662	592,983	163,955	162,660	162,660	397,690	13,684	264,321
Temperature (°C)	160	153	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	260.01	342.47	44.08	-78.54	-231.09	104.63	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,058.75	-3,419.32	-8,973.63	-9,042.09	-9,194.65	-528.90	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.234	30.109	43.513	43.997	43.997	28.030	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	22,479	43,419	8,307	8,151	8,151	31,279	1,741	20,940
V-L Flowrate (lb/hr)	724,575	1,307,304	361,459	358,604	358,604	876,757	30,169	582,729
Temperature (°F)	320	307	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	111.8	147.2	18.9	-33.8	-99.4	45.0	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,744.9	-1,470.0	-3,858.0	-3,887.4	-3,953.0	-227.4	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.054	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-9. Energy and mass balance diagram for case CM95-B3

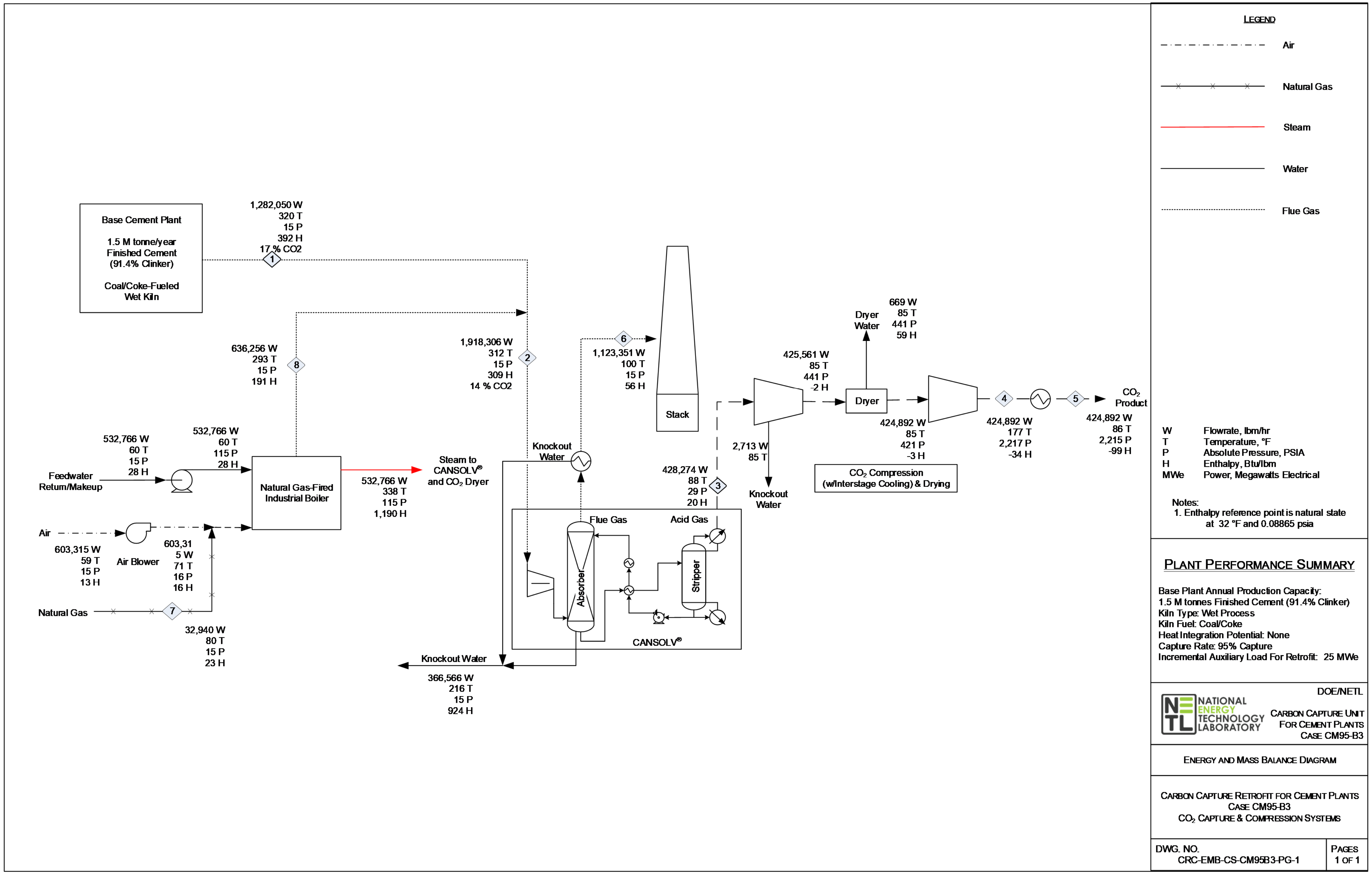

Exhibit A-10. Stream table for case CM95-B3

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0027	0.0000	0.0000	0.0000	0.0048	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1714	0.1440	0.9809	0.9995	0.9995	0.0126	0.0100	0.0869
H_2O	0.3931	0.3227	0.0191	0.0005	0.0005	0.0554	0.0000	0.1758
N_2	0.4234	0.5157	0.0000	0.0000	0.0000	0.9013	0.0160	0.7083
O_2	0.0121	0.0148	0.0000	0.0000	0.0000	0.0259	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	21,639	32,010	4,465	4,380	4,380	18,315	862	10,371
V-L Flowrate (kg/hr)	581,528	870,129	194,262	192,728	192,728	509,544	14,941	288,601
Temperature (°C)	160	155	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	854.17	718.46	44.08	-78.54	-231.09	129.67	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-5,882.29	-4,801.67	-8,973.63	-9,042.09	-9,194.65	-646.73	-4,454.70	-2,624.24
Density (kg/m^3)	0.8	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	26.874	27.183	43.513	43.997	43.997	27.821	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	47,707	70,570	9,843	9,657	9,657	40,378	1,901	22,863
V-L Flowrate (lb/hr)	1,282,050	1,918,306	428,274	424,892	424,892	1,123,351	32,940	636,256
Temperature (°F)	320	312	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	367.2	308.9	18.9	-33.8	-99.4	55.7	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-2,528.9	-2,064.3	-3,858.0	-3,887.4	-3,953.0	-278.0	-1,915.2	-1,128.2
Density (lb/ft^3)	0.047	0.048	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-11. Energy and mass balance diagram for case CM95-B4

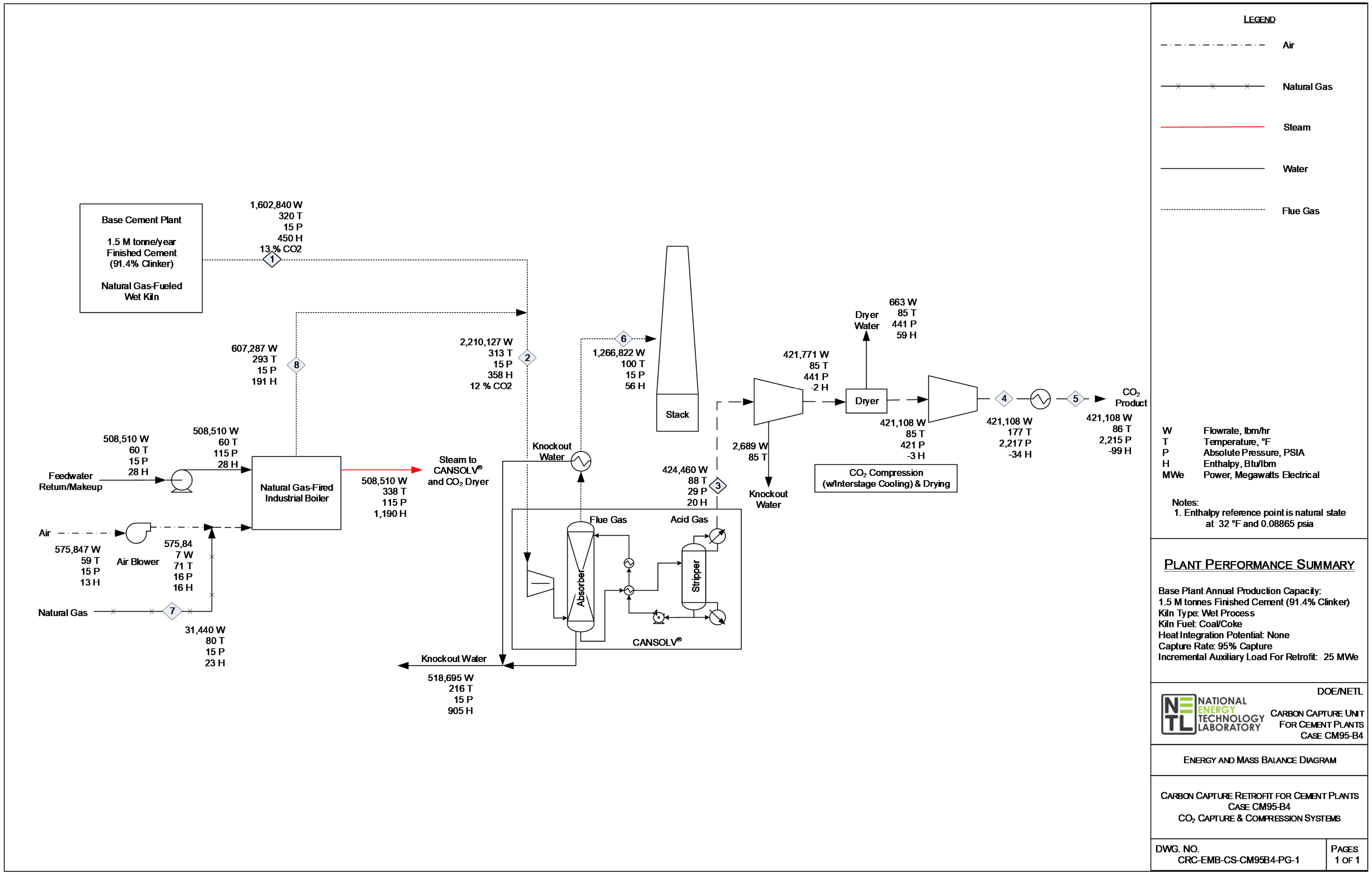

Exhibit A-12. Stream table for case CM95-B4

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0022	0.0000	0.0000	0.0000	0.0040	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1312	0.1197	0.9809	0.9995	0.9995	0.0111	0.0100	0.0869
H_2O	0.4440	0.3744	0.0191	0.0005	0.0005	0.0554	0.0000	0.1758
N_2	0.4137	0.4901	0.0000	0.0000	0.0000	0.9045	0.0160	0.7083
O_2	0.0111	0.0135	0.0000	0.0000	0.0000	0.0250	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	28,269	38,168	4,425	4,341	4,341	20,682	823	9,898
V-L Flowrate (kg/hr)	727,036	1,002,497	192,532	191,011	191,011	574,621	14,261	275,461
Temperature (°C)	160	156	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	980.46	833.33	44.08	-78.54	-231.09	129.84	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-6,010.82	-5,080.28	-8,973.63	-9,042.09	-9,194.65	-625.77	-4,454.70	-2,624.24
Density (kg/m^3)	0.7	0.7	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	25.718	26.266	43.513	43.997	43.997	27.784	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	62,323	84,145	9,755	9,571	9,571	45,596	1,814	21,822
V-L Flowrate (lb/hr)	1,602,840	2,210,127	424,460	421,108	421,108	1,266,822	31,440	607,287
Temperature (°F)	320	313	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	421.5	358.3	18.9	-33.8	-99.4	55.8	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-2,584.2	-2,184.1	-3,858.0	-3,887.4	-3,953.0	-269.0	-1,915.2	-1,128.2
Density (lb/ft^3)	0.045	0.047	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-13. Energy and mass balance diagram for case CM95-B5

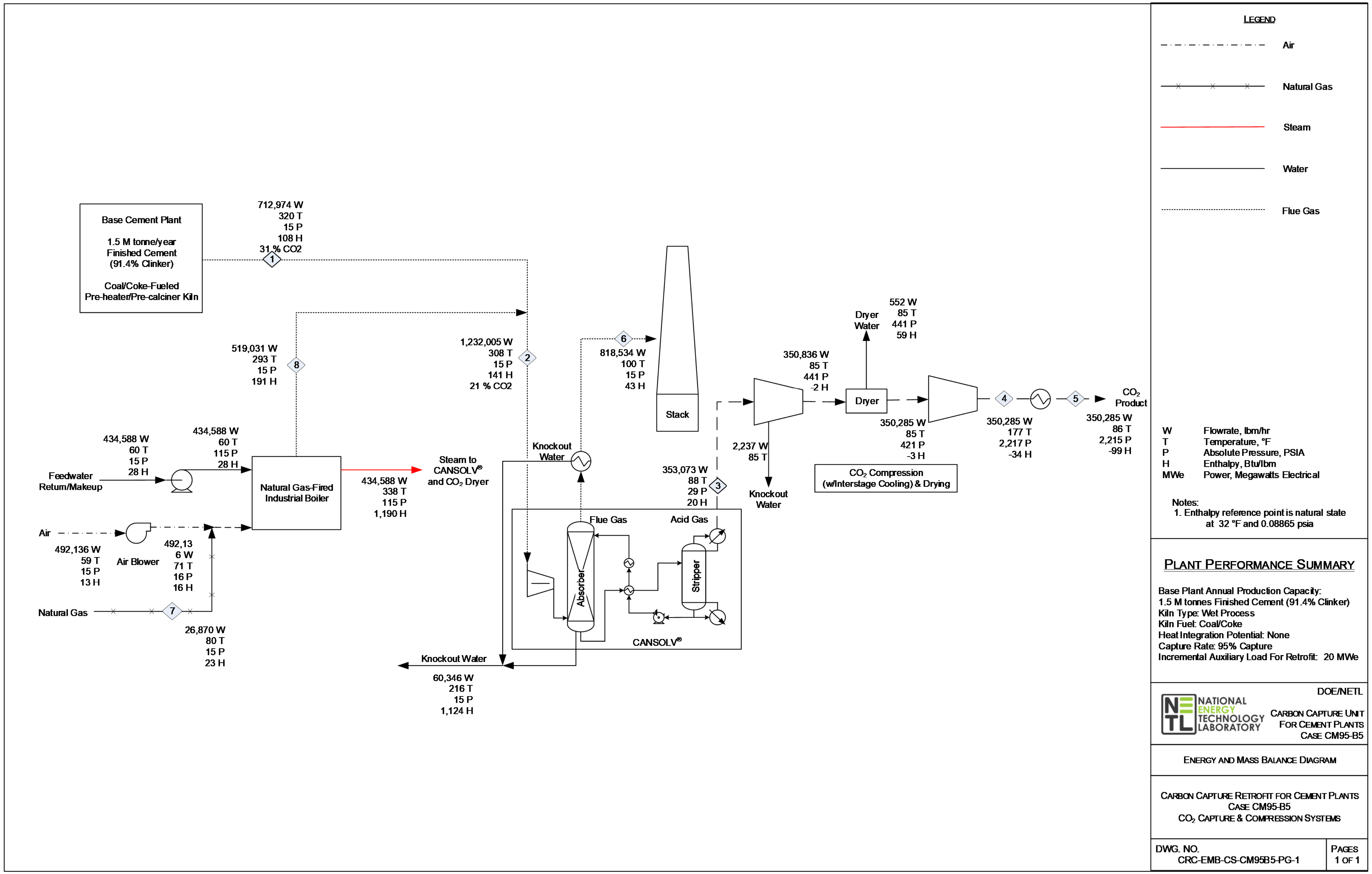

Exhibit A-14. Stream table for case CM95-B5

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0039	0.0000	0.0000	0.0000	0.0054	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3075	0.2062	0.9809	0.9995	0.9995	0.0144	0.0100	0.0869
H_2O	0.0595	0.1129	0.0191	0.0005	0.0005	0.0371	0.0000	0.1758
N_2	0.6051	0.6525	0.0000	0.0000	0.0000	0.9091	0.0160	0.7083
O_2	0.0278	0.0244	0.0000	0.0000	0.0000	0.0340	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,966	18,426	3,681	3,611	3,611	13,226	703	8,460
V-L Flowrate (kg/hr)	323,399	558,828	160,151	158,886	158,886	371,281	12,188	235,428
Temperature (°C)	160	153	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	243.66	328.48	44.08	-78.54	-231.09	98.99	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,036.64	-3,441.61	-8,973.63	-9,042.09	-9,194.65	-507.97	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.450	30.328	43.513	43.997	43.997	28.073	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,972	40,623	8,114	7,962	7,962	29,158	1,551	18,651
V-L Flowrate (lb/hr)	712,974	1,232,005	353,073	350,285	350,285	818,534	26,870	519,031
Temperature (°F)	320	308	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	104.8	141.2	18.9	-33.8	-99.4	42.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,735.4	-1,479.6	-3,858.0	-3,887.4	-3,953.0	-218.4	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.054	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-15. Energy and mass balance diagram for case CM95-B6

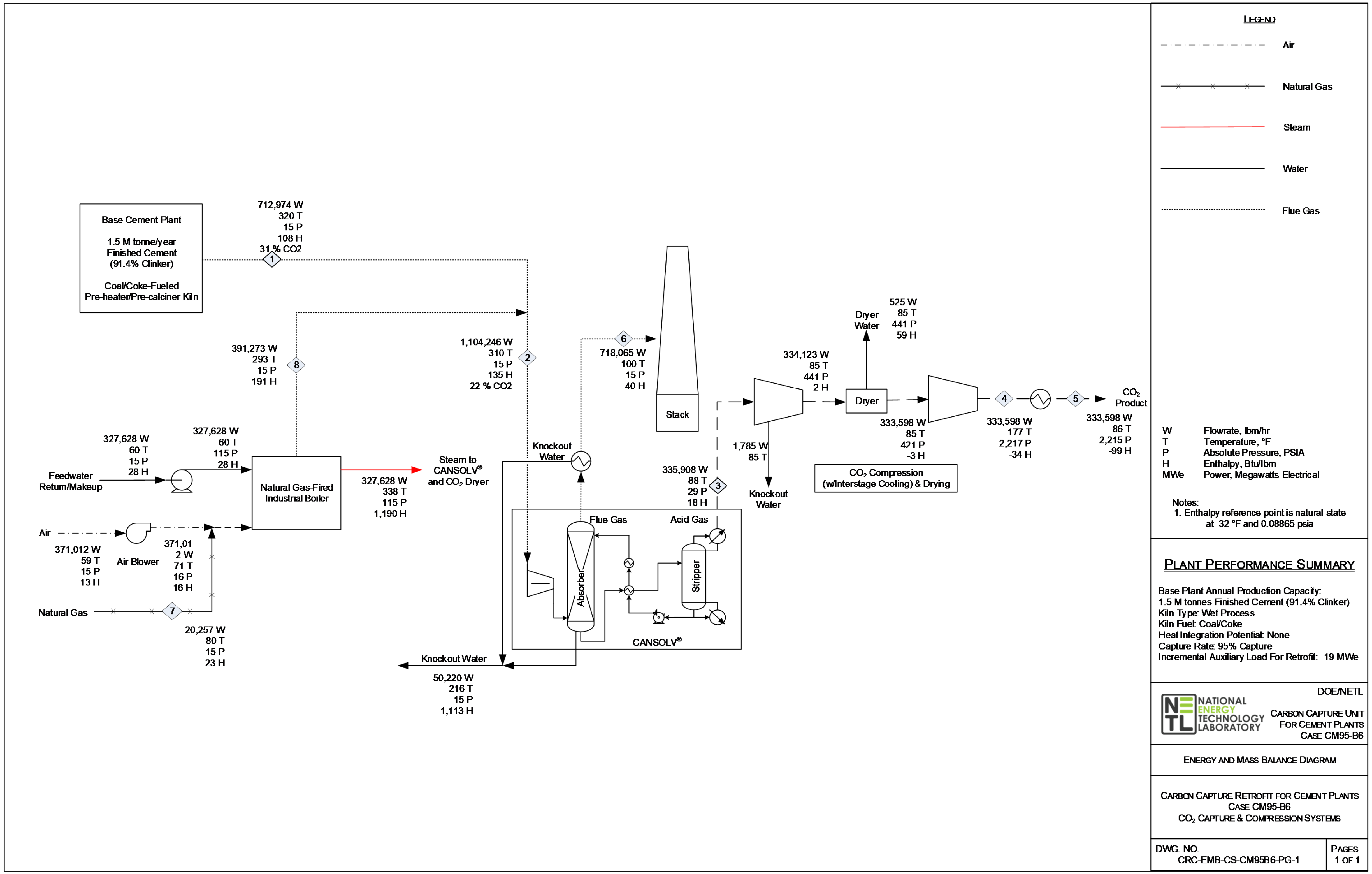

Exhibit A-16. Stream table for case CM95-B6

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0033	0.0000	0.0000	0.0000	0.0047	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3075	0.2215	0.9833	0.9995	0.9995	0.0156	0.0100	0.0869
H_2O	0.0595	0.1049	0.0167	0.0005	0.0005	0.0338	0.0000	0.1758
N_2	0.6051	0.6454	0.0000	0.0000	0.0000	0.9107	0.0160	0.7083
O_2	0.0278	0.0249	0.0000	0.0000	0.0000	0.0352	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,966	16,344	3,497	3,439	3,439	11,582	530	6,378
V-L Flowrate (kg/hr)	323,399	500,878	152,366	151,317	151,317	325,709	9,188	177,478
Temperature (°C)	160	154	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	243.66	315.00	41.50	-78.54	-231.09	93.55	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,036.64	-3,536.18	-8,969.07	-9,042.09	-9,194.65	-496.36	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.450	30.647	43.576	43.997	43.997	28.121	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,972	36,032	7,709	7,582	7,582	25,535	1,169	14,060
V-L Flowrate (lb/hr)	712,974	1,104,246	335,908	333,598	333,598	718,065	20,257	391,273
Temperature (°F)	320	310	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	104.8	135.4	17.8	-33.8	-99.4	40.2	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,735.4	-1,520.3	-3,856.0	-3,887.4	-3,953.0	-213.4	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.055	0.217	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-17. Energy and mass balance diagram for case CM95-B7

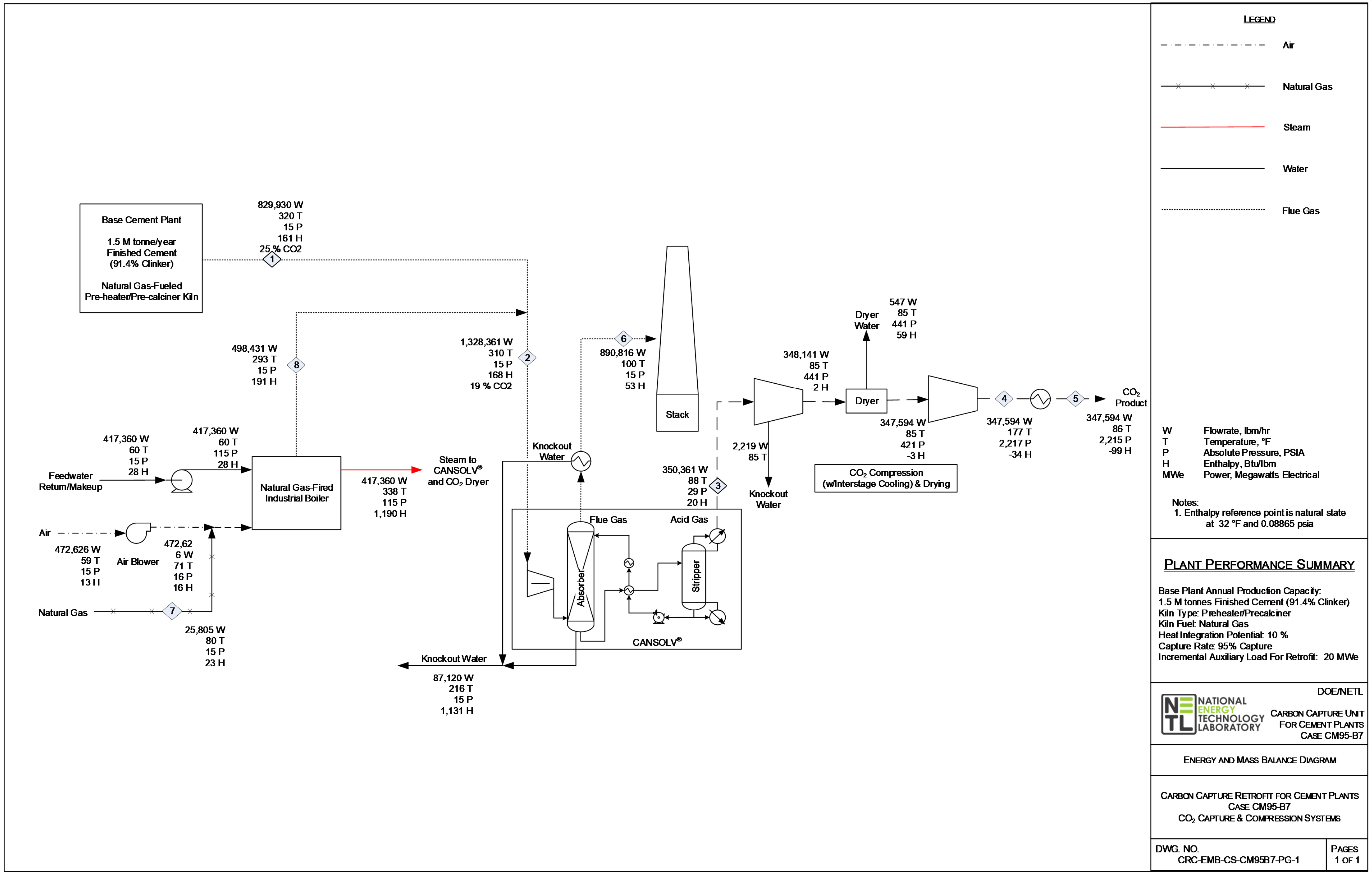

Exhibit A-18. Stream table for case CM95-B7

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0034	0.0000	0.0000	0.0000	0.0047	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.2510	0.1855	0.9809	0.9995	0.9995	0.0130	0.0100	0.0869
H_2O	0.1305	0.1486	0.0191	0.0005	0.0005	0.0524	0.0000	0.1758
N_2	0.5923	0.6387	0.0000	0.0000	0.0000	0.8964	0.0160	0.7083
O_2	0.0261	0.0238	0.0000	0.0000	0.0000	0.0335	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	12,211	20,335	3,652	3,584	3,584	14,489	675	8,124
V-L Flowrate (kg/hr)	376,450	602,534	158,921	157,666	157,666	404,067	11,705	226,085
Temperature (°C)	160	154	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	358.88	391.19	44.08	-78.54	-231.09	124.37	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,085.43	-3,537.16	-8,973.63	-9,042.09	-9,194.65	-624.50	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	30.829	29.630	43.513	43.997	43.997	27.888	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	26,921	44,831	8,052	7,900	7,900	31,942	1,489	17,911
V-L Flowrate (lb/hr)	829,930	1,328,361	350,361	347,594	347,594	890,816	25,805	498,431
Temperature (°F)	320	310	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	154.3	168.2	18.9	-33.8	-99.4	53.5	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,756.4	-1,520.7	-3,858.0	-3,887.4	-3,953.0	-268.5	-1,915.2	-1,128.2
Density (lb/ft^3)	0.054	0.053	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-19. Energy and mass balance diagram for case CM95-B8

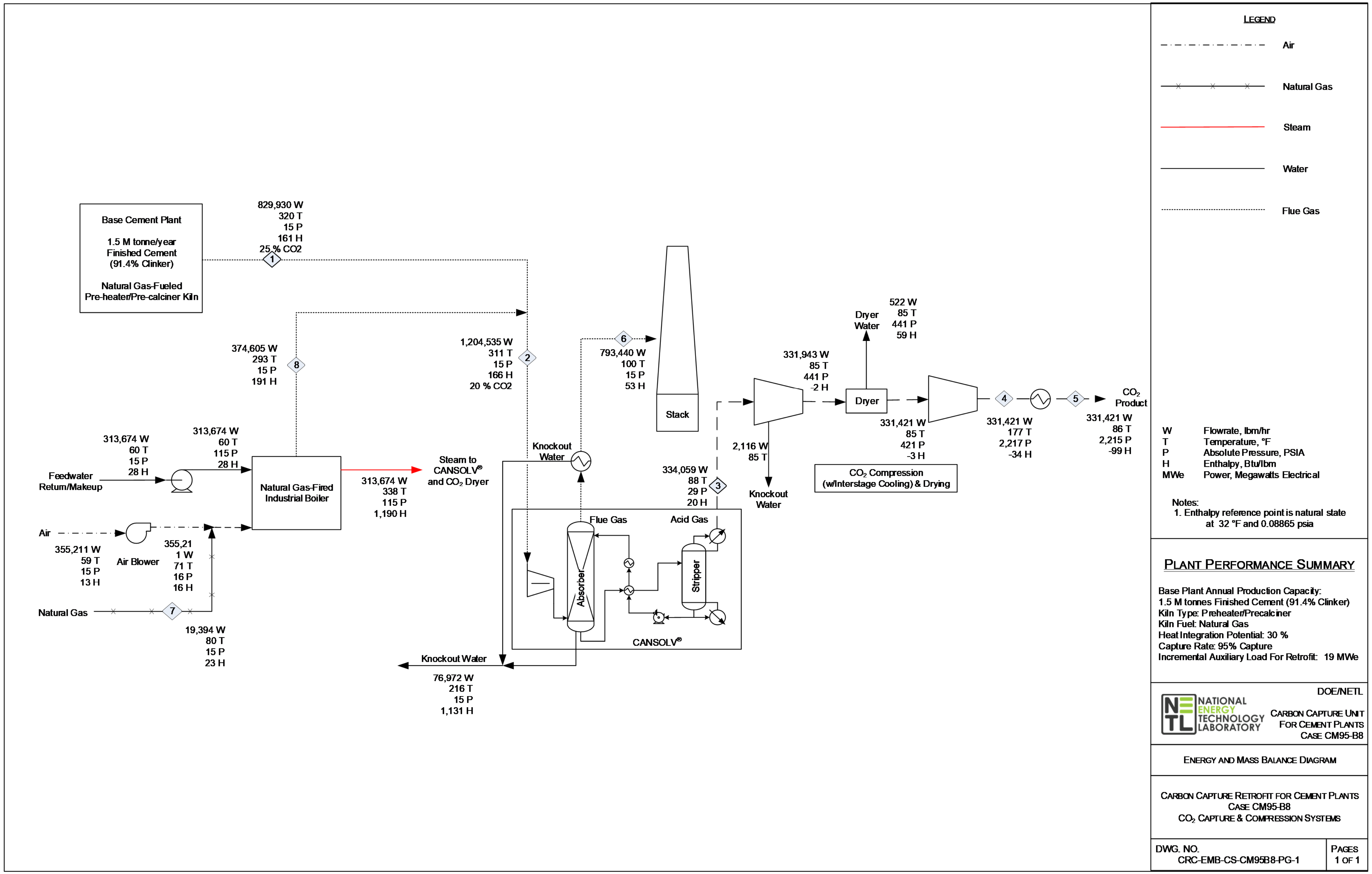

Exhibit A-20. Stream table for case CM95-B8

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0028	0.0000	0.0000	0.0000	0.0040	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.2510	0.1963	0.9809	0.9995	0.9995	0.0140	0.0100	0.0869
H_2O	0.1305	0.1456	0.0191	0.0005	0.0005	0.0514	0.0000	0.1758
N_2	0.5923	0.6310	0.0000	0.0000	0.0000	0.8963	0.0160	0.7083
O_2	0.0261	0.0242	0.0000	0.0000	0.0000	0.0344	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	12,211	18,317	3,482	3,417	3,417	12,896	508	6,106
V-L Flowrate (kg/hr)	376,450	546,368	151,527	150,330	150,330	359,898	8,797	169,918
Temperature (°C)	160	155	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	358.88	385.66	44.08	-78.54	-231.09	122.70	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,085.43	-3,631.01	-8,973.63	-9,042.09	-9,194.65	-628.62	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	30.829	29.829	43.513	43.997	43.997	27.908	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	26,921	40,382	7,677	7,533	7,533	28,431	1,119	13,461
V-L Flowrate (lb/hr)	829,930	1,204,535	334,059	331,421	331,421	793,440	19,394	374,605
Temperature (°F)	320	311	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	154.3	165.8	18.9	-33.8	-99.4	52.8	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,756.4	-1,561.1	-3,858.0	-3,887.4	-3,953.0	-270.3	-1,915.2	-1,128.2
Density (lb/ft^3)	0.054	0.053	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-21. Energy and mass balance diagram for case CM95-B-S300-N1000

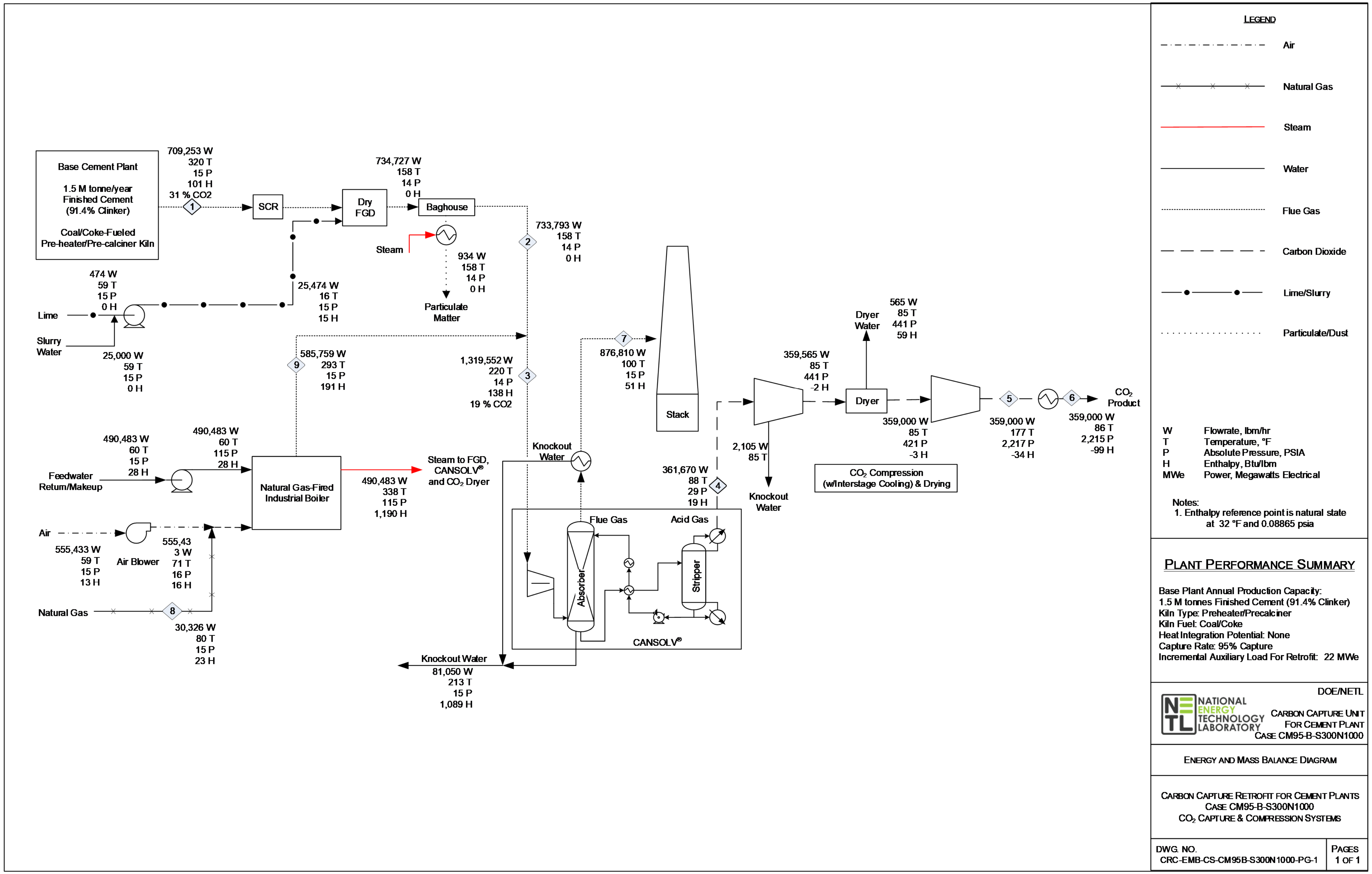

Exhibit A-22. Stream table for case CM95-B-S300-N1000

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0040	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3106	0.2921	0.1944	0.9821	0.9995	0.9995	0.0137	0.0100	0.0869
H_2O	0.0501	0.1070	0.1398	0.0179	0.0005	0.0005	0.0487	0.0000	0.1758
N_2	0.6109	0.5745	0.6383	0.0000	0.0000	0.0000	0.8988	0.0160	0.7083
O_2	0.0281	0.0264	0.0236	0.0000	0.0000	0.0000	0.0332	0.0000	0.0205
SO_2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,867	10,492	20,040	3,767	3,701	3,701	14,232	794	9,548
V-L Flowrate (kg/hr)	321,712	332,843	598,539	164,051	162,840	162,840	397,714	13,756	265,696
Temperature (°C)	160	70	105	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	235.40	235.19	339.17	44.17	-78.54	-231.09	124.95	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-3,987.22	-4,393.77	-3,608.26	-8,971.41	-9,042.09	-9,194.65	-600.62	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	1.1	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.604	31.722	29.867	43.544	43.997	43.997	27.946	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,754	23,132	44,180	8,306	8,160	8,160	31,375	1,750	21,049
V-L Flowrate (lb/hr)	709,253	733,793	1,319,552	361,670	359,000	359,000	876,810	30,326	585,759
Temperature (°F)	320	158	220	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	101.2	101.1	145.8	19.0	-33.8	-99.4	53.7	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,714.2	-1,889.0	-1,551.3	-3,857.0	-3,887.4	-3,953.0	-258.2	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.067	0.057	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-23. Energy and mass balance diagram for case CM95-B1-S300-N1000

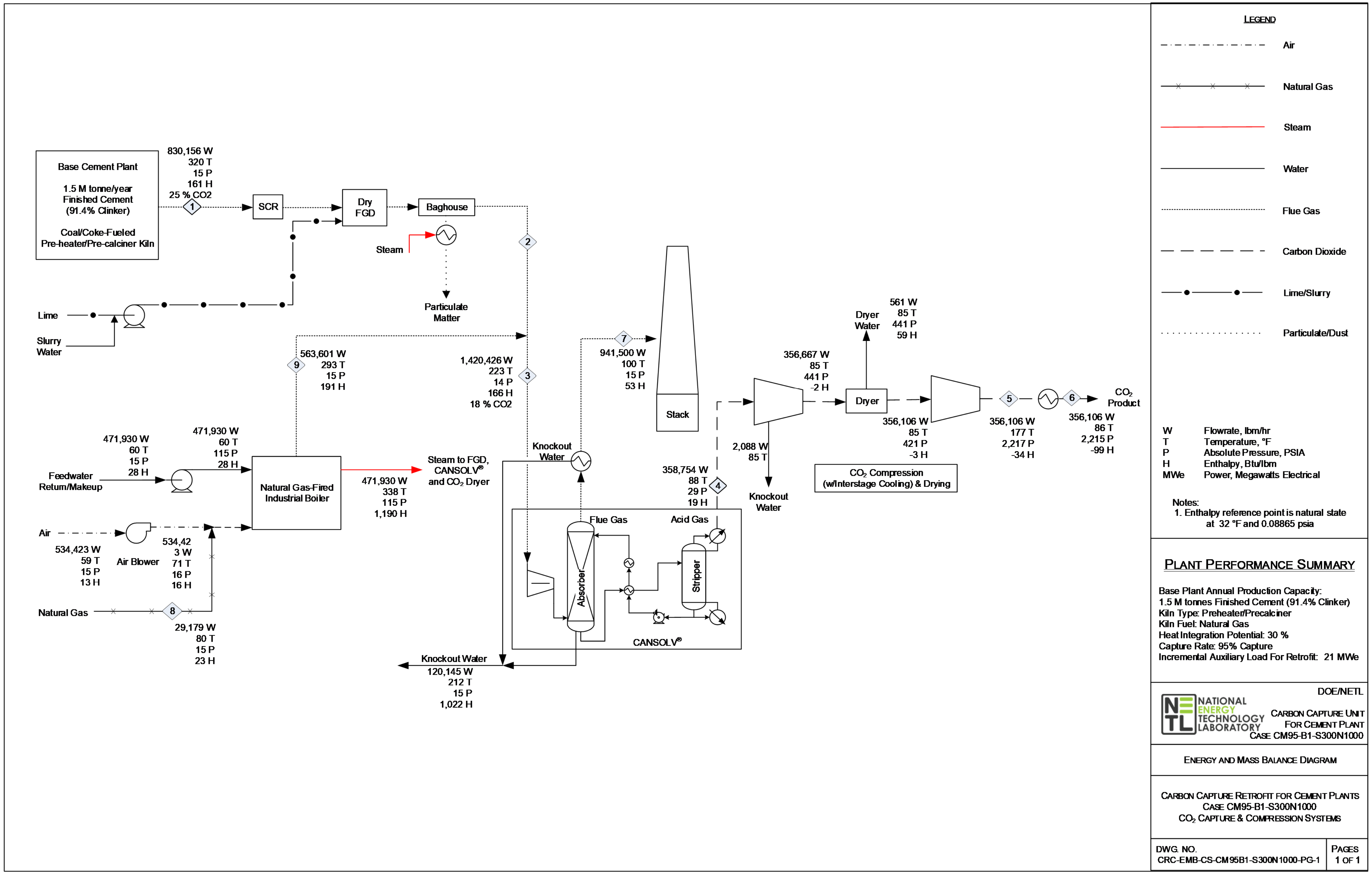

Exhibit A-24. Stream table for case CM95-B1-S300-N1000

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0035	0.0000	0.0000	0.0000	0.0051	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.2510	0.2378	0.1750	0.9821	0.9995	0.9995	0.0126	0.0100	0.0869
H_2O	0.1305	0.1767	0.1763	0.0179	0.0005	0.0005	0.0523	0.0000	0.1758
N_2	0.5921	0.5608	0.6222	0.0000	0.0000	0.0000	0.8969	0.0160	0.7083
O_2	0.0261	0.0247	0.0229	0.0000	0.0000	0.0000	0.0331	0.0000	0.0205
SO_2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	12,210	12,891	22,077	3,737	3,671	3,671	15,315	764	9,186
V-L Flowrate (kg/hr)	376,553	388,649	644,294	162,728	161,527	161,527	427,057	13,235	255,645
Temperature (°C)	160	80	106	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	375.21	370.92	410.01	44.17	-78.54	-231.09	131.58	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,086.76	-4,462.57	-3,733.15	-8,971.41	-9,042.09	-9,194.65	-618.15	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	1.0	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	30.838	30.149	29.184	43.544	43.997	43.997	27.885	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	26,919	28,419	48,672	8,239	8,094	8,094	33,764	1,684	20,252
V-L Flowrate (lb/hr)	830,156	856,824	1,420,426	358,754	356,106	356,106	941,500	29,179	563,601
Temperature (°F)	320	175	223	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	161.3	159.5	176.3	19.0	-33.8	-99.4	56.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,757.0	-1,918.6	-1,605.0	-3,857.0	-3,887.4	-3,953.0	-265.8	-1,915.2	-1,128.2
Density (lb/ft^3)	0.054	0.062	0.056	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-25. Energy and mass balance diagram for case CM95-B3-S300-N1000

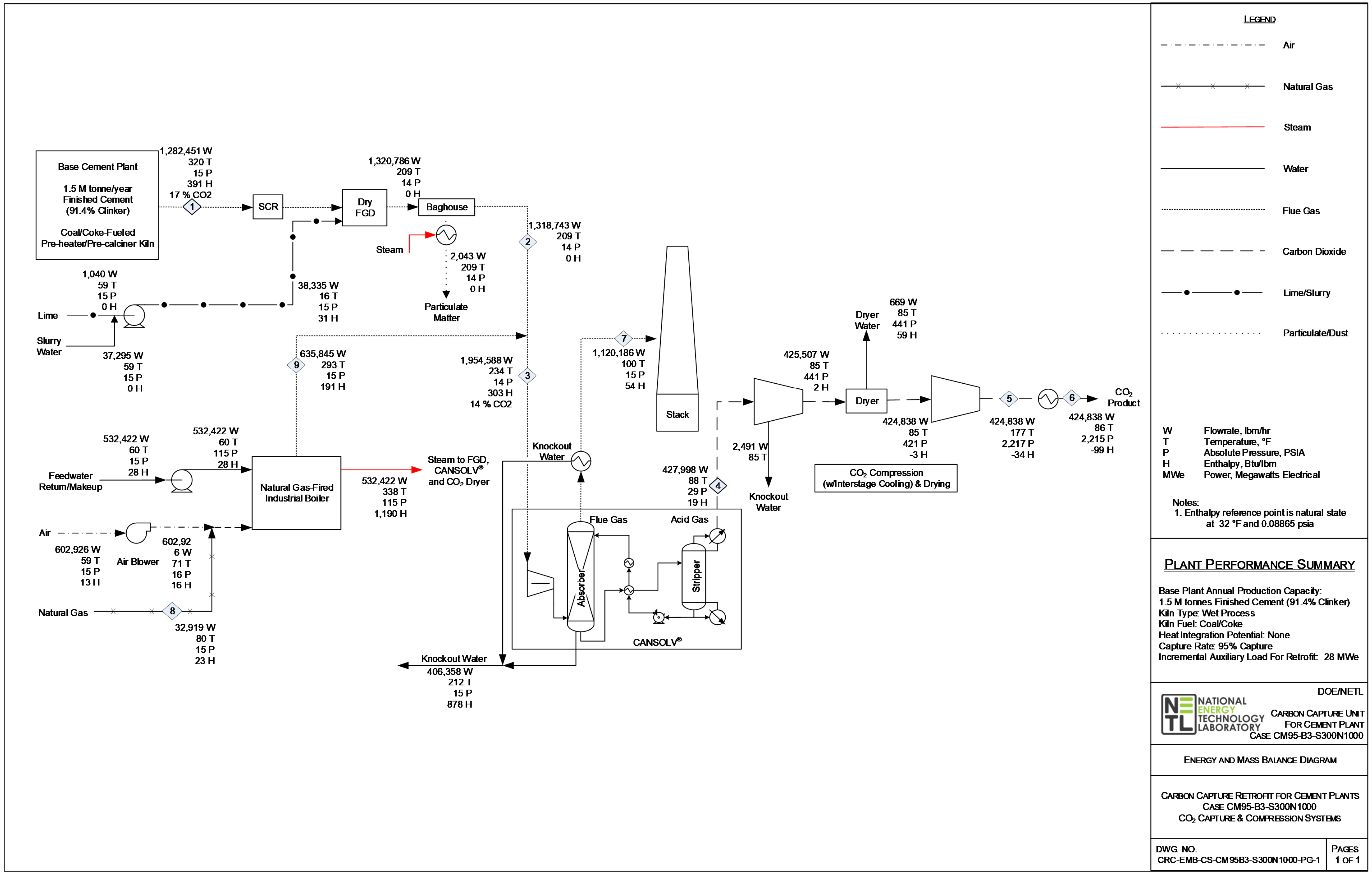

Exhibit A-26. Stream table for case CM95-B3-S300-N1000

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0027	0.0000	0.0000	0.0000	0.0048	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1714	0.1643	0.1400	0.9821	0.9995	0.9995	0.0126	0.0100	0.0869
H_2O	0.3931	0.4184	0.3421	0.0179	0.0005	0.0005	0.0523	0.0000	0.1758
N_2	0.4231	0.4057	0.5009	0.0000	0.0000	0.0000	0.9043	0.0160	0.7083
O_2	0.0121	0.0116	0.0144	0.0000	0.0000	0.0000	0.0260	0.0000	0.0205
SO_2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	21,639	22,568	32,932	4,458	4,380	4,380	18,242	862	10,364
V-L Flowrate (kg/hr)	581,710	598,172	886,586	194,136	192,703	192,703	508,108	14,932	288,414
Temperature (°C)	160	98	112	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	910.60	892.63	754.96	44.17	-78.54	-231.09	131.73	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-5,883.22	-6,167.29	-5,014.71	-8,971.41	-9,042.09	-9,194.65	-619.12	-4,454.70	-2,624.24
Density (kg/m^3)	0.8	0.8	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	26.883	26.505	26.922	43.544	43.997	43.997	27.854	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	47,705	49,754	72,603	9,829	9,656	9,656	40,217	1,900	22,848
V-L Flowrate (lb/hr)	1,282,451	1,318,743	1,954,588	427,998	424,838	424,838	1,120,186	32,919	635,845
Temperature (°F)	320	209	234	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	391.5	383.8	324.6	19.0	-33.8	-99.4	56.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-2,529.3	-2,651.5	-2,155.9	-3,857.0	-3,887.4	-3,953.0	-266.2	-1,915.2	-1,128.2
Density (lb/ft^3)	0.047	0.052	0.051	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-27. Energy and mass balance diagram for case CM95-B4-S300-N1000

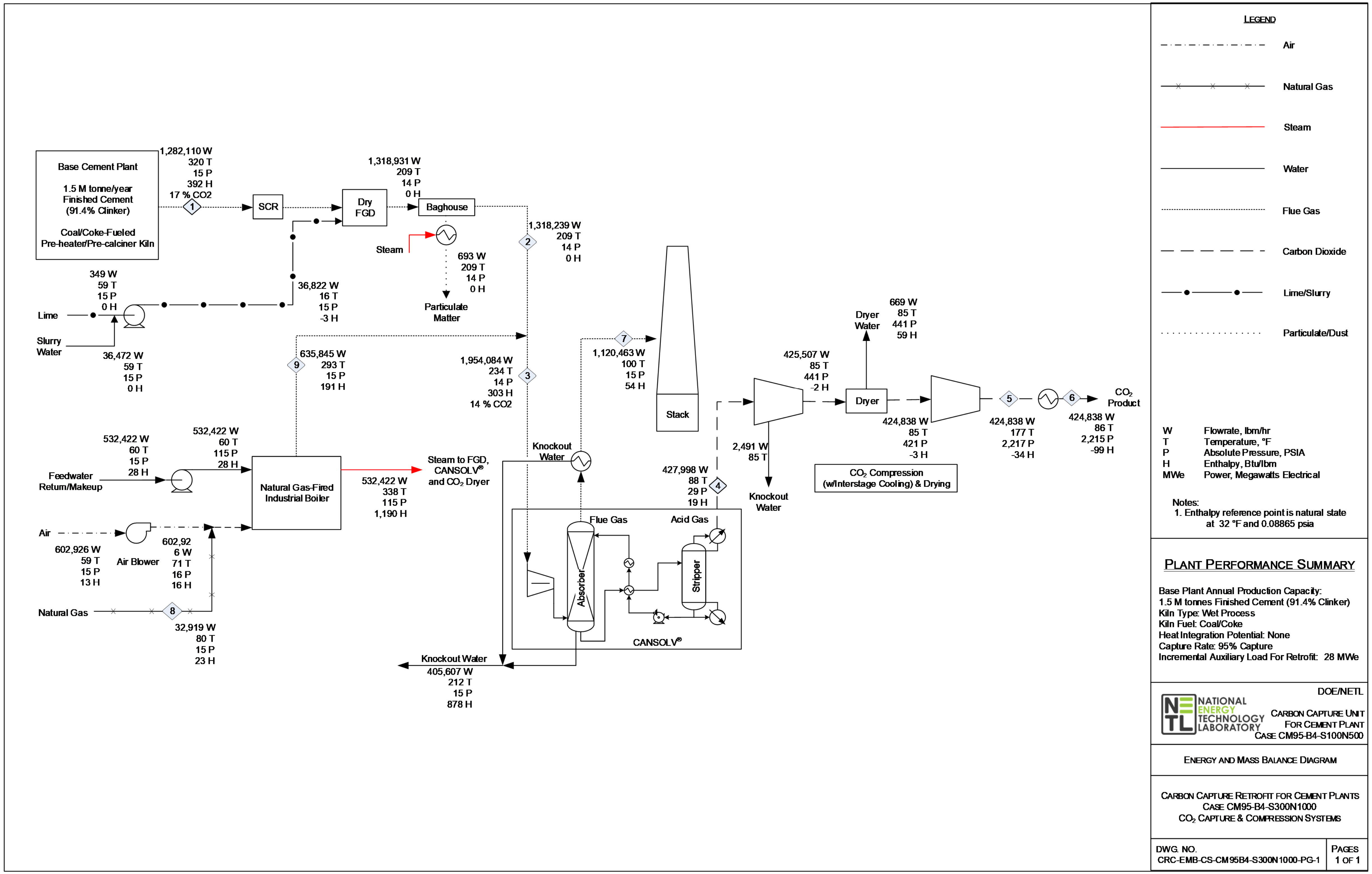

Exhibit A-28. Stream table for case CM95-B4-S300-N1000

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0021	0.0000	0.0000	0.0000	0.0041	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1312	0.1260	0.1162	0.9821	0.9995	0.9995	0.0111	0.0100	0.0869
H_2O	0.4440	0.4661	0.3931	0.0179	0.0005	0.0005	0.0523	0.0000	0.1758
N_2	0.4134	0.3972	0.4755	0.0000	0.0000	0.0000	0.9075	0.0160	0.7083
O_2	0.0111	0.0107	0.0131	0.0000	0.0000	0.0000	0.0251	0.0000	0.0205
SO_2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	28,268	29,424	39,316	4,419	4,341	4,341	20,599	822	9,892
V-L Flowrate (kg/hr)	727,273	747,724	1,023,008	192,408	190,988	190,988	572,992	14,252	275,284
Temperature (°C)	160	101	112	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	1,047.04	1,025.57	875.92	44.17	-78.54	-231.09	131.90	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-6,011.76	-6,290.83	-5,304.18	-8,971.41	-9,042.09	-9,194.65	-598.07	-4,454.70	-2,624.24
Density (kg/m^3)	0.7	0.8	0.8	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	25.728	25.412	26.020	43.544	43.997	43.997	27.817	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	62,320	64,868	86,677	9,741	9,570	9,570	45,413	1,813	21,808
V-L Flowrate (lb/hr)	1,603,363	1,648,448	2,255,346	424,188	421,056	421,056	1,263,232	31,420	606,898
Temperature (°F)	320	214	233	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	450.1	440.9	376.6	19.0	-33.8	-99.4	56.7	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-2,584.6	-2,704.6	-2,280.4	-3,857.0	-3,887.4	-3,953.0	-257.1	-1,915.2	-1,128.2
Density (lb/ft^3)	0.045	0.049	0.049	0.216	26.998	39.338	0.068	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-29. Energy and mass balance diagram for case CM95-B at 250°F

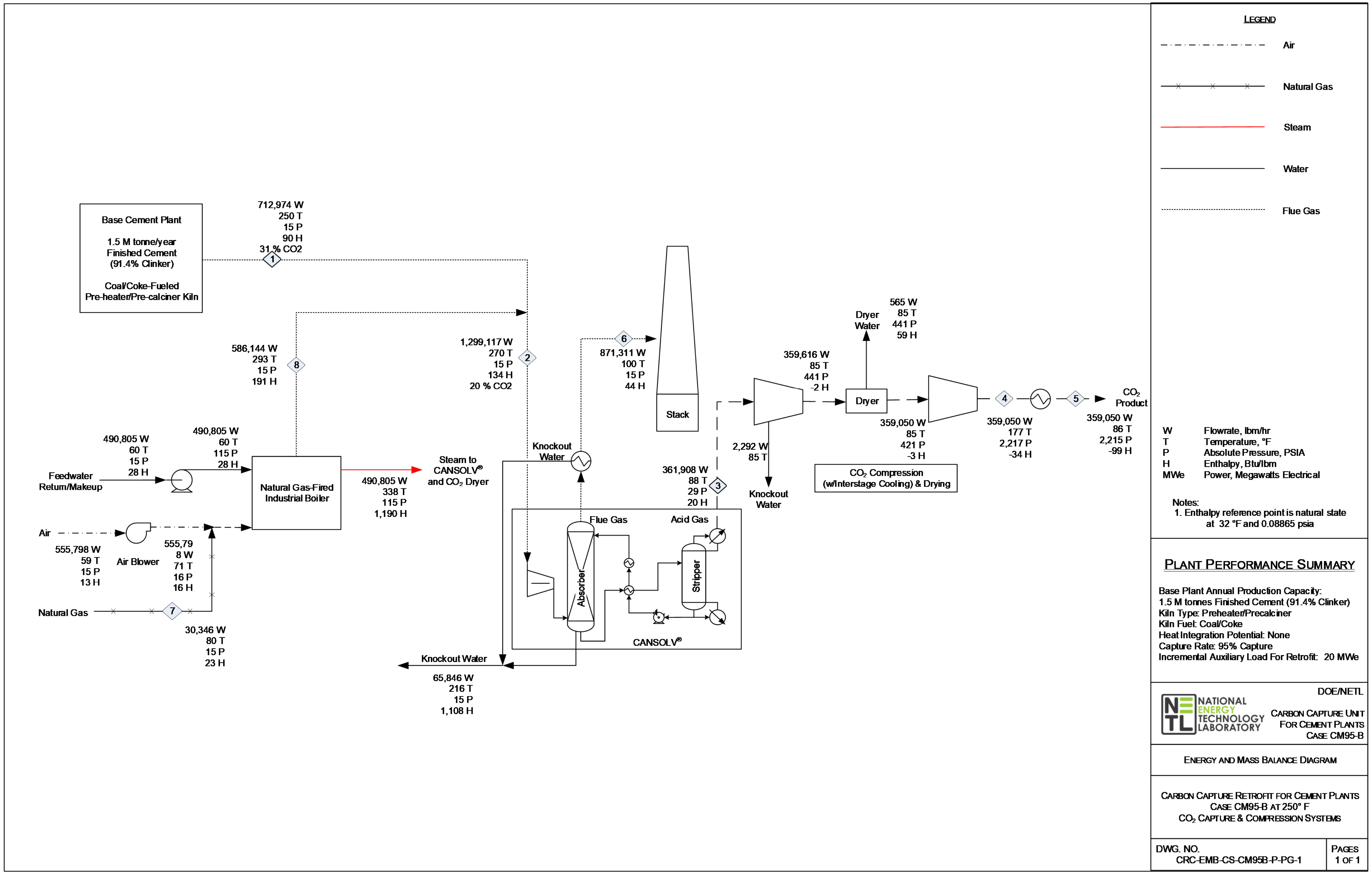

Exhibit A-30. Stream table for case CM95-B at 250°F

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0000	0.0041	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3075	0.1996	0.9809	0.9995	0.9995	0.0138	0.0100	0.0869
H_2O	0.0595	0.1164	0.0191	0.0005	0.0005	0.0385	0.0000	0.1758
N_2	0.6051	0.6556	0.0000	0.0000	0.0000	0.9084	0.0160	0.7083
O_2	0.0278	0.0242	0.0000	0.0000	0.0000	0.0335	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,966	19,520	3,773	3,702	3,702	14,089	794	9,554
V-L Flowrate (kg/hr)	323,399	589,270	164,159	162,862	162,862	395,220	13,765	265,870
Temperature (°C)	121	132	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	203.37	312.39	44.08	-78.54	-231.09	101.35	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,076.93	-3,421.50	-8,973.63	-9,042.09	-9,194.65	-512.99	-4,454.70	-2,624.24
Density (kg/m^3)	1.0	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.450	30.188	43.513	43.997	43.997	28.052	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,972	43,034	8,317	8,161	8,161	31,061	1,751	21,063
V-L Flowrate (lb/hr)	712,974	1,299,117	361,908	359,050	359,050	871,311	30,346	586,144
Temperature (°F)	250	270	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	87.4	134.3	18.9	-33.8	-99.4	43.6	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,752.8	-1,471.0	-3,858.0	-3,887.4	-3,953.0	-220.5	-1,915.2	-1,128.2
Density (lb/ft^3)	0.063	0.057	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-31. Energy and mass balance diagram for case CM95-B at 250°F with air in-leakage up to 400,000 ACFM

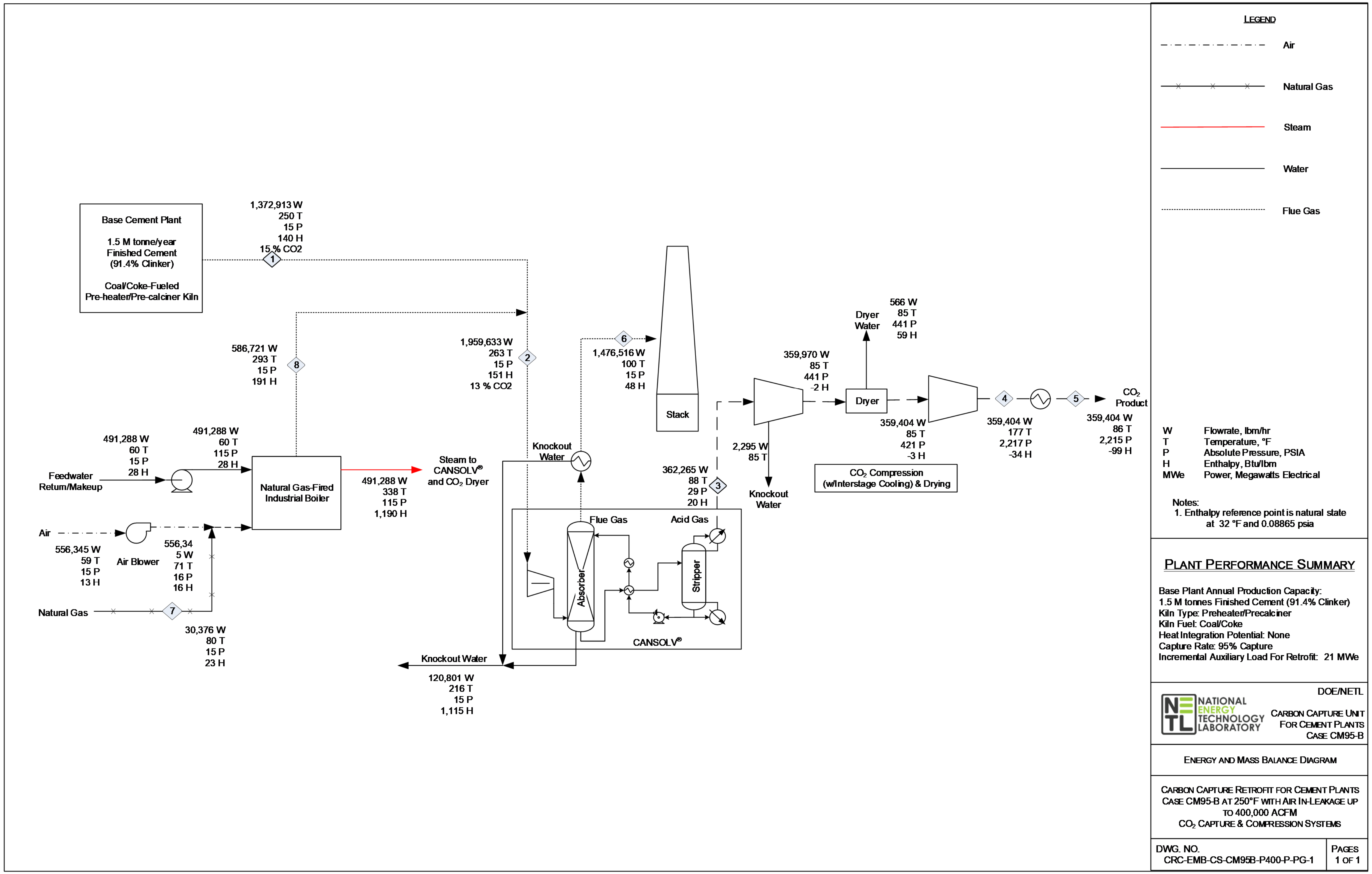

Exhibit A-32. Stream table for case CM95-B at 250°F with air in-leakage up to 400,000 ACFM

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0041	0.0054	0.0000	0.0000	0.0000	0.0070	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1459	0.1275	0.9809	0.9995	0.9995	0.0082	0.0100	0.0869
H_2O	0.1200	0.1374	0.0191	0.0005	0.0005	0.0459	0.0000	0.1758
N_2	0.6259	0.6517	0.0000	0.0000	0.0000	0.8386	0.0160	0.7083
O_2	0.1041	0.0780	0.0000	0.0000	0.0000	0.1003	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	21,030	30,594	3,776	3,705	3,705	23,775	795	9,563
V-L Flowrate (kg/hr)	622,743	888,875	164,320	163,023	163,023	669,736	13,778	266,132
Temperature (°C)	121	128	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	309.55	350.10	44.08	-78.54	-231.09	112.67	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-2,817.63	-2,759.73	-8,973.63	-9,042.09	-9,194.65	-495.34	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	29.611	29.054	43.513	43.997	43.997	28.169	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	46,364	67,448	8,326	8,169	8,169	52,416	1,753	21,083
V-L Flowrate (lb/hr)	1,372,913	1,959,633	362,265	359,404	359,404	1,476,516	30,376	586,721
Temperature (°F)	250	263	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	133.1	150.5	18.9	-33.8	-99.4	48.4	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,211.4	-1,186.5	-3,858.0	-3,887.4	-3,953.0	-213.0	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.055	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-33. Energy and mass balance diagram for case CM95-B at 250°F with air in-leakage up to 700,000 ACFM

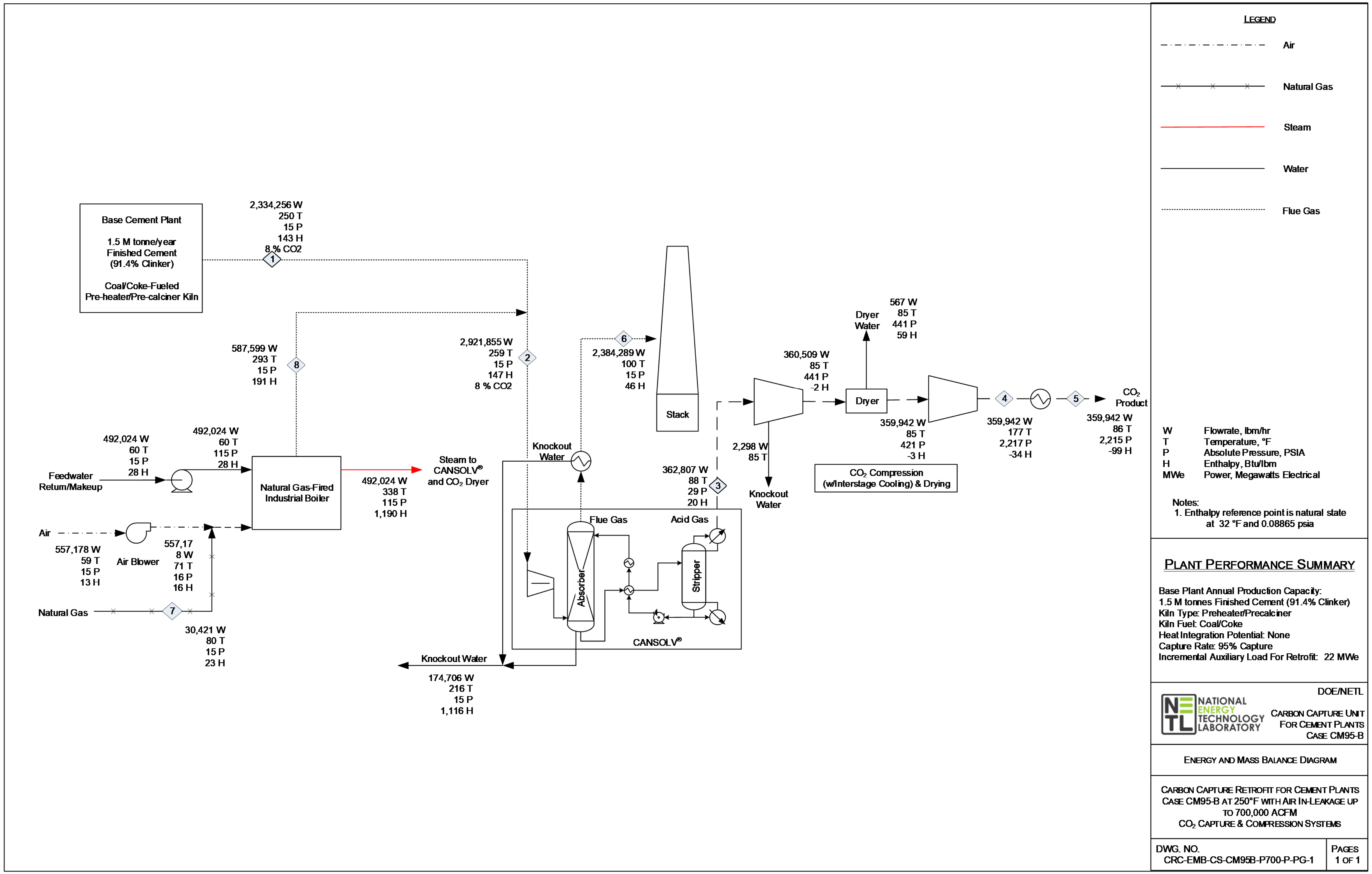

Exhibit A-34. Stream table for case CM95-B at 250°F with air in-leakage up to 700,000 ACFM

	1	2	3	4	5	6	7	8
V-L Mole Fraction								
AR	0.0058	0.0064	0.0000	0.0000	0.0000	0.0077	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.0835	0.0842	0.9809	0.9995	0.9995	0.0051	0.0100	0.0869
H_2O	0.1200	0.1315	0.0191	0.0005	0.0005	0.0426	0.0000	0.1758
N_2	0.6522	0.6638	0.0000	0.0000	0.0000	0.8059	0.0160	0.7083
O_2	0.1385	0.1141	0.0000	0.0000	0.0000	0.1386	0.0000	0.0205
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	36,800	46,378	3,782	3,711	3,711	38,197	796	9,578
V-L Flowrate (kg/hr)	1,058,800	1,325,331	164,566	163,267	163,267	1,081,495	13,799	266,530
Temperature (°C)	121	126	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	316.07	342.00	44.08	-78.54	-231.09	106.87	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-2,048.69	-2,164.44	-8,973.63	-9,042.09	-9,194.65	-422.09	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	28.771	28.577	43.513	43.997	43.997	28.314	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	81,131	102,246	8,338	8,181	8,181	84,210	1,756	21,115
V-L Flowrate (lb/hr)	2,334,256	2,921,855	362,807	359,942	359,942	2,384,289	30,421	587,599
Temperature (°F)	250	259	88	177	86	100	80	293
Pressure (psia)	14.7	14.7	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	135.9	147.0	18.9	-33.8	-99.4	45.9	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-880.8	-930.5	-3,858.0	-3,887.4	-3,953.0	-181.5	-1,915.2	-1,128.2
Density (lb/ft^3)	0.056	0.054	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-35. Energy and mass balance diagram for case CM95-B-S100N500 at 250°F

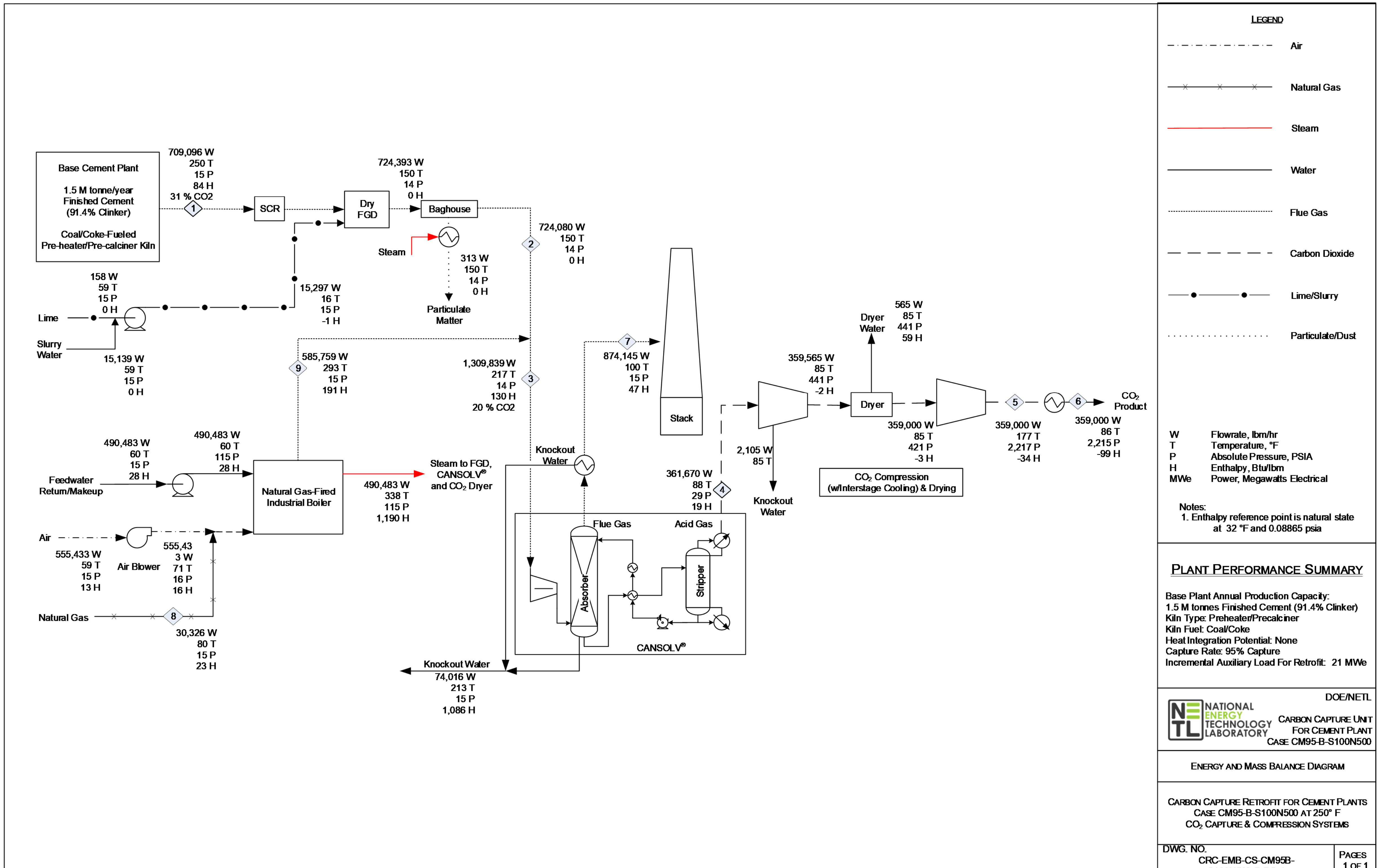

Exhibit A-36. Stream table for case CM95-B-S100N500 at 250°F

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0000	0.0000	0.0041	0.0000	0.0000	0.0000	0.0057	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.3106	0.2991	0.1968	0.9821	0.9995	0.9995	0.0138	0.0100	0.0869
H_2O	0.0501	0.0854	0.1290	0.0179	0.0005	0.0005	0.0440	0.0000	0.1758
N_2	0.6111	0.5885	0.6463	0.0000	0.0000	0.0000	0.9033	0.0160	0.7083
O_2	0.0281	0.0270	0.0238	0.0000	0.0000	0.0000	0.0333	0.0000	0.0205
SO_2	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	9,867	10,247	19,794	3,767	3,701	3,701	14,163	794	9,548
V-L Flowrate (kg/hr)	321,641	328,437	594,133	164,051	162,840	162,840	396,506	13,756	265,696
Temperature (°C)	121	66	103	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	195.35	195.49	318.00	44.17	-78.54	-231.09	116.46	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-4,026.38	-4,275.94	-3,537.30	-8,971.41	-9,042.09	-9,194.65	-559.73	-4,454.70	-2,624.24
Density (kg/m^3)	1.0	1.1	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	32.597	32.052	30.015	43.544	43.997	43.997	27.995	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	21,754	22,591	43,639	8,306	8,160	8,160	31,225	1,750	21,049
V-L Flowrate (lb/hr)	709,096	724,080	1,309,839	361,670	359,000	359,000	874,145	30,326	585,759
Temperature (°F)	250	150	217	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	84.0	84.0	136.7	19.0	-33.8	-99.4	50.1	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,731.0	-1,838.3	-1,520.8	-3,857.0	-3,887.4	-3,953.0	-240.6	-1,915.2	-1,128.2
Density (lb/ft^3)	0.063	0.069	0.058	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-37. Energy and mass balance diagram for case CM95-B-S100N500 at 250°F with air in-leakage up to 400,000 ACFM

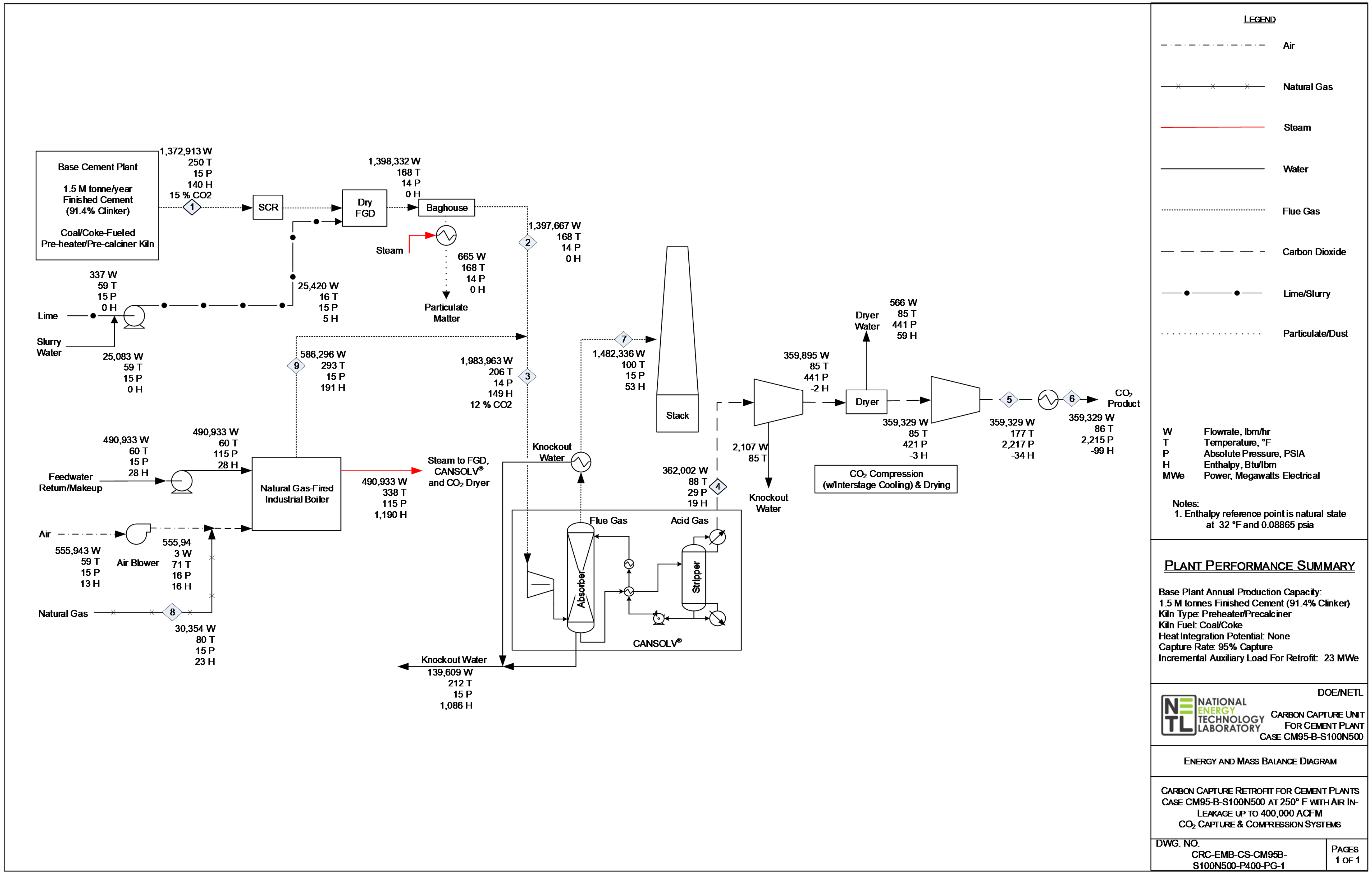

Exhibit A-38. Stream table for case CM95-B-S100N500 at 250°F with air in-leakage up to 400,000 ACFM

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0040	0.0039	0.0053	0.0000	0.0000	0.0000	0.0069	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.1459	0.1416	0.1249	0.9821	0.9995	0.9995	0.0082	0.0100	0.0869
H_2O	0.1200	0.1456	0.1549	0.0179	0.0005	0.0005	0.0523	0.0000	0.1758
N_2	0.6259	0.6078	0.6386	0.0000	0.0000	0.0000	0.8330	0.0160	0.7083
O_2	0.1041	0.1011	0.0764	0.0000	0.0000	0.0000	0.0997	0.0000	0.0205
SO_2	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	21,029	21,657	31,214	3,771	3,705	3,705	23,928	795	9,556
V-L Flowrate (kg/hr)	622,743	633,971	899,911	164,201	162,989	162,989	672,376	13,768	265,940
Temperature (°C)	121	76	97	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	325.36	323.34	366.51	44.17	-78.54	-231.09	130.52	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-2,818.10	-3,053.45	-2,926.61	-8,971.41	-9,042.09	-9,194.65	-550.81	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	1.0	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	29.613	29.273	28.831	43.544	43.997	43.997	28.100	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	46,361	47,746	68,814	8,313	8,167	8,167	52,751	1,752	21,068
V-L Flowrate (lb/hr)	1,372,913	1,397,667	1,983,963	362,002	359,329	359,329	1,482,336	30,354	586,296
Temperature (°F)	250	168	206	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	139.9	139.0	157.6	19.0	-33.8	-99.4	56.1	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-1,211.6	-1,312.7	-1,258.2	-3,857.0	-3,887.4	-3,953.0	-236.8	-1,915.2	-1,128.2
Density (lb/ft^3)	0.057	0.061	0.057	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-39. Energy and mass balance diagram for case CM95-B-S100N500 at 250°F with air in-leakage up to 700,000 ACFM

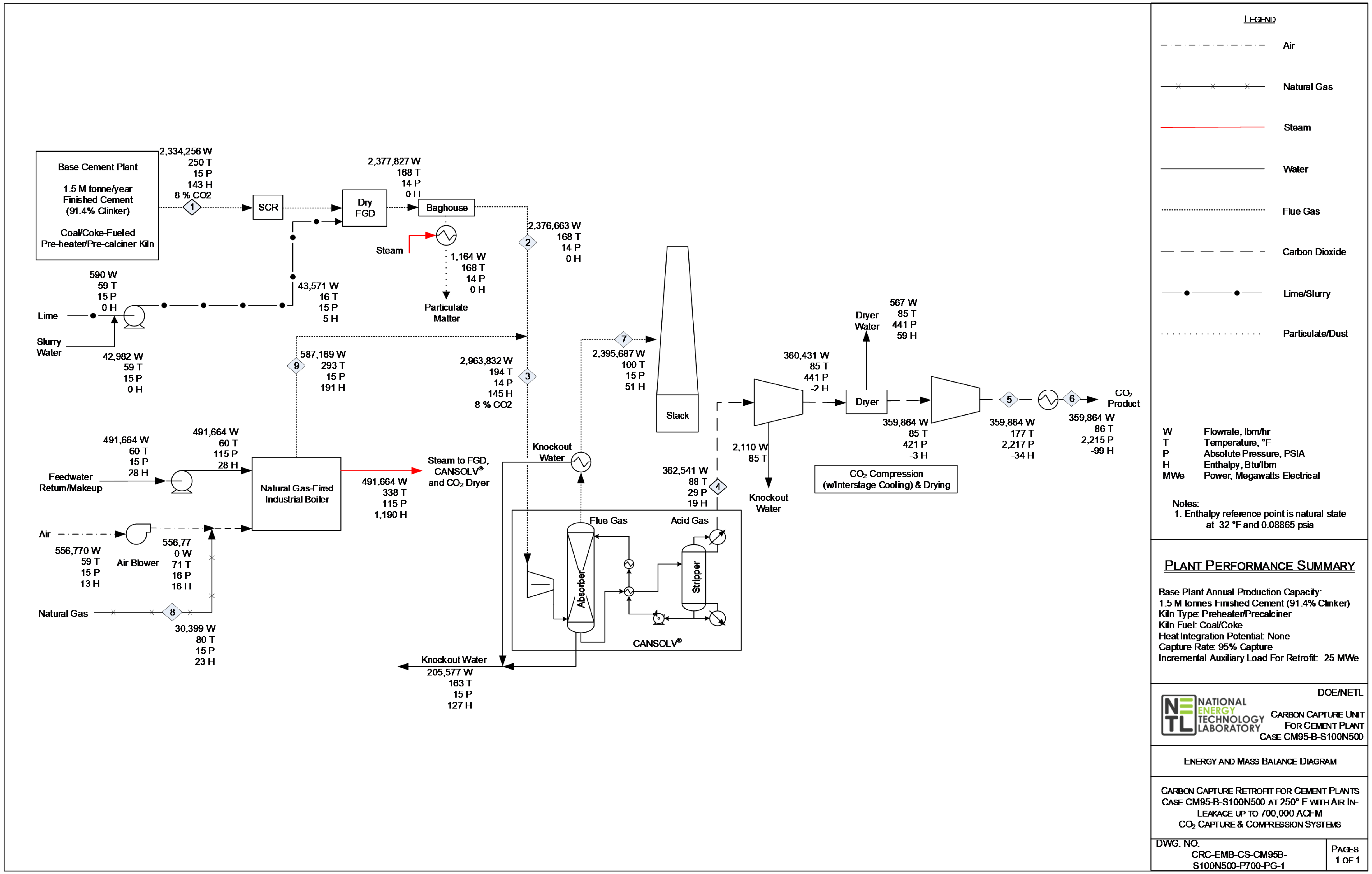

Exhibit A-40. Stream table for case CM95-B-S100N500 at 250°F with air in-leakage up to 700,000 ACFM

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
AR	0.0057	0.0056	0.0062	0.0000	0.0000	0.0000	0.0076	0.0000	0.0085
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9310	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
CO_2	0.0835	0.0811	0.0823	0.9821	0.9995	0.9995	0.0051	0.0100	0.0869
H_2O	0.1200	0.1451	0.1513	0.0179	0.0005	0.0005	0.0503	0.0000	0.1758
N_2	0.6522	0.6336	0.6487	0.0000	0.0000	0.0000	0.7996	0.0160	0.7083
O_2	0.1385	0.1346	0.1115	0.0000	0.0000	0.0000	0.1375	0.0000	0.0205
SO_2	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/hr)	36,798	37,874	47,445	3,777	3,710	3,710	38,492	796	9,571
V-L Flowrate (kg/hr)	1,058,800	1,078,036	1,344,371	164,446	163,232	163,232	1,086,665	13,789	266,335
Temperature (°C)	121	76	90	31	80	30	38	27	145
Pressure (MPa, abs)	0.10	0.10	0.10	0.20	15.28	15.27	0.10	0.10	0.10
Steam Table Enthalpy (kJ/kg)[A]	332.35	330.21	357.79	44.17	-78.54	-231.09	126.36	54.53	445.00
Aspen Plus Enthalpy (kJ/kg)[B]	-2,049.28	-2,300.14	-2,364.35	-8,971.41	-9,042.09	-9,194.65	-488.00	-4,454.70	-2,624.24
Density (kg/m^3)	0.9	1.0	0.9	3.5	432.5	630.1	1.1	0.7	0.8
V-L Molecular Weight	28.774	28.463	28.335	43.544	43.997	43.997	28.231	17.328	27.829
V-L Flowrate (lb_{mol}/hr)	81,125	83,499	104,598	8,326	8,179	8,179	84,861	1,754	21,099
V-L Flowrate (lb/hr)	2,334,256	2,376,663	2,963,832	362,541	359,864	359,864	2,395,687	30,399	587,169
Temperature (°F)	250	168	194	88	177	86	100	80	293
Pressure (psia)	14.7	14.0	14.0	28.9	2,216.9	2,214.7	14.7	14.7	14.7
Steam Table Enthalpy (Btu/lb)[A]	142.9	142.0	153.8	19.0	-33.8	-99.4	54.3	23.4	191.3
Aspen Plus Enthalpy (Btu/lb)[B]	-881.0	-988.9	-1,016.5	-3,857.0	-3,887.4	-3,953.0	-209.8	-1,915.2	-1,128.2
Density (lb/ft^3)	0.056	0.059	0.057	0.216	26.998	39.338	0.069	0.044	0.051

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

APPENDIX B: MAJOR EQUIPMENT LISTS

Major equipment items for the carbon dioxide (CO_2) capture equipment are shown in the following tables. In general, the design conditions include a 10 percent design allowance for flows and heat duties and a 21 percent design allowance for heads on pumps and fans. For brevity, Account 11 and Account 12 are not repeated for each case, as the descriptions of those accounts shown for Case CM99-B apply to all cases. Likewise, only the equipment lists for the sensitivity cases with midpoint combinations of oxides of sulfur (SOx) and oxides of nitrogen (NOx) concentrations (i.e., SOx at 300 ppm_v and NOx at 1,000 ppm_v) are presented.

CASE CM99-B

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	674 lpm @ 10 m H_2O (178 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,955 lpm @ 20 m H_2O (800 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	4 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	4,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	9 lpm (2.4 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	674,000 kg/hr (1,485,000 lb/hr) 28.6 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 45 m^3/min @ 3.0 MPa (1,604 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 273 kg/hr (601 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m^3/min @ 15 MPa, 80°C (178 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 26 GJ/hr (25 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	152,000 lpm @ 30 m (40,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 840 GJ/hr (800 MMBtu/hr) heat duty	1	0

Account 11: Accessory Electric Plant

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	High Voltage Auxiliary Transformer	Oil-filled	345 kV/13.8 kV, 7 MVA, 3-ph, 60 Hz	2	0
2	Medium Voltage Transformer	Oil-filled	18 kV/4.16 kV, 6 MVA, 3-ph, 60 Hz	1	1
3	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 4 MVA, 3-ph, 60 Hz	1	1
6	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
7	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
8	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Account 12: Instrumentation and Control

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser color); Engineering printer (laser B&W)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

Case CM95-B

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	616 lpm @ 10 m H_2O (163 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,706 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	4 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	4,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	8 lpm (2.2 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	648,000 kg/hr (1,429,000 lb/hr) 29.1 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 43 m³/min @ 3.0 MPa (1,509 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 256 kg/hr (565 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (167 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 25 GJ/hr (24 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	140,000 lpm @ 30 m (37,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 780 GJ/hr (740 MMBtu/hr) heat duty	1	0

Case CM95-B1

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	593 lpm @ 10 m H_2O (157 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,523 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	4 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	3,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	8 lpm (2.1 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	695,000 kg/hr (1,533,000 lb/hr) 26.9 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 42 m³/min @ 3.0 MPa (1,497 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 254 kg/hr (561 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (166 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 25 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	136,000 lpm @ 30 m (36,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 760 GJ/hr (720 MMBtu/hr) heat duty	1	0

Case CM95-B2

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	613 lpm @ 10 m H_2O (162 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,689 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	4 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	4,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	8 lpm (2.1 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	652,000 kg/hr (1,438,000 lb/hr) 28.9 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 43 m³/min @ 3.0 MPa (1,507 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 256 kg/hr (565 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (167 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 25 GJ/hr (24 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	139,000 lpm @ 30 m (37,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 780 GJ/hr (740 MMBtu/hr) heat duty	1	0

Case CM95-B3

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	553 lpm @ 10 m H_2O (146 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	1,527 lpm @ 20 m H_2O (400 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	3 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	3,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.9 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	791,000 kg/hr (1,744,000 lb/hr) 23.3 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 42 m³/min @ 3.0 MPa (1,476 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 251 kg/hr (553 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (164 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	131,000 lpm @ 30 m (35,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 730 GJ/hr (690 MMBtu/hr) heat duty	1	0

Case CM95-B4

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	528 lpm @ 10 m H_2O (139 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	916 lpm @ 20 m H_2O (200 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	3 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	3,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.8 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	911,000 kg/hr (2,009,000 lb/hr) 20.1 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 41 m³/min @ 3.0 MPa (1,463 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 249 kg/hr (548 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (162 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	127,000 lpm @ 30 m (33,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 710 GJ/hr (670 MMBtu/hr) heat duty	1	0

Case CM95-B5

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	546 lpm @ 10 m H_2O (144 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,671 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	3 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	3,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.9 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	615,000 kg/hr (1,355,000 lb/hr) 29.9 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 42 m³/min @ 3.0 MPa (1,472 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 250 kg/hr (552 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (163 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	137,000 lpm @ 30 m (36,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 760 GJ/hr (720 MMBtu/hr) heat duty	1	0

Case CM95-B6

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	411 lpm @ 10 m H_2O (109 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,600 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	2 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	2,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	5 lpm (1.4 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	551,000 kg/hr (1,215,000 lb/hr) 31.8 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 40 m^3/min @ 3.0 MPa (1,402 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 238 kg/hr (525 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	4 m^3/min @ 15 MPa, 80°C (155 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 23 GJ/hr (22 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	132,000 lpm @ 30 m (35,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 730 GJ/hr (700 MMBtu/hr) heat duty	1	0

Case CM95-B7

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	524 lpm @ 10 m H_2O (138 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,491 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	3 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	3,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.8 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	663,000 kg/hr (1,461,000 lb/hr) 27.5 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 41 m^3/min @ 3.0 MPa (1,461 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 248 kg/hr (547 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m^3/min @ 15 MPa, 80°C (162 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	134,000 lpm @ 30 m (35,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 750 GJ/hr (710 MMBtu/hr) heat duty	1	0

Case CM95-B8

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	394 lpm @ 10 m H_2O (104 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,415 lpm @ 20 m H_2O (600 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	2 lpm @ 50 m H_2O (1 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	2,000 liter (1,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	5 lpm (1.4 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	CANSOLV®	Amine-based CO_2 capture technology	601,000 kg/hr (1,325,000 lb/hr) 29.0 wt% CO_2 concentration	1	0
2	CO_2 Dryer	Triethylene glycol	Inlet: 39 m^3/min @ 3.0 MPa (1,393 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 237 kg/hr (522 lb/hr)	1	0
3	CO_2 Compressor	Integrally geared, multi-stage centrifugal	4 m^3/min @ 15 MPa, 80°C (154 acfm @ 2,217 psia, 177°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 23 GJ/hr (22 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	128,000 lpm @ 30 m (34,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 710 GJ/hr (680 MMBtu/hr) heat duty	1	0

Case CM95-B-S300-N1000

Account 2: Sorbent Preparation and Feed[d]

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Lime Slaker	N/A	0.3 tonne/hr (0.4 tph)	1	1
2	Lime Slurry Tank	Field Erected	3,628 tonne/hr (3999 tph)	1	1
3	Lime Slurry Feed Pumps	Horizontal centrifugal	20 lpm @ 9m H_2O (5 gpm @ 30 ft H_2O)	1	1

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	616 lpm @ 10 m H_2O (163 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,744 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	98 lpm @ 50 m H_2O (26 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	94,000 liter (25,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	8 lpm (2.2 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	366,000 kg/hr (807,000 lb/hr) 98.5% efficiency	1	0
2	Spray Dryer	Co-current open spray	6,000 m^3/min (227,000 acfm)	1	0
3	Atomizer	Rotary	17 lpm @ 25 m H_2O (5 gpm @ 80 ft H_2O)	1	1
4	Solids Conveying	–	–	1	0
5	CANSOLV®	Amine-based CO_2 capture technology	658,000 kg/hr (1,452,000 lb/hr) 28.6 wt% CO_2 concentration	1	0
6	CO_2 Dryer	Triethylene glycol	Inlet: 43 m^3/min @ 3.0 MPa (1,509 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 256 kg/hr (565 lb/hr)	1	0
7	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m^3/min @ 15 MPa, 80°C (167 acfm @ 2,217 psia, 177°F)	1	0
8	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 25 GJ/hr (24 MMBtu/hr)	1	0

[d] The costs for Account 2 are included with costs in Account 5.2 of the capital cost tables for each sensitivity case. The equipment descriptions are included in a separate list (Account 2) for consistency with other NETL studies.

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0
2	SCR Reactor	–	290,000 kg/hr (640,000 lb/hr)	1	0
3	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
4	Dilution Air Blowers	Centrifugal	80 m³/min @ 108 cm WG (2,820 scfm @ 42 in WG)	1	1
5	Ammonia Feed Pump	Centrifugal	17 lpm @ 90 m H_2O (4 gpm @ 300 ft H_2O)	1	1
6	Ammonia Storage Tank	Horizontal tank	242,000 liter (64,000 gal)	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	139,000 lpm @ 30 m (37,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 780 GJ/hr (740 MMBtu/hr) heat duty	1	0

Case CM95-B1-S300-N1000

Account 2: Sorbent Preparation and Feed

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Lime Slaker	N/A	0.4 tonne/hr (0.4 tph)	1	1
2	Lime Slurry Tank	Field Erected	4,490 tonne/hr (4949 tph)	1	1
3	Lime Slurry Feed Pumps	Horizontal centrifugal	20 lpm @ 9m H_2O (6 gpm @ 30 ft H_2O)	1	1

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	593 lpm @ 10 m H_2O (157 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	2,518 lpm @ 20 m H_2O (700 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	107 lpm @ 50 m H_2O (28 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	102,000 liter (27,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	8 lpm (2.1 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	428,000 kg/hr (923,000 lb/hr) 98.8% efficiency	1	0
2	Spray Dryer	Co-current open spray	8,000 m³/min (281,000 acfm)	1	0
3	Atomizer	Rotary	21 lpm @ 25 m H_2O (6 gpm @ 80 ft H_2O)	1	1
4	Solids Conveying	–	–	1	0
5	CANSOLV®	Amine-based CO_2 capture technology	709,000 kg/hr (1,562,000 lb/hr) 26.4 wt% CO_2 concentration	1	0
6	CO_2 Dryer	Triethylene glycol	Inlet: 42 m³/min @ 3.0 MPa (1,497 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 254 kg/hr (561 lb/hr)	1	0
7	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m³/min @ 15 MPa, 80°C (166 acfm @ 2,217 psia, 177°F)	1	0
8	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 25 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0
2	SCR Reactor	–	280,000 kg/hr (620,000 lb/hr)	1	0
3	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
4	Dilution Air Blowers	Centrifugal	99 m³/min @ 108 cm WG (3,500 scfm @ 42 in WG)	1	1
5	Ammonia Feed Pump	Centrifugal	21 lpm @ 90 m H_2O (6 gpm @ 300 ft H_2O)	1	1
6	Ammonia Storage Tank	Horizontal tank	301,000 liter (79,000 gal)	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	136,000 lpm @ 30 m (36,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 760 GJ/hr (720 MMBtu/hr) heat duty	1	0

Case CM95-B3-S300-N1000

Account 2: Sorbent Preparation and Feed

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Lime Slaker	N/A	0.6 tonne/hr (0.6 tph)	1	1
2	Lime Slurry Tank	Field Erected	6,576 tonne/hr (7249 tph)	1	1
3	Lime Slurry Feed Pumps	Horizontal centrifugal	30 lpm @ 9m H_2O (8 gpm @ 30 ft H_2O)	1	1

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	553 lpm @ 10 m H_2O (146 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	1,516 lpm @ 20 m H_2O (400 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	120 lpm @ 50 m H_2O (32 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	115,000 liter (30,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.9 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	544,000 kg/hr (1,451,000 lb/hr) 99.2% efficiency	1	0
2	Spray Dryer	Co-current open spray	12,000 m^3/min (411,000 acfm)	1	0
3	Atomizer	Rotary	31 lpm @ 25 m H_2O (8 gpm @ 80 ft H_2O)	1	1
4	Solids Conveying	–	–	1	0
5	CANSOLV®	Amine-based CO_2 capture technology	806,000 kg/hr (1,777,000 lb/hr) 22.9 wt% CO_2 concentration	1	0
6	CO_2 Dryer	Triethylene glycol	Inlet: 42 m^3/min @ 3.0 MPa (1,476 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 251 kg/hr (553 lb/hr)	1	0
7	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m^3/min @ 15 MPa, 80°C (164 acfm @ 2,217 psia, 177°F)	1	0
8	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0
2	SCR Reactor	–	260,000 kg/hr (580,000 lb/hr)	1	0
3	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
4	Dilution Air Blowers	Centrifugal	146 m^3/min @ 108 cm WG (5,150 scfm @ 42 in WG)	1	1
5	Ammonia Feed Pump	Centrifugal	31 lpm @ 90 m H_2O (8 gpm @ 300 ft H_2O)	1	1
6	Ammonia Storage Tank	Horizontal tank	442,000 liter (117,000 gal)	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	126,000 lpm @ 30 m (33,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 700 GJ/hr (670 MMBtu/hr) heat duty	1	0

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Account 2: Sorbent Preparation and Feed

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Lime Slaker	N/A	0.8 tonne/hr (0.8 tph)	1	1
2	Lime Slurry Tank	Field Erected	8,592 tonne/hr (9471 tph)	1	1
3	Lime Slurry Feed Pumps	Horizontal centrifugal	40 lpm @ 9m H_2O (11 gpm @ 30 ft H_2O)	1	1

Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Feedwater Start-up Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed from LP feedwater	528 lpm @ 10 m H_2O (139 gpm @ 20 ft H_2O)	2	2
2	Raw Water Pumps	Stainless steel, single suction	904 lpm @ 20 m H_2O (200 gpm @ 60 ft H_2O)	2	1
3	Filtered Water Pumps	Stainless steel, single suction	148 lpm @ 50 m H_2O (39 gpm @ 160 ft H_2O)	2	1
4	Filtered Water Tank	Vertical, cylindrical	142,000 liter (38,000 gal)	1	0
5	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	7 lpm (1.8 gpm)	1	0
6	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0

Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	680,000 kg/hr (1,813,000 lb/hr) 99.4% efficiency	1	0
2	Spray Dryer	Co-current open spray	15,000 m^3/min (537,000 acfm)	1	0
3	Atomizer	Rotary	41 lpm @ 25 m H_2O (11 gpm @ 80 ft H_2O)	1	1
4	Solids Conveying	–	–	1	0
5	CANSOLV®	Amine-based CO_2 capture technology	930,000 kg/hr (2,050,000 lb/hr) 19.7 wt% CO_2 concentration	1	0
6	CO_2 Dryer	Triethylene glycol	Inlet: 41 m^3/min @ 3.0 MPa (1,463 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 249 kg/hr (548 lb/hr)	1	0
7	CO_2 Compressor	Integrally geared, multi-stage centrifugal	5 m^3/min @ 15 MPa, 80°C (162 acfm @ 2,217 psia, 177°F)	1	0
8	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15 MPa, 30°C (2,215 psia, 86°F) Duty: 24 GJ/hr (23 MMBtu/hr)	1	0

Account 7: Ductwork and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	23 m (75 ft) high x 1.6 m (5 ft) diameter	1	0
2	SCR Reactor	–	250,000 kg/hr (550,000 lb/hr)	1	0
3	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
4	Dilution Air Blowers	Centrifugal	191 m^3/min @ 108 cm WG (6,740 scfm @ 42 in WG)	1	1
5	Ammonia Feed Pump	Centrifugal	40 lpm @ 90 m H_2O (11 gpm @ 300 ft H_2O)	1	1
6	Ammonia Storage Tank	Horizontal tank	578,000 liter (153,000 gal)	1	0

Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	126,000 lpm @ 30 m (33,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (52°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT / 700 GJ/hr (670 MMBtu/hr) heat duty	1	0

APPENDIX C: CARBON BALANCES

Exhibit C-1. Carbon balance for case CM99-B

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	10,875 (23,976)	Stack Gas	492 (1,085)
Air (CO_2)	38 (83)	CO_2 Product	47,224 (104,112)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	8.5 (19)
		CO_2 Knockouts	0.1 (0.2)
Total	**47,725 (105,216)**	**Total**	**47,725 (105,216)**

Exhibit C-2. Carbon balance for case CM95-B

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	9,942 (21,918)	Stack Gas	2,342 (5,163)
Air (CO_2)	34 (76)	CO_2 Product	44,439 (97,971)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	8.0 (18)
		CO_2 Knockouts	0.1 (0.2)
Total	**46,789 (103,151)**	**Total**	**46,789 (103,151)**

Exhibit C-3. Carbon balance for case CM95-B1

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	9,566 (21,089)	Stack Gas	2,323 (5,121)
Air (CO_2)	33 (73)	CO_2 Product	44,080 (97,180)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.9 (17)
		CO_2 Knockouts	0.1 (0.2)
Total	**46,411 (102,319)**	**Total**	**46,411 (102,319)**

Exhibit C-4. Carbon balance for case CM95-B2

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	9,884 (21,790)	Stack Gas	2,339 (5,156)
Air (CO_2)	34 (75)	CO_2 Product	44,384 (97,849)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	8.0 (18)
		CO_2 Knockouts	0.1 (0.2)
Total	**46,730 (103,023)**	**Total**	**46,730 (103,023)**

Exhibit C-5. Carbon balance for case CM95-B3

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	10,792 (23,792)	Stack Gas	2,771 (6,109)
Air (CO_2)	37 (82)	CO_2 Product	52,588 (115,936)
Kiln Off-Gas	44,539 (98,193)	CO_2 Dryer Vent	9.4 (21)
		CO_2 Knockouts	0.2 (0.4)
Total	**55,369 (122,067)**	**Total**	**55,369 (122,067)**

Exhibit C-6. Carbon balance for case CM95-B4

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	10,301 (22,709)	Stack Gas	2,747 (6,055)
Air (CO_2)	36 (79)	CO_2 Product	52,119 (114,904)
Kiln Off-Gas	44,539 (98,193)	CO_2 Dryer Vent	9.4 (21)
		CO_2 Knockouts	0.2 (0.5)
Total	**54,876 (120,980)**	**Total**	**54,876 (120,980)**

Exhibit C-7. Carbon balance for case CM95-B5

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	8,803 (19,408)	Stack Gas	2,285 (5,037)
Air (CO_2)	30 (67)	CO_2 Product	43,354 (95,579)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.8 (17)
		CO_2 Knockouts	0.1 (0.2)
Total	**45,646 (100,632)**	**Total**	**45,646 (100,632)**

Exhibit C-8. Carbon balance for case CM95-B6

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	6,637 (14,631)	Stack Gas	2,176 (4,797)
Air (CO_2)	23 (51)	CO_2 Product	41,289 (91,026)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.4 (16)
		CO_2 Knockouts	0.1 (0.2)
Total	**43,472 (95,839)**	**Total**	**43,472 (95,839)**

Exhibit C-9. Carbon balance for case CM95-B7

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	8,454 (18,638)	Stack Gas	2,267 (4,998)
Air (CO_2)	29 (64)	CO_2 Product	43,021 (94,845)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.7 (17)
		CO_2 Knockouts	0.1 (0.2)
Total	**45,296 (99,860)**	**Total**	**45,296 (99,860)**

Exhibit C-10. Carbon balance for case CM95-B8

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	6,354 (14,008)	Stack Gas	2,162 (4,765)
Air (CO_2)	22 (48)	CO_2 Product	41,019 (90,432)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.4 (16)
		CO_2 Knockouts	0.1 (0.2)
Total	**43,188 (95,214)**	**Total**	**43,188 (95,214)**

Exhibit C-11. Carbon balance for case CM95-B-S300-N1000

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	9,935 (21,904)	Stack Gas	2,341 (5,162)
Air (CO_2)	34 (76)	CO_2 Product	44,433 (97,957)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	8.0 (18)
		CO_2 Knockouts	0.1 (0.2)
Total	**46,782 (103,137)**	**Total**	**46,782 (103,137)**

Exhibit C-12. Carbon balance for case CM95-B1-S300-N1000

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	9,560 (21,075)	Stack Gas	2,323 (5,120)
Air (CO_2)	33 (73)	CO_2 Product	44,074 (97,167)
Kiln Off-Gas	36,812 (81,157)	CO_2 Dryer Vent	7.9 (17)
		CO_2 Knockouts	0.1 (0.3)
Total	**46,405 (102,305)**	**Total**	**46,405 (102,305)**

Exhibit C-13. Carbon balance for case CM95-B3-S300-N1000

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	10,785 (23,777)	Stack Gas	2,771 (6,109)
Air (CO_2)	37 (82)	CO_2 Product	52,581 (115,921)
Kiln Off-Gas	44,539 (98,193)	CO_2 Dryer Vent	9.4 (21)
		CO_2 Knockouts	0.3 (0.7)
Total	**55,362 (122,052)**	**Total**	**55,362 (122,052)**

Exhibit C-14. Carbon balance for case CM95-B4-S300-N1000

Carbon In		Carbon Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	10,294 (22,694)	Stack Gas	2,746 (6,054)
Air (CO_2)	36 (79)	CO_2 Product	52,113 (114,890)
Kiln Off-Gas	44,539 (98,193)	CO_2 Dryer Vent	9.4 (21)
		CO_2 Knockouts	0.4 (0.9)
Total	**54,869 (120,965)**	**Total**	**54,869 (120,965)**

APPENDIX D: WATER BALANCES

A water balance was performed for each case on the major water consumers in the process. The total water demand for each subsystem was determined. Raw water withdrawal is the water removed from the ground or diverted from a municipal source for use in the plant. Raw water consumption is also accounted for as the portion of the raw water withdrawn that is evaporated, transpired, incorporated into products, or otherwise not returned to the water source from which it was withdrawn.

Raw water makeup was assumed to be provided 50 percent by a publicly owned treatment works (POTW) and 50 percent from groundwater. Raw water withdrawal is defined as the water metered from a raw water source and used in the plant processes for all purposes, such as cooling tower makeup, and flue gas desulfurization (FGD) system makeup, depending on the technology examined. The difference between withdrawal and process water returned to the source is consumption. Consumption represents the net impact of the process on the water source. The cooling tower blowdown was assumed to be treated and 90 percent returned to the water source.

The largest consumer of raw water in all cases is cooling tower makeup. It was assumed that all cases utilized a mechanical draft, evaporative cooling tower. The design ambient wet bulb temperature of 11°C (51.5°F) was used to achieve a cooling water temperature of 16°C (60°F) using an approach of 5°C (8.5°F). The cooling water range was assumed to be 11°C (20°F). The cooling tower makeup rate was determined using the following [26]:

- Evaporative losses of 0.8 percent of the circulating water flow rate per 5.5°C (10°F) of range
- Drift losses of 0.001 percent of the circulating water flow rate
- Blowdown losses were calculated as follows:

$$BDL = \frac{EL}{CC - 1}$$

Where:

BDL – Blowdown losses

EL – Evaporative losses

CC – Cycles of concentration

The cycles of concentration are a measure of water quality and a mid-range value of four was chosen for this report. The water balances presented in subsequent sections include the water demand of the major water consumers within the process, the amount of raw water withdrawal, the amount of process water returned to the source, and the raw water consumption, by difference.

Exhibit D-1. Water balance for case CM99-B

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.2)	0.0 (-1.2)
CO_2 Capture Recovery	–	–	0.5 (134)	-0.5 (-134)
CO_2 Compression Recovery	–	–	0.0 (4.9)	0.0 (-4.9)
Deaerator Vent	–	–	0.0 (2.1)	0.0 (-2.1)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (2.1)	0.0 (2.1)	–	0.0 (2.1)
Cooling Tower	5.9 (1,554)	5.9 (1,554)	1.3 (349)	4.6 (1,204)
Total	**5.9 (1,556)**	**5.9 (1,556)**	**1.9 (492)**	**4.0 (1,062)**

Exhibit D-2. Water balance for case CM95-B

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.5 (132)	-0.5 (-132)
CO_2 Compression Recovery	–	–	0.0 (4.6)	0.0 (-4.6)
Deaerator Vent	–	–	0.0 (2.0)	0.0 (-2.0)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (2.0)	0.0 (2.0)	–	0.0 (2.0)
Cooling Tower	5.4 (1,431)	5.4 (1,431)	1.2 (322)	4.2 (1,109)
Total	**5.4 (1,433)**	**5.4 (1,433)**	**1.7 (461)**	**3.7 (970)**

Exhibit D-3. Water balance for case CM95-B1

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.7 (185)	-0.7 (-185)
CO_2 Compression Recovery	–	–	0.0 (4.5)	0.0 (-4.5)
Deaerator Vent	–	–	0.0 (1.9)	0.0 (-1.9)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (1.9)	0.0 (1.9)	–	0.0 (1.9)
Cooling Tower	5.3 (1,397)	5.3 (1,397)	1.2 (314)	4.1 (1,083)
Total	**5.3 (1,399)**	**5.3 (1,399)**	**1.9 (507)**	**3.4 (890)**

Exhibit D-4. Water balance for case CM95-B2

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.5 (138)	-0.5 (-138)
CO_2 Compression Recovery	–	–	0.0 (4.6)	0.0 (-4.6)
Deaerator Vent	–	–	0.0 (2.0)	0.0 (-2.0)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (2.0)	0.0 (2.0)	–	0.0 (2.0)
Cooling Tower	5.4 (1,429)	5.4 (1,429)	1.2 (321)	4.2 (1,108)
Total	**5.4 (1,431)**	**5.4 (1,431)**	**1.8 (467)**	**3.6 (962)**

Exhibit D-5. Water balance for case CM95-B3

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.3)	0.0 (-1.3)
CO_2 Capture Recovery	–	–	2.8 (733)	-2.8 (-733)
CO_2 Compression Recovery	–	–	0.0 (5.4)	0.0 (-5.4)
Deaerator Vent	–	–	0.0 (2.1)	0.0 (-2.1)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (2.1)	0.0 (2.1)	–	0.0 (2.1)
Cooling Tower	6.1 (1,621)	6.1 (1,621)	1.4 (364)	4.8 (1,256)
Total	**6.1 (1,623)**	**6.1 (1,623)**	**4.2 (1,106)**	**1.9 (514)**

Exhibit D-6. Water balance for case CM95-B4

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.3)	0.0 (-1.3)
CO_2 Capture Recovery	–	–	3.9 (1,037)	-3.9 (-1,037)
CO_2 Compression Recovery	–	–	0.0 (5.4)	0.0 (-5.4)
Deaerator Vent	–	–	0.0 (2.0)	0.0 (-2.0)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (2.0)	0.0 (2.0)	–	0.0 (2.0)
Cooling Tower	5.9 (1,570)	5.9 (1,570)	1.3 (353)	4.6 (1,217)
Total	**6.0 (1,572)**	**6.0 (1,572)**	**5.3 (1,399)**	**0.6 (171)**

Exhibit D-7. Water balance for case CM95-B5

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.5 (121)	-0.5 (-121)
CO_2 Compression Recovery	–	–	0.0 (4.5)	0.0 (-4.5)
Deaerator Vent	–	–	0.0 (1.7)	0.0 (-1.7)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (1.7)	0.0 (1.7)	–	0.0 (1.7)
Cooling Tower	5.3 (1,404)	5.3 (1,404)	1.2 (316)	4.1 (1,088)
Total	**5.3 (1,406)**	**5.3 (1,406)**	**1.7 (444)**	**3.6 (960)**

Exhibit D-8. Water balance for case CM95-B6

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.4 (100)	-0.4 (-100)
CO_2 Compression Recovery	–	–	0.0 (3.6)	0.0 (-3.6)
Deaerator Vent	–	–	0.0 (1.3)	0.0 (-1.3)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (1.3)	0.0 (1.3)	–	0.0 (1.3)
Cooling Tower	5.1 (1,349)	5.1 (1,349)	1.1 (303)	4.0 (1,046)
Total	**5.1 (1,351)**	**5.1 (1,351)**	**1.6 (410)**	**3.6 (939)**

Exhibit D-9. Water balance for case CM95-B7

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.7 (174)	-0.7 (-174)
CO_2 Compression Recovery	–	–	0.0 (4.4)	0.0 (-4.4)
Deaerator Vent	–	–	0.0 (1.7)	0.0 (-1.7)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (1.7)	0.0 (1.7)	–	0.0 (1.7)
Cooling Tower	5.2 (1,371)	5.2 (1,371)	1.2 (308)	4.0 (1,062)
Total	**5.2 (1,372)**	**5.2 (1,372)**	**1.9 (490)**	**3.3 (881)**

Exhibit D-10. Water balance for case CM95-B8

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.0)	0.0 (-1.0)
CO_2 Capture Recovery	–	–	0.6 (154)	-0.6 (-154)
CO_2 Compression Recovery	–	–	0.0 (4.2)	0.0 (-4.2)
Deaerator Vent	–	–	0.0 (1.3)	0.0 (-1.3)
FGD Process Makeup	–	–	–	–
Feedwater Makeup	0.0 (1.3)	0.0 (1.3)	–	0.0 (1.3)
Cooling Tower	5.0 (1,314)	5.0 (1,314)	1.1 (296)	3.9 (1,018)
Total	**5.0 (1,315)**	**5.0 (1,315)**	**1.7 (456)**	**3.2 (858)**

Exhibit D-11. Water balance for case CM95-B-S300-N1000

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.6 (162)	-0.6 (-162)
CO_2 Compression Recovery	–	–	0.0 (4.2)	0.0 (-4.2)
Deaerator Vent	–	–	0.0 (2.0)	0.0 (-2.0)
FGD Process Makeup	0.2 (50)	0.2 (50)	–	0.2 (50)
Feedwater Makeup	0.0 (2.0)	0.0 (2.0)	–	0.0 (2.0)
Cooling Tower	5.4 (1,430)	5.4 (1,430)	1.2 (322)	4.2 (1,108)
Total	**5.6 (1,482)**	**5.6 (1,482)**	**1.9 (491)**	**3.7 (989)**

Exhibit D-12. Water balance for case CM95-B1-S300-N1000

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.1)	0.0 (-1.1)
CO_2 Capture Recovery	–	–	0.9 (240)	-0.9 (-240)
CO_2 Compression Recovery	–	–	0.0 (4.2)	0.0 (-4.2)
Deaerator Vent	–	–	0.0 (1.9)	0.0 (-1.9)
FGD Process Makeup	0.2 (54)	0.2 (54)	–	0.2 (54)
Feedwater Makeup	0.0 (1.9)	0.0 (1.9)	–	0.0 (1.9)
Cooling Tower	5.3 (1,395)	5.3 (1,395)	1.2 (314)	4.1 (1,082)
Total	**5.5 (1,452)**	**5.5 (1,452)**	**2.1 (561)**	**3.4 (889)**

Exhibit D-13. Water balance for case CM95-B3-S300-N1000

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.3)	0.0 (-1.3)
CO_2 Capture Recovery	–	–	3.1 (813)	-3.1 (-813)
CO_2 Compression Recovery	–	–	0.0 (5.0)	0.0 (-5.0)
Deaerator Vent	–	–	0.0 (2.1)	0.0 (-2.1)
FGD Process Makeup	0.3 (75)	0.3 (75)	–	0.3 (75)
Feedwater Makeup	0.0 (2.1)	0.0 (2.1)	–	0.0 (2.1)
Cooling Tower	6.1 (1,619)	6.1 (1,619)	1.4 (364)	4.8 (1,255)
Total	**6.4 (1,696)**	**6.4 (1,696)**	**4.5 (1,185)**	**1.9 (508)**

Exhibit D-14. Water balance for case CM95-B4-S300-N1000

Water Use	Water Demand	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	0.0 (1.3)	0.0 (-1.3)
CO_2 Capture Recovery	–	–	4.3 (1,136)	-4.3 (-1,136)
CO_2 Compression Recovery	–	–	0.0 (4.9)	0.0 (-4.9)
Deaerator Vent	–	–	0.0 (2.0)	0.0 (-2.0)
FGD Process Makeup	0.4 (93)	0.4 (93)	–	0.4 (93)
Feedwater Makeup	0.0 (2.0)	0.0 (2.0)	–	0.0 (2.0)
Cooling Tower	5.9 (1,568)	5.9 (1,568)	1.3 (353)	4.6 (1,216)
Total	**6.3 (1,663)**	**6.3 (1,663)**	**5.7 (1,497)**	**0.6 (164)**

Appendix E: Sulfur Balances

Exhibit E-1. Sulfur balance for case CM99-B

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.2 (0.4)	Solvent Reclaiming	12 (26)
Kiln Off-Gas	12 (26)		
Total	**12 (26)**	**Total**	**12 (26)**

Exhibit E-2. Sulfur balance for case CM95-B

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.1 (0.3)	Solvent Reclaiming	12 (26)
Kiln Off-Gas	12 (26)		
Total	**12 (26)**	**Total**	**12 (26)**

Exhibit E-3. Sulfur balance for case CM95-B1

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.1 (0.3)	Solvent Reclaiming	15 (32)
Kiln Off-Gas	15 (32)		
Total	**15 (32)**	**Total**	**15 (32)**

Exhibit E-4. Sulfur balance for case CM95-B2

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.1 (0.3)	Solvent Reclaiming	12 (27)
Kiln Off-Gas	12 (27)		
Total	**12 (27)**	**Total**	**12 (27)**

Exhibit E-5. Sulfur balance for case CM95-B3

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.2 (0.3)	Solvent Reclaiming	26 (57)
Kiln Off-Gas	26 (57)		
Total	**26 (57)**	**Total**	**26 (57)**

Exhibit E-6. Sulfur balance for case CM95-B4

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		**kg/hr (lb/hr)**
Natural Gas	0.2 (0.3)	Solvent Reclaiming	34 (75)
Kiln Off-Gas	34 (75)		
Total	**34 (75)**	**Total**	**34 (75)**

Exhibit E-7. Sulfur balance for case CM95-B5

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.3)	Solvent Reclaiming	12 (26)
Kiln Off-Gas	12 (26)		
Total	**12 (26)**	**Total**	**12 (26)**

Exhibit E-8. Sulfur balance for case CM95-B6

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.2)	Solvent Reclaiming	12 (26)
Kiln Off-Gas	12 (26)		
Total	**12 (26)**	**Total**	**12 (26)**

Exhibit E-9. Sulfur balance for case CM95-B7

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.3)	Solvent Reclaiming	15 (32)
Kiln Off-Gas	15 (32)		
Total	**15 (32)**	**Total**	**15 (32)**

Exhibit E-10. Sulfur balance for case CM95-B8

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.2)	Solvent Reclaiming	15 (32)
Kiln Off-Gas	15 (32)		
Total	**15 (32)**	**Total**	**15 (32)**

Exhibit E-11. Sulfur balance for case CM95-B-S300-N1000

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.3)	Gypsum Production	90 (199)
Kiln Off-Gas	95 (209)	Solvent Reclaiming	4.9 (11)
Total	**95 (210)**	**Total**	**95 (210)**

Exhibit E-12. Sulfur balance for case CM95-B1-S300-N1000

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.3)	Gypsum Production	112 (246)
Kiln Off-Gas	117 (259)	Solvent Reclaiming	6.0 (13)
Total	**118 (259)**	**Total**	**118 (259)**

Exhibit E-13. Sulfur balance for case CM95-B3-S300-N1000

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.2 (0.3)	Gypsum Production	198 (436)
Kiln Off-Gas	208 (459)	Solvent Reclaiming	11 (23)
Total	**208 (459)**	**Total**	**208 (459)**

Exhibit E-14. Sulfur balance for case CM95-B4-S300-N1000

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.2 (0.3)	Gypsum Production	258 (570)
Kiln Off-Gas	272 (600)	Solvent Reclaiming	14 (30)
Total	**272 (600)**	**Total**	**272 (600)**

Appendix F: Cost Details for Air In-Leakage Scenarios

Exhibit F-1. Capital costs for case CM95-B at 250°F

	Case:	CM95-B at 250°F							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3						Feedwater & Miscellaneous BOP Systems					
3.1	Feedwater System	$1,019	$1,746	$873	$0	$3,638	$637	$0	$855	$5,129	$4
3.2	Water Makeup & Pretreating	$2,661	$266	$1,508	$0	$4,434	$776	$0	$1,042	$6,252	$4
3.3	Other Feedwater Subsystems	$494	$162	$154	$0	$810	$142	$0	$190	$1,142	$1
3.4	Industrial Boiler Package w/Deaerator	$6,584	$0	$1,914	$0	$8,499	$1,487	$0	$1,997	$11,983	$8
3.5	Other Boiler Plant Systems	$119	$43	$109	$0	$271	$47	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,023	$44	$33	$0	$1,100	$193	$0	$259	$1,551	$1
3.7	Waste Water Treatment Equipment	$5,340	$0	$3,273	$0	$8,612	$1,507	$0	$2,024	$12,143	$9
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$17,381**	**$2,280**	**$7,935**	**$0**	**$27,596**	**$4,829**	**$0**	**$6,485**	**$38,911**	**$27**
5						Flue Gas Cleanup					
5.1	CANSOLV CO_2 Capture System	$88,841	$39,054	$82,014	$0	$209,908	$36,734	$35,684	$56,465	$338,792	$237
5.4	CO_2 Compression & Drying	$25,270	$3,791	$8,449	$0	$37,510	$6,564	$0	$8,815	$52,889	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.12	Gas Cleanup Foundations	$0	$101	$89	$0	$190	$33	$0	$45	$267	$0
	Subtotal	**$114,321**	**$42,979**	**$90,641**	**$0**	**$247,941**	**$43,390**	**$35,684**	**$65,403**	**$392,418**	**$275**
7						Ductwork & Stack					
7.3	Ductwork	$0	$2,455	$1,706	$0	$4,161	$728	$0	$978	$5,867	$4
7.4	Stack	$10,390	$0	$6,037	$0	$16,427	$2,875	$0	$3,860	$23,163	$16
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,390**	**$2,687**	**$8,019**	**$0**	**$21,096**	**$3,692**	**$0**	**$4,958**	**$29,746**	**$21**
9						Cooling Water System					
9.1	Cooling Towers	$2,357	$0	$729	$0	$3,086	$540	$0	$725	$4,351	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$376	$0
9.3	Circulating Water System Aux.	$3,008	$0	$398	$0	$3,406	$596	$0	$800	$4,803	$3
9.4	Circulating Water Piping	$0	$1,391	$1,260	$0	$2,651	$464	$0	$623	$3,737	$3

Case:	CM95-B at 250°F							Estimate Type:	Conceptual	
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/(tonne CO_2/year)
9.5	Make-up Water System	$315	$0	$405	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$403	$71	$0	$95	$568	$0
	Subtotal	**$6,146**	**$1,543**	**$3,227**	**$0**	**$10,915**	**$1,910**	**$0**	**$2,565**	**$15,390**	**$11**
11						**Accessory Electric Plant**					
11.2	Station Service Equipment	$3,902	$0	$335	$0	$4,236	$741	$0	$996	$5,973	$4
11.3	Switchgear & Motor Control	$6,057	$0	$1,051	$0	$7,108	$1,244	$0	$1,670	$10,022	$7
11.4	Conduit & Cable Tray	$0	$787	$2,269	$0	$3,056	$535	$0	$718	$4,310	$3
11.5	Wire & Cable	$0	$2,085	$3,727	$0	$5,812	$1,017	$0	$1,366	$8,195	$6
	Subtotal	**$9,958**	**$2,873**	**$7,382**	**$0**	**$20,213**	**$3,537**	**$0**	**$4,750**	**$28,500**	**$20**
12						**Instrumentation & Control**					
12.8	Instrument Wiring & Tubing	$549	$439	$1,757	$0	$2,746	$481	$0	$645	$3,872	$3
12.9	Other I&C Equipment	$675	$0	$1,563	$0	$2,238	$392	$0	$526	$3,156	$2
	Subtotal	**$1,224**	**$439**	**$3,321**	**$0**	**$4,984**	**$872**	**$0**	**$1,171**	**$7,028**	**$5**
13						**Improvements to Site**					
13.1	Site Preparation	$0	$37	$746	$0	$783	$137	$0	$184	$1,104	$1
13.2	Site Improvements	$0	$174	$230	$0	$404	$71	$0	$95	$570	$0
13.3	Site Facilities	$199	$0	$209	$0	$408	$71	$0	$96	$575	$0
	Subtotal	**$199**	**$211**	**$1,186**	**$0**	**$1,595**	**$279**	**$0**	**$375**	**$2,250**	**$2**
14						**Buildings & Structures**					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$159,619**	**$53,091**	**$121,773**	**$0**	**$334,483**	**$58,534**	**$35,684**	**$85,740**	**$514,442**	**$361**
					Retrofit Values	**$351,207**	**$61,461**	**$37,469**	**$90,027**	**$540,164**	**$379**

Exhibit F-2. Owners' costs for case CM95-B at 250°F

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$2,827	$2
1-Month Maintenance Materials	$508	$0
1-Month Non-Fuel Consumables	$593	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$10,803	$8
Total	**$14,738**	**$10**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$1,046	$1
0.5% of TPC (spare parts)	$2,701	$2
Total	**$3,747**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$81,025	$57
Financing Costs	$14,584	$10
TOC	**$654,258**	**$459**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$731,476**	**$513**

Exhibit F-3. Initial and annual O&M costs for case CM95-B at 250°F

Case:	**CM95-B at 250°F**					**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**					**Operation (%):**	**85**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:			0.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			0.0
				Lab Techs, etc.:			0.0
				Total:			**2.3**
Fixed Operating Costs							
						Annual Cost	
						($)	**$/(tonne CO_2/year)**
Annual Operating Labor:						$1,066,625	$0.88
Maintenance Labor:						$3,457,050	$2.85
Administrative & Support Labor:						$1,130,919	$0.93
Property Taxes and Insurance:						$10,803,283	$8.91
Total:						**$16,457,877**	**$13.57**
Variable Operating Costs							
						($)	**$/(tonne CO_2/year)**
Maintenance Material:						$5,185,576	$4.28
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (/1000 gallons):	0	1,032	$2.24	$0		$715,598	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0		$617,061	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary					$4,005,743	$3.30
Triethylene Glycol (gal):	w/equip.	286	$8.00	$0		$710,807	$0.59
Subtotal:				**$0**		**$6,049,209**	**$4.99**
Waste Disposal							
Triethylene Glycol (gal):		286	$0.41	$0		$36,586	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0		$23,430	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0		$422	$0.00
Subtotal:				**$0**		**$60,438**	**$0.05**
Variable Operating Costs Total:				**$0**		**$11,295,222**	**$9.31**
Fuel and Purchased Power Costs							
Natural Gas (MMBTU):	0	16,374	$4.61	$0		$23,424,656	$19.32
Purchased Power (MWh):	0	20	$67.28	$0		$10,224,686	$8.43
Total:				**$0**		**$33,649,342**	**$27.75**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

Exhibit F-4. Capital costs for case CM95-B at 250°F with air in-leakage up to 400,000 ACFM

Case:		CM95-B at 250°F 400,000 ACFM							Estimate Type:	Conceptual	
Representative Plant Size:		1.5 M tonnes cement/year (91.4% clinker)							Cost Base:	Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$1,019	$1,747	$874	$0	$3,640	$637	$0	$855	$5,132	$4
3.2	Water Makeup & Pretreating	$2,663	$266	$1,509	$0	$4,438	$777	$0	$1,043	$6,257	$4
3.3	Other Feedwater Subsystems	$495	$162	$154	$0	$811	$142	$0	$191	$1,143	$1
3.4	Industrial Boiler Package w/Deaerator	$6,590	$0	$1,916	$0	$8,506	$1,489	$0	$1,999	$11,994	$8
3.5	Other Boiler Plant Systems	$119	$43	$109	$0	$272	$48	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,024	$44	$33	$0	$1,101	$193	$0	$259	$1,552	$1
3.7	Waste Water Treatment Equipment	$6,217	$0	$3,811	$0	$10,028	$1,755	$0	$2,357	$14,139	$10
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$18,268**	**$2,282**	**$8,476**	**$0**	**$29,026**	**$5,080**	**$0**	**$6,821**	**$40,927**	**$29**
5	Flue Gas Cleanup										
5.1	CANSOLV CO_2 Capture System	$98,825	$43,443	$91,231	$0	$233,499	$40,862	$39,695	$62,811	$376,867	$264
5.4	CO_2 Compression & Drying	$25,282	$3,793	$8,453	$0	$37,528	$6,567	$0	$8,819	$52,915	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.12	Gas Cleanup Foundations	$0	$132	$115	$0	$247	$43	$0	$58	$348	$0
	Subtotal	**$124,318**	**$47,401**	**$99,889**	**$0**	**$271,607**	**$47,531**	**$39,695**	**$71,767**	**$430,600**	**$302**
7	Ductwork & Stack										
7.3	Ductwork	$0	$3,340	$2,321	$0	$5,660	$991	$0	$1,330	$7,981	$6
7.4	Stack	$10,721	$0	$6,230	$0	$16,951	$2,966	$0	$3,984	$23,901	$17
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,721**	**$3,572**	**$8,826**	**$0**	**$23,119**	**$4,046**	**$0**	**$5,433**	**$32,598**	**$23**
9	Cooling Water System										
9.1	Cooling Towers	$2,359	$0	$729	$0	$3,088	$540	$0	$726	$4,355	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$376	$0
9.3	Circulating Water System Aux.	$3,010	$0	$398	$0	$3,408	$596	$0	$801	$4,805	$3
9.4	Circulating Water Piping	$0	$1,392	$1,260	$0	$2,652	$464	$0	$623	$3,740	$3
9.5	Make-up Water System	$315	$0	$405	$0	$720	$126	$0	$169	$1,015	$1

	Case:	CM95-B at 250°F 400,000 ACFM						Estimate Type:		Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/ year)
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$403	$71	$0	$95	$569	$0
	Subtotal	**$6,150**	**$1,543**	**$3,229**	**$0**	**$10,922**	**$1,911**	**$0**	**$2,567**	**$15,400**	**$11**
11						**Accessory Electric Plant**					
11.2	Station Service Equipment	$3,936	$0	$338	$0	$4,274	$748	$0	$1,004	$6,026	$4
11.3	Switchgear & Motor Control	$6,110	$0	$1,060	$0	$7,170	$1,255	$0	$1,685	$10,110	$7
11.4	Conduit & Cable Tray	$0	$794	$2,289	$0	$3,083	$540	$0	$725	$4,347	$3
11.5	Wire & Cable	$0	$2,104	$3,760	$0	$5,863	$1,026	$0	$1,378	$8,267	$6
	Subtotal	**$10,046**	**$2,898**	**$7,447**	**$0**	**$20,390**	**$3,568**	**$0**	**$4,792**	**$28,751**	**$20**
12						**Instrumentation & Control**					
12.8	Instrument Wiring & Tubing	$551	$441	$1,762	$0	$2,753	$482	$0	$647	$3,882	$3
12.9	Other I&C Equipment	$677	$0	$1,567	$0	$2,244	$393	$0	$527	$3,164	$2
	Subtotal	**$1,227**	**$441**	**$3,329**	**$0**	**$4,997**	**$875**	**$0**	**$1,174**	**$7,046**	**$5**
13						**Improvements to Site**					
13.1	Site Preparation	$0	$37	$749	$0	$786	$138	$0	$185	$1,109	$1
13.2	Site Improvements	$0	$175	$231	$0	$406	$71	$0	$95	$573	$0
13.3	Site Facilities	$200	$0	$210	$0	$409	$72	$0	$96	$577	$0
	Subtotal	**$200**	**$212**	**$1,190**	**$0**	**$1,602**	**$280**	**$0**	**$376**	**$2,259**	**$2**
14						**Buildings & Structures**					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$170,930**	**$58,427**	**$132,450**	**$0**	**$361,807**	**$63,316**	**$39,695**	**$92,964**	**$557,782**	**$391**
					Retrofit Values	**$379,897**	**$66,482**	**$41,680**	**$97,612**	**$585,671**	**$410**

Exhibit F-5. Owners' costs for case CM95-B at 250°F with air in-leakage up to 400,000 ACFM

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,009	$2
1-Month Maintenance Materials	$551	$0
1-Month Non-Fuel Consumables	$593	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$11,713	$8
Total	**$15,873**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$1,046	$1
0.5% of TPC (spare parts)	$2,928	$2
Total	**$3,974**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$87,851	$62
Financing Costs	$15,813	$11
TOC	**$709,182**	**$497**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$792,882**	**$555**

Exhibit F-6. Initial and annual O&M costs for case CM95-B at 250°F with air in-leakage up to 400,000 ACFM

Case:	CM95-B at 250°F 400,000 ACFM				Cost Base:	Dec 2018
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operation (%):	85
Operating & Maintenance Labor						
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):		40.72	$/hour	Skilled Operator:		0.0
Operating Labor Burden:		30.00	% of base	Operator:		2.3
Labor O-H Charge Rate:		25.00	% of labor	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$3,748,294	$3.09
Administrative & Support Labor:					$1,203,730	$0.99
Property Taxes and Insurance:					$11,713,417	$9.65
Total:					**$17,732,065**	**$14.61**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,622,440	$4.63
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	1,033	$2.24	$0	$716,303	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$617,669	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,743	$3.30
Triethylene Glycol (gal):	w/equip.	287	$8.00	$0	$711,507	$0.59
Subtotal:				**$0**	**$6,051,221**	**$4.99**
Waste Disposal						
Triethylene Glycol (gal):		287	$0.41	$0	$36,622	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,453	$0.02
Pre-scrubber Blowdown Waste (ton):		0.05	$44.70	$0	$652	$0.00
Subtotal:				**$0**	**$60,726**	**$0.05**
Variable Operating Costs Total:				**$0**	**$11,734,388**	**$9.67**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,390	$4.61	$0	$23,447,728	$19.32
Purchased Power (MWh):	0	21	$67.28	$0	$10,435,091	$8.60
Total:				**$0**	**$33,882,819**	**$27.91**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

Exhibit F-7. Capital costs for case CM95-B at 250°F with air in-leakage up to 700,000 ACFM

Case:		CM95-B at 250°F 700,000 ACFM						Estimate Type:		Conceptual	
Representative Plant Size:		1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3					Feedwater & Miscellaneous BOP Systems						
3.1	Feedwater System	$1,020	$1,749	$874	$0	$3,644	$638	$0	$856	$5,138	$4
3.2	Water Makeup & Pretreating	$2,665	$267	$1,510	$0	$4,442	$777	$0	$1,044	$6,264	$4
3.3	Other Feedwater Subsystems	$495	$162	$154	$0	$812	$142	$0	$191	$1,145	$1
3.4	Industrial Boiler Package w/Deaerator	$6,599	$0	$1,919	$0	$8,518	$1,491	$0	$2,002	$12,010	$8
3.5	Other Boiler Plant Systems	$120	$44	$109	$0	$272	$48	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,024	$44	$33	$0	$1,102	$193	$0	$259	$1,553	$1
3.7	Waste Water Treatment Equipment	$7,033	$0	$4,310	$0	$11,343	$1,985	$0	$2,666	$15,993	$11
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$19,098**	**$2,284**	**$8,982**	**$0**	**$30,364**	**$5,314**	**$0**	**$7,135**	**$42,813**	**$30**
5					Flue Gas Cleanup						
5.1	CANSOLV CO_2 Capture System	$110,847	$48,728	$102,329	$0	$261,904	$45,833	$44,524	$70,452	$422,713	$296
5.4	CO_2 Compression & Drying	$25,307	$3,796	$8,461	$0	$37,565	$6,574	$0	$8,828	$52,966	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$334	$58	$0	$78	$471	$0
5.12	Gas Cleanup Foundations	$0	$168	$148	$0	$316	$55	$0	$74	$445	$0
	Subtotal	**$136,365**	**$52,726**	**$111,028**	**$0**	**$300,118**	**$52,521**	**$44,524**	**$79,433**	**$476,595**	**$333**
7					Ductwork & Stack						
7.3	Ductwork	$0	$4,450	$3,092	$0	$7,542	$1,320	$0	$1,772	$10,634	$7
7.4	Stack	$11,031	$0	$6,410	$0	$17,440	$3,052	$0	$4,098	$24,591	$17
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$11,031**	**$4,682**	**$9,778**	**$0**	**$25,490**	**$4,461**	**$0**	**$5,990**	**$35,941**	**$25**
9					Cooling Water System						
9.1	Cooling Towers	$2,362	$0	$730	$0	$3,092	$541	$0	$727	$4,360	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$377	$0
9.3	Circulating Water System Aux.	$3,013	$0	$399	$0	$3,411	$597	$0	$802	$4,810	$3

	Case:	CM95-B at 250°F 700,000 ACFM							Estimate Type:		Conceptual
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)							Cost Base:		Nov 2022
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
9.4	Circulating Water Piping	$0	$1,393	$1,262	$0	$2,655	$465	$0	$624	$3,743	$3
9.5	Make-up Water System	$315	$0	$405	$0	$720	$126	$0	$169	$1,016	$1
9.6	Component Cooling Water System	$217	$0	$167	$0	$384	$67	$0	$90	$541	$0
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$404	$71	$0	$95	$569	$0
	Subtotal	**$6,156**	**$1,545**	**$3,232**	**$0**	**$10,933**	**$1,913**	**$0**	**$2,569**	**$15,415**	**$11**
11						**Accessory Electric Plant**					
11.2	Station Service Equipment	$3,987	$0	$342	$0	$4,330	$758	$0	$1,017	$6,105	$4
11.3	Switchgear & Motor Control	$6,190	$0	$1,074	$0	$7,264	$1,271	$0	$1,707	$10,242	$7
11.4	Conduit & Cable Tray	$0	$805	$2,319	$0	$3,124	$547	$0	$734	$4,404	$3
11.5	Wire & Cable	$0	$2,131	$3,809	$0	$5,940	$1,040	$0	$1,396	$8,376	$6
	Subtotal	**$10,178**	**$2,936**	**$7,544**	**$0**	**$20,658**	**$3,615**	**$0**	**$4,855**	**$29,127**	**$20**
12						**Instrumentation & Control**					
12.8	Instrument Wiring & Tubing	$553	$442	$1,769	$0	$2,764	$484	$0	$650	$3,897	$3
12.9	Other I&C Equipment	$679	$0	$1,573	$0	$2,253	$394	$0	$529	$3,177	$2
	Subtotal	**$1,232**	**$442**	**$3,342**	**$0**	**$5,017**	**$878**	**$0**	**$1,179**	**$7,074**	**$5**
13						**Improvements to Site**					
13.1	Site Preparation	$0	$37	$754	$0	$791	$138	$0	$186	$1,116	$1
13.2	Site Improvements	$0	$176	$233	$0	$408	$71	$0	$96	$576	$0
13.3	Site Facilities	$201	$0	$211	$0	$412	$72	$0	$97	$581	$0
	Subtotal	**$201**	**$213**	**$1,198**	**$0**	**$1,612**	**$282**	**$0**	**$379**	**$2,272**	**$2**
14						**Buildings & Structures**					
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$184,260**	**$64,907**	**$145,166**	**$0**	**$394,334**	**$69,008**	**$44,524**	**$101,573**	**$609,439**	**$426**
					Retrofit Values	**$414,050**	**$72,459**	**$46,750**	**$106,652**	**$639,911**	**$447**

Exhibit F-8. Owners' costs for case CM95-B at 250°F with air in-leakage up to 700,000 ACFM

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,226	$2
1-Month Maintenance Materials	$602	$0
1-Month Non-Fuel Consumables	$594	$0
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$12,798	$9
Total	**$17,226**	**$12**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$1,046	$1
0.5% of TPC (spare parts)	$3,200	$2
Total	**$4,246**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0
Land	$0	$0
Other Owner's Costs	$95,987	$67
Financing Costs	$17,278	$12
TOC	**$774,647**	**$542**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$866,074**	**$606**

Exhibit F-9. Initial and annual O&M costs for case CM95-B at 250°F with air in-leakage up to 700,000 ACFM

Case:	CM95-B at 250°F 700,000 ACFM				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operation (%):	85
Operating & Maintenance Labor						
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$4,095,429	$3.37
Administrative & Support Labor:					$1,290,513	$1.06
Property Taxes and Insurance:					$12,798,216	$10.53
Total:					**$19,250,783**	**$15.84**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$6,143,143	$5.05
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	1,034	$2.24	$0	$717,375	$0.59
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$618,594	$0.51
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,743	$3.30
Triethylene Glycol (gal):	w/equip.	287	$8.00	$0	$712,572	$0.59
Subtotal:				**$0**	**$6,054,284**	**$4.98**
Waste Disposal						
Triethylene Glycol (gal):		286	$0.41	$0	$36,677	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,488	$0.02
Pre-scrubber Blowdown Waste (ton):		0.07	$44.70	$0	$992	$0.00
Subtotal:				**$0**	**$61,157**	**$0.05**
Variable Operating Costs Total:				**$0**	**$12,258,584**	**$10.08**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,415	$4.61	$0	$23,482,834	$19.32
Purchased Power (MWh):	0	20	$67.28	$0	$10,755,708	$8.85
Total:				**$0**	**$34,238,543**	**$28.16**

[A]CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

Exhibit F-10. Capital costs for case CM95-B-S100N500 at 250°F

Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
	Case:	CM95-B-S100N500 at 250°F					Estimate Type:			Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)					Cost Base:			Nov 2022	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$1,018	$1,745	$873	$0	$3,636	$636	$0	$854	$5,127	$4
3.2	Water Makeup & Pretreating	$2,700	$270	$1,530	$0	$4,499	$787	$0	$1,057	$6,344	$4
3.3	Other Feedwater Subsystems	$494	$162	$154	$0	$809	$142	$0	$190	$1,141	$1
3.4	Industrial Boiler Package w/Deaerator	$6,581	$0	$1,913	$0	$8,494	$1,486	$0	$1,996	$11,976	$8
3.5	Other Boiler Plant Systems	$119	$43	$108	$0	$271	$47	$0	$64	$382	$0
3.6	NG Pipeline and Start-Up System	$1,023	$44	$33	$0	$1,100	$192	$0	$258	$1,551	$1
3.7	Waste Water Treatment Equipment	$5,468	$0	$3,351	$0	$8,819	$1,543	$0	$2,072	$12,435	$9
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$17,543**	**$2,283**	**$8,034**	**$0**	**$27,860**	**$4,876**	**$0**	**$6,547**	**$39,283**	**$28**
5	Flue Gas Cleanup										
5.1	CANSOLV CO_2 Removal System	$88,530	$38,917	$81,726	$0	$209,173	$36,605	$35,559	$56,268	$337,605	$237
5.2	SDA & Accessories	$13,404	$0	$2,866	$0	$16,270	$2,847	$0	$3,823	$22,940	$16
5.3	Other FGD	$171	$0	$193	$0	$364	$64	$0	$86	$514	$0
5.4	CO_2 Compression & Drying	$25,258	$3,789	$8,445	$0	$37,492	$6,561	$0	$8,811	$52,863	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$9,080	$0	$5,185	$0	$14,265	$2,496	$0	$3,352	$20,114	$14
5.12	Gas Cleanup Foundations	$0	$100	$88	$0	$188	$33	$0	$44	$265	$0
	Subtotal	**$136,652**	**$42,839**	**$98,593**	**$0**	**$278,085**	**$48,665**	**$35,559**	**$72,462**	**$434,771**	**$305**
7	Ductwork & Stack										
7.3	Ductwork	$0	$2,428	$1,688	$0	$4,116	$720	$0	$967	$5,804	$4
7.4	Stack	$10,393	$0	$6,039	$0	$16,433	$2,876	$0	$3,862	$23,170	$16
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,393**	**$2,661**	**$8,003**	**$0**	**$21,056**	**$3,685**	**$0**	**$4,948**	**$29,690**	**$21**
9	Cooling Water System										
9.1	Cooling Towers	$2,355	$0	$728	$0	$3,084	$540	$0	$725	$4,348	$3

Case:	CM95-B-S100N500 at 250°F						Estimate Type:		Conceptual	
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
9.2	Circulating Water Pumps	$249	$0	$18	$0	$266	$47	$0	$63	$375	$0
9.3	Circulating Water System Aux.	$3,006	$0	$398	$0	$3,404	$596	$0	$800	$4,800	$3
9.4	Circulating Water Piping	$0	$1,390	$1,259	$0	$2,649	$464	$0	$623	$3,735	$3
9.5	Make-up Water System	$315	$0	$404	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0
9.7	Circulating Water System Foundations	$0	$151	$251	$0	$403	$71	$0	$95	$568	$0
	Subtotal	**$6,142**	**$1,542**	**$3,225**	**$0**	**$10,908**	**$1,909**	**$0**	**$2,563**	**$15,380**	**$11**
11	**Accessory Electric Plant**										
11.2	Station Service Equipment	$4,045	$0	$347	$0	$4,392	$769	$0	$1,032	$6,192	$4
11.3	Switchgear & Motor Control	$6,279	$0	$1,089	$0	$7,368	$1,289	$0	$1,732	$10,389	$7
11.4	Conduit & Cable Tray	$0	$816	$2,352	$0	$3,168	$554	$0	$745	$4,467	$3
11.5	Wire & Cable	$0	$2,162	$3,864	$0	$6,025	$1,054	$0	$1,416	$8,496	$6
	Subtotal	**$10,323**	**$2,978**	**$7,652**	**$0**	**$20,953**	**$3,667**	**$0**	**$4,924**	**$29,544**	**$21**
12	**Instrumentation & Control**										
12.8	Instrument Wiring & Tubing	$555	$444	$1,777	$0	$2,776	$486	$0	$652	$3,914	$3
12.9	Other I&C Equipment	$682	$0	$1,580	$0	$2,263	$396	$0	$532	$3,190	$2
	Subtotal	**$1,238**	**$444**	**$3,357**	**$0**	**$5,039**	**$882**	**$0**	**$1,184**	**$7,104**	**$5**
13	**Improvements to Site**										
13.1	Site Preparation	$0	$38	$759	$0	$796	$139	$0	$187	$1,123	$1
13.2	Site Improvements	$0	$177	$234	$0	$411	$72	$0	$97	$580	$0
13.3	Site Facilities	$202	$0	$212	$0	$415	$73	$0	$97	$585	$0
	Subtotal	**$202**	**$214**	**$1,206**	**$0**	**$1,622**	**$284**	**$0**	**$381**	**$2,288**	**$2**
14	**Buildings & Structures**										
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$200	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$200**	**$0**
	Total	**$182,494**	**$53,040**	**$130,131**	**$0**	**$365,666**	**$63,992**	**$35,559**	**$93,043**	**$558,260**	**$391**
	Retrofit Values					**$383,949**	**$67,191**	**$37,337**	**$97,696**	**$586,173**	**$411**

Exhibit F-11. Owners' costs for case CM95-B-S100N500 at 250°F

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,011	$2
1-Month Maintenance Materials	$552	$0
1-Month Non-Fuel Consumables	$722	$1
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$11,723	$8
Total	**$16,014**	**$11**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$1,300	$1
0.5% of TPC (spare parts)	$2,931	$2
Total	**$4,231**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$143	$0
Land	$0	$0
Other Owner's Costs	$87,926	$62
Financing Costs	$15,827	$11
TOC	**$710,313**	**$498**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$794,147**	**$557**

Exhibit F-12. Initial and annual O&M costs for case CM95-B-S100N500 at 250°F

Case:	CM95-B-S100N500 at 250°F				Cost Base:	Nov 2022
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operation (%):**	**85**
			Operating & Maintenance Labor			
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
			Fixed Operating Costs			
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$3,751,508	$3.09
Administrative & Support Labor:					$1,204,533	$0.99
Property Taxes and Insurance:					$11,723,463	$9.67
Total:					**$17,746,129**	**$14.64**
			Variable Operating Costs			
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$5,627,262	$4.64
			Consumables			
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	1,053	$2.24	$0	$730,040	$0.60
Makeup and Waste Water Treatment Chemicals (ton):	0	3.1	$647.04	$0	$629,514	$0.52
CO_2 Capture System Chemicals[A]:			Proprietary		$4,005,004	$3.30
Triethylene Glycol (gal):	w/equip.	286	$8.00	$0	$710,707	$0.59
Lime (ton):	0	2	$188.23	$0	$110,782	$0.09
Ammonia (19 wt%, ton):	0	10.5	$352.93	$0	$1,149,811	$0.95
SCR Catalyst (ft^3):	808	0.4	$176.46	$142,559	$24,235	$0.02
Subtotal:				**$142,559**	**$7,360,093**	**$6.07**
			Waste Disposal			
SCR Catalyst (ft^3):		0.4	$2.94	$0	$404	$0.00
Triethylene Glycol (gal):		286	$0.41	$0	$36,581	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,426	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$424	$0.00
Subtotal:				**$0**	**$60,835**	**$0.05**
Variable Operating Costs Total:				**$142,559**	**$13,048,191**	**$10.76**
			Fuel and Purchased Power Costs			
Natural Gas (MMBTU):	0	16,363	$4.42	$0	$23,409,297	$19.31
Purchased Power (MWh):	0	22	$60.00	$0	$11,117,222	$9.17
Total:				**$0**	**$34,526,519**	**$28.48**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

Exhibit F-13. Capital costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 400,000 ACFM

Case:		CM95-B-S100N500 at 250°F 400,000 ACFM					Estimate Type:			Conceptual	
Representative Plant Size:		1.5 M tonnes cement/year (91.4% clinker)					Cost Base:			Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3				Feedwater & Miscellaneous BOP Systems							
3.1	Feedwater System	$1,019	$1,746	$873	$0	$3,638	$637	$0	$855	$5,130	$4
3.2	Water Makeup & Pretreating	$2,728	$273	$1,546	$0	$4,547	$796	$0	$1,069	$6,411	$4
3.3	Other Feedwater Subsystems	$494	$162	$154	$0	$810	$142	$0	$190	$1,142	$1
3.4	Industrial Boiler Package w/Deaerator	$6,586	$0	$1,915	$0	$8,501	$1,488	$0	$1,998	$11,986	$8
3.5	Other Boiler Plant Systems	$119	$43	$109	$0	$271	$47	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,023	$44	$33	$0	$1,100	$193	$0	$259	$1,551	$1
3.7	Waste Water Treatment Equipment	$6,500	$0	$3,984	$0	$10,484	$1,835	$0	$2,464	$14,782	$10
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$18,611**	**$2,287**	**$8,685**	**$0**	**$29,583**	**$5,177**	**$0**	**$6,952**	**$41,712**	**$29**
5				Flue Gas Cleanup							
5.1	CANSOLV CO_2 Removal System	$98,415	$43,263	$90,852	$0	$232,529	$40,693	$39,530	$62,550	$375,302	$263
5.2	SDA & Accessories	$23,288	$0	$4,979	$0	$28,267	$4,947	$0	$6,643	$39,857	$28
5.3	Other FGD	$298	$0	$335	$0	$633	$111	$0	$149	$893	$1
5.4	CO_2 Compression & Drying	$25,270	$3,791	$8,449	$0	$37,510	$6,564	$0	$8,815	$52,889	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$333	$58	$0	$78	$470	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$12,296	$0	$7,021	$0	$19,317	$3,380	$0	$4,539	$27,236	$19
5.12	Gas Cleanup Foundations	$0	$130	$114	$0	$245	$43	$0	$57	$345	$0
	Subtotal	**$159,776**	**$47,217**	**$111,840**	**$0**	**$318,834**	**$55,796**	**$39,530**	**$82,832**	**$496,991**	**$348**
7				Ductwork & Stack							
7.3	Ductwork	$0	$3,303	$2,295	$0	$5,598	$980	$0	$1,316	$7,893	$6
7.4	Stack	$10,726	$0	$6,232	$0	$16,958	$2,968	$0	$3,985	$23,911	$17
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$10,726**	**$3,535**	**$8,803**	**$0**	**$23,064**	**$4,036**	**$0**	**$5,420**	**$32,520**	**$23**
9				Cooling Water System							
9.1	Cooling Towers	$2,357	$0	$729	$0	$3,086	$540	$0	$725	$4,351	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$376	$0
9.3	Circulating Water System Aux.	$3,008	$0	$398	$0	$3,406	$596	$0	$800	$4,802	$3
9.4	Circulating Water Piping	$0	$1,391	$1,260	$0	$2,651	$464	$0	$623	$3,737	$3
9.5	Make-up Water System	$315	$0	$405	$0	$719	$126	$0	$169	$1,014	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$540	$0

Case:	CM95-B-S100N500 at 250°F 400,000 ACFM						Estimate Type:		Conceptual		
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022		
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$403	$71	$0	$95	$568	$0
	Subtotal	**$6,146**	**$1,542**	**$3,227**	**$0**	**$10,915**	**$1,910**	**$0**	**$2,565**	**$15,390**	**$11**
11	**Accessory Electric Plant**										
11.2	Station Service Equipment	$4,129	$0	$354	$0	$4,483	$785	$0	$1,054	$6,321	$4
11.3	Switchgear & Motor Control	$6,410	$0	$1,112	$0	$7,522	$1,316	$0	$1,768	$10,606	$7
11.4	Conduit & Cable Tray	$0	$833	$2,401	$0	$3,235	$566	$0	$760	$4,561	$3
11.5	Wire & Cable	$0	$2,207	$3,944	$0	$6,151	$1,076	$0	$1,446	$8,673	$6
	Subtotal	**$10,539**	**$3,040**	**$7,812**	**$0**	**$21,391**	**$3,743**	**$0**	**$5,027**	**$30,162**	**$21**
12	**Instrumentation & Control**										
12.8	Instrument Wiring & Tubing	$559	$447	$1,788	$0	$2,793	$489	$0	$656	$3,939	$3
12.9	Other I&C Equipment	$687	$0	$1,590	$0	$2,277	$398	$0	$535	$3,210	$2
	Subtotal	**$1,245**	**$447**	**$3,378**	**$0**	**$5,070**	**$887**	**$0**	**$1,191**	**$7,149**	**$5**
13	**Improvements to Site**										
13.1	Site Preparation	$0	$38	$766	$0	$804	$141	$0	$189	$1,134	$1
13.2	Site Improvements	$0	$179	$237	$0	$415	$73	$0	$98	$585	$0
13.3	Site Facilities	$204	$0	$214	$0	$419	$73	$0	$98	$590	$0
	Subtotal	**$204**	**$217**	**$1,217**	**$0**	**$1,638**	**$287**	**$0**	**$385**	**$2,310**	**$2**
14	**Buildings & Structures**										
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$207,247**	**$58,364**	**$145,026**	**$0**	**$410,637**	**$71,861**	**$39,530**	**$104,406**	**$626,434**	**$439**
					Retrofit Values	**$431,169**	**$75,455**	**$41,506**	**$109,626**	**$657,756**	**$461**

Exhibit F-14. Owners' costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 400,000 ACFM

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,298	$2
1-Month Maintenance Materials	$619	$0
1-Month Non-Fuel Consumables	$868	$1
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$13,155	$9
Total	**$17,946**	**$13**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$1,590	$1
0.5% of TPC (spare parts)	$3,289	$2
Total	**$4,879**	**$3**
Other Costs		
Initial Cost for Catalyst and Chemicals	$225	$0
Land	$0	$0
Other Owner's Costs	$98,663	$69
Financing Costs	$17,759	$12
TOC	**$797,228**	**$558**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$891,319**	**$624**

Exhibit F-15. Initial and annual O&M costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 400,000 ACFM

Case:	**CM95-B-S100N500 at 250°F 400,000 ACFM**				**Cost Base:**	**Nov 2022**
Representative Plant Size:	**1.5 M tonnes cement/year (91.4% clinker)**				**Operation (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		40.72	**$/hour**	Skilled Operator:		0.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**$/(tonne CO_2/year)**
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$4,209,637	$3.47
Administrative & Support Labor:					$1,319,065	$1.09
Property Taxes and Insurance:					$13,155,114	$10.84
Total:					**$19,750,441**	**$16.27**
Variable Operating Costs						
					($)	**$/(tonne CO_2/year)**
Maintenance Material:					$6,314,455	$5.20
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	1,068	$2.24	$0	$740,625	$0.61
Makeup and Waste Water Treatment Chemicals (ton):	0	3.2	$647.04	$0	$638,642	$0.53
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,015	$3.30
Triethylene Glycol (gal):	w/equip.	287	$8.00	$0	$711,359	$0.59
Lime (ton):	0	4	$188.23	$0	$236,097	$0.19
Ammonia (19 wt%, ton):	0	22.7	$352.93	$0	$2,480,359	$2.04
SCR Catalyst (ft^3):	1,274	0.7	$176.46	$224,799	$38,216	$0.03
Subtotal:				**$224,799**	**$8,850,314**	**$7.29**
Waste Disposal						
SCR Catalyst (ft^3):		0.7	$2.94	$0	$637	$0.00
Triethylene Glycol (gal):		287	$0.41	$0	$36,614	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,448	$0.02
Pre-scrubber Blowdown Waste (ton):		0.03	$44.70	$0	$656	$0.00
Subtotal:				**$0**	**$61,355**	**$0.05**
Variable Operating Costs Total:				**$224,799**	**$15,226,124**	**$12.55**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,378	$4.61	$0	$23,430,773	$19.31
Purchased Power (MWh):	0	23	$67.28	$0	$11,665,169	$9.61
Total:				**$0**	**$35,095,942**	**$28.92**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

Exhibit F-16. Capital costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 700,000 ACFM

	Case:	CM95-B-S100N500 at 250°F 700,000 ACFM						Estimate Type:		Conceptual	
	Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$1,020	$1,748	$874	$0	$3,642	$637	$0	$856	$5,135	$4
3.2	Water Makeup & Pretreating	$2,779	$278	$1,575	$0	$4,632	$811	$0	$1,088	$6,531	$5
3.3	Other Feedwater Subsystems	$495	$162	$154	$0	$811	$142	$0	$191	$1,144	$1
3.4	Industrial Boiler Package w/Deaerator	$6,595	$0	$1,917	$0	$8,512	$1,490	$0	$2,000	$12,002	$8
3.5	Other Boiler Plant Systems	$120	$43	$109	$0	$272	$48	$0	$64	$383	$0
3.6	NG Pipeline and Start-Up System	$1,024	$44	$33	$0	$1,101	$193	$0	$259	$1,553	$1
3.7	Waste Water Treatment Equipment	$7,475	$0	$4,582	$0	$12,057	$2,110	$0	$2,833	$17,000	$12
3.9	Miscellaneous Plant Equipment	$141	$19	$72	$0	$232	$41	$0	$54	$327	$0
	Subtotal	**$19,649**	**$2,294**	**$9,315**	**$0**	**$31,258**	**$5,470**	**$0**	**$7,346**	**$44,074**	**$31**
5	Flue Gas Cleanup										
5.1	CANSOLV CO_2 Removal System	$109,986	$48,350	$101,534	$0	$259,870	$45,477	$44,178	$69,905	$419,430	$293
5.2	SDA & Accessories	$35,039	$0	$7,492	$0	$42,531	$7,443	$0	$9,995	$59,968	$42
5.3	Other FGD	$448	$0	$505	$0	$953	$167	$0	$224	$1,343	$1
5.4	CO_2 Compression & Drying	$25,295	$3,794	$8,457	$0	$37,546	$6,571	$0	$8,823	$52,941	$37
5.5	CO_2 Compressor Aftercooler	$210	$33	$90	$0	$334	$58	$0	$78	$471	$0
5.9	Particulate Removal (Bag House & Accessories) (w/5.2)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.11	Selective Catalytic Reduction	$16,200	$0	$9,250	$0	$25,450	$4,454	$0	$5,981	$35,885	$25
5.12	Gas Cleanup Foundations	$0	$166	$145	$0	$311	$54	$0	$73	$438	$0
	Subtotal	**$187,178**	**$52,343**	**$127,473**	**$0**	**$366,994**	**$64,224**	**$44,178**	**$95,079**	**$570,476**	**$399**
7	Ductwork & Stack										
7.3	Ductwork	$0	$4,369	$3,036	$0	$7,405	$1,296	$0	$1,740	$10,442	$7
7.4	Stack	$11,036	$0	$6,413	$0	$17,449	$3,054	$0	$4,100	$24,603	$17
7.5	Duct & Stack Foundations	$0	$232	$276	$0	$508	$89	$0	$119	$716	$1
	Subtotal	**$11,036**	**$4,601**	**$9,725**	**$0**	**$25,362**	**$4,438**	**$0**	**$5,960**	**$35,760**	**$25**
9	Cooling Water System										
9.1	Cooling Towers	$2,360	$0	$730	$0	$3,089	$541	$0	$726	$4,356	$3
9.2	Circulating Water Pumps	$249	$0	$18	$0	$267	$47	$0	$63	$376	$0
9.3	Circulating Water System Aux.	$3,011	$0	$398	$0	$3,409	$597	$0	$801	$4,807	$3
9.4	Circulating Water Piping	$0	$1,392	$1,261	$0	$2,653	$464	$0	$623	$3,741	$3
9.5	Make-up Water System	$315	$0	$405	$0	$720	$126	$0	$169	$1,015	$1
9.6	Component Cooling Water System	$217	$0	$166	$0	$383	$67	$0	$90	$541	$0

Case:	CM95-B-S100N500 at 250°F 700,000 ACFM						Estimate Type:		Conceptual	
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)						Cost Base:		Nov 2022	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/(tonne CO_2/year)
9.7	Circulating Water System Foundations	$0	$152	$252	$0	$403	$71	$0	$95	$569	$0
	Subtotal	**$6,152**	**$1,544**	**$3,230**	**$0**	**$10,925**	**$1,912**	**$0**	**$2,567**	**$15,405**	**$11**
11	**Accessory Electric Plant**										
11.2	Station Service Equipment	$4,244	$0	$364	$0	$4,608	$806	$0	$1,083	$6,498	$5
11.3	Switchgear & Motor Control	$6,589	$0	$1,143	$0	$7,732	$1,353	$0	$1,817	$10,902	$8
11.4	Conduit & Cable Tray	$0	$857	$2,468	$0	$3,325	$582	$0	$781	$4,688	$3
11.5	Wire & Cable	$0	$2,268	$4,055	$0	$6,323	$1,107	$0	$1,486	$8,915	$6
	Subtotal	**$10,833**	**$3,125**	**$8,030**	**$0**	**$21,988**	**$3,848**	**$0**	**$5,167**	**$31,004**	**$22**
12	**Instrumentation & Control**										
12.8	Instrument Wiring & Tubing	$563	$451	$1,803	$0	$2,817	$493	$0	$662	$3,972	$3
12.9	Other I&C Equipment	$692	$0	$1,603	$0	$2,296	$402	$0	$540	$3,237	$2
	Subtotal	**$1,256**	**$451**	**$3,406**	**$0**	**$5,113**	**$895**	**$0**	**$1,201**	**$7,209**	**$5**
13	**Improvements to Site**										
13.1	Site Preparation	$0	$38	$776	$0	$814	$143	$0	$191	$1,148	$1
13.2	Site Improvements	$0	$181	$240	$0	$421	$74	$0	$99	$593	$0
13.3	Site Facilities	$207	$0	$217	$0	$424	$74	$0	$100	$598	$0
	Subtotal	**$207**	**$219**	**$1,233**	**$0**	**$1,659**	**$290**	**$0**	**$390**	**$2,339**	**$2**
14	**Buildings & Structures**										
14.5	Circulation Water Pumphouse	$0	$79	$63	$0	$142	$25	$0	$33	$201	$0
	Subtotal	**$0**	**$79**	**$63**	**$0**	**$142**	**$25**	**$0**	**$33**	**$201**	**$0**
	Total	**$236,311**	**$64,657**	**$162,475**	**$0**	**$463,442**	**$81,102**	**$44,178**	**$117,745**	**$706,467**	**$494**
					Retrofit Values	**$486,615**	**$85,158**	**$46,387**	**$123,632**	**$741,791**	**$519**

Exhibit F-17. Owners' costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 700,000 ACFM

Description	$/1,000	$/(tonne CO_2/year)
Pre-Production Costs		
6 Months All Labor	$3,634	$3
1-Month Maintenance Materials	$698	$0
1-Month Non-Fuel Consumables	$1,075	$1
1-Month Waste Disposal	$6	$0
25% of 1-Month Fuel Cost at 100% operating basis	$0	$0
2% of TPC	$14,836	$10
Total	**$20,249**	**$14**
Inventory Capital		
60-Day Supply of Fuel and Consumables at 100% operating basis	$2,001	$1
0.5% of TPC (spare parts)	$3,709	$3
Total	**$5,709**	**$4**
Other Costs		
Initial Cost for Catalyst and Chemicals	$342	$0
Land	$0	$0
Other Owner's Costs	$111,269	$78
Financing Costs	$20,028	$14
TOC	**$899,387**	**$629**
TASC Multiplier (Cement, 33 year)	1.118	
TASC	**$1,005,536**	**$703**

Exhibit F-18. Initial and annual O&M costs for case CM95-B-S100N500 at 250°F with air in-leakage up to 700,000 ACFM

Case:	CM95-B-S100N500 at 250°F 700,000 ACFM				Cost Base:	Nov 2022
Representative Plant Size:	1.5 M tonnes cement/year (91.4% clinker)				Operation (%):	85
Operating & Maintenance Labor						
Operating Labor				Operating Labor Requirements per Shift		
Operating Labor Rate (base):		40.72	$/hour	Skilled Operator:		0.0
Operating Labor Burden:		30.00	% of base	Operator:		2.3
Labor O-H Charge Rate:		25.00	% of labor	Foreman:		0.0
				Lab Techs, etc.:		0.0
				Total:		**2.3**
Fixed Operating Costs						
					Annual Cost	
					($)	$/(tonne CO_2/year)
Annual Operating Labor:					$1,066,625	$0.88
Maintenance Labor:					$4,747,460	$3.91
Administrative & Support Labor:					$1,453,521	$1.20
Property Taxes and Insurance:					$14,835,814	$12.21
Total:					**$22,103,420**	**$18.19**
Variable Operating Costs						
					($)	$/(tonne CO_2/year)
Maintenance Material:					$7,121,191	$5.86
Consumables						
	Initial Fill	Per Day	Per Unit	Initial Fill		
Water (/1000 gallons):	0	1,095	$2.24	$0	$759,565	$0.62
Makeup and Waste Water Treatment Chemicals (ton):	0	3.3	$647.04	$0	$654,974	$0.54
CO_2 Capture System Chemicals[A]:	Proprietary				$4,005,031	$3.30
Triethylene Glycol (gal):	w/equip.	287	$8.00	$0	$712,418	$0.59
Lime (ton):	0	7	$188.23	$0	$413,135	$0.34
Ammonia (19 wt%, ton):	0	39.8	$352.93	$0	$4,359,063	$3.59
SCR Catalyst (ft^3):	1,936	1.1	$176.46	$341,695	$58,088	$0.05
Subtotal:				**$341,695**	**$10,962,273**	**$9.02**
Waste Disposal						
SCR Catalyst (ft^3):		1	$2.94	$0	$968	$0.00
Triethylene Glycol (gal):		287	$0.41	$0	$36,669	$0.03
Thermal Reclaimer Unit Waste (ton):		1.69	$44.70	$0	$23,483	$0.02
Pre-scrubber Blowdown Waste (ton):		0.1	$44.70	$0	$1,000	$0.00
Subtotal:				**$0**	**$62,120**	**$0.05**
Variable Operating Costs Total:				**$341,695**	**$18,145,584**	**$14.93**
Fuel and Purchased Power Costs						
Natural Gas (MMBTU):	0	16,403	$4.61	$0	$23,465,644	$19.31
Purchased Power (MWh):	0	25	$67.28	$0	$12,436,354	$10.23
Total:				**$0**	**$35,901,998**	**$29.54**

[A] CO_2 capture system chemicals includes NaOH and CANSOLV® solvent

APPENDIX G: RESULTS IN DECEMBER 2018 DOLLARS

The results presented in the main body of this report are expressed in real November 2022 dollars. Here, the cost results are presented in real December 2018 dollars to allow for retrospective comparison to other reports published by NETL. The financial assumptions summarized in Exhibit G-1 were developed by NETL's Energy Markets Analysis Team in October 2021 based on market data respective to the cement sector, where all values are expressed in real dollar terms. These factors are defined in detail the 2019 revision of the QGESS "Cost Estimation Methodology for NETL Assessment of Power Plant Performance." [5]

Exhibit G-1. Financial assumptions for retrofit capture at cement plants

Financial Parameter	Value
Fixed Charge Rate	5.08%
TASC/TOC Ratio	1.054
Capital Charge Factor	5.35%
Debt/Equity Ratio	42/58
Operating Life/Depreciation Period	30 years
Interest on Debt	5.15%
Levered Return on Equity	1.42%
Weighted Average Cost of Capital	2.99%
Capital Expenditure Period	3 years
Capital Distribution	1st year – 10% 2nd year – 60% 3rd year – 30%

December 2018 dollar basis consumable, waste disposal, and labor costs are based on vendor-furnished costs provided during the development of NETL's "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" (the "Fossil Energy Baseline"). [9] For comparability between studies, natural gas fuel and purchased electricity costs on a December 2018 dollar basis mirror those found in NETL's "Cost of Capturing CO_2 from Industrial Sources" published in September 2022. [27] Those unit costs are summarized in Exhibit G-2.

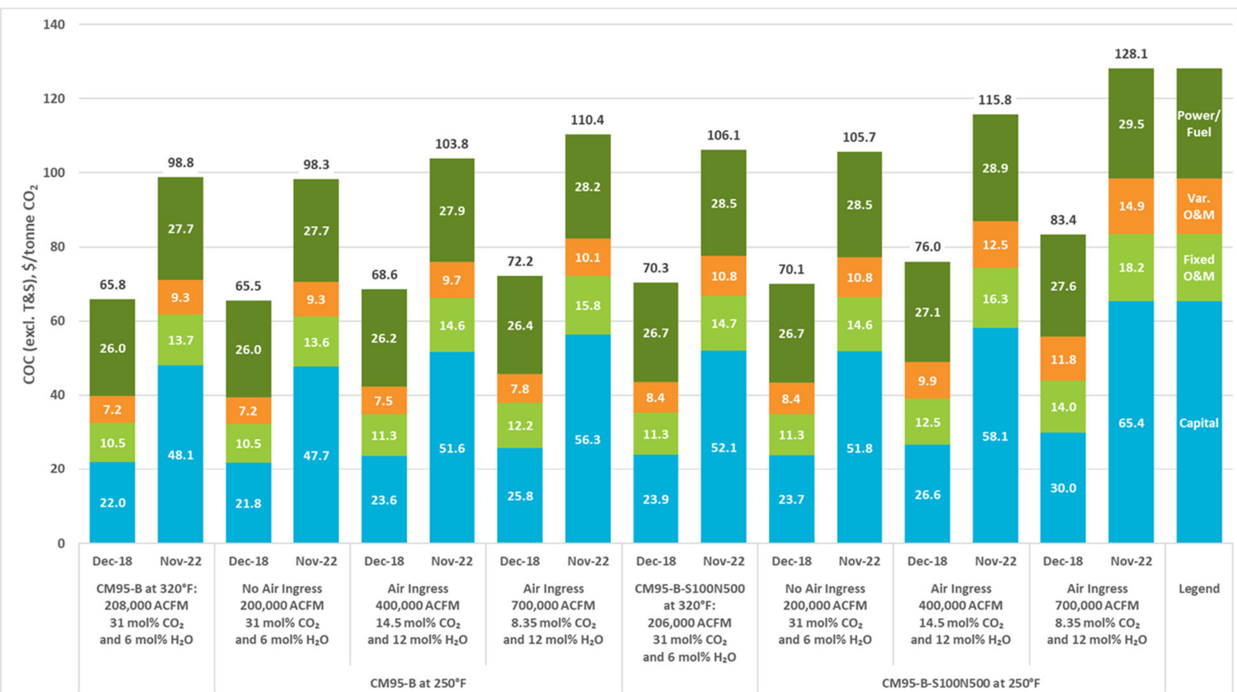
Exhibit G-2. December 2018 basis O&M costs

Parameter (Units)	Per Unit Cost
Labor	
Operating Labor Rate (hour):	$38.50
Consumables	
Water (/1,000 gallons):	$1.90
Makeup and Waste Water Treatment Chemicals (ton):	$550
Triethylene Glycol (gal):	$6.80
Lime (ton):	$160
Ammonia (19 wt%, ton):	$300
SCR Catalyst (ft^3):	$150
Waste Disposal	
SCR Catalyst (ft^3):	$2.50
Triethylene Glycol (gal):	$0.35
Thermal Reclaimer Unit Waste (ton):	$38.00
Pre-scrubber Blowdown Waste (ton):	$38.00
Electricity/Fuel	
Natural Gas Fuel (MMBtu):	$4.42
Purchased Electricity (MWh):	$60.00

Changing financial assumptions impacts the capital components of the COC, and changing labor, consumable, and waste disposal prices affect O&M, fuel, and power COC components. Collectively, those changes impact the conclusions related to the total COC. For instance, with less weight associated with capital costs in the December 2018 basis, the benefits of heat integration potential at 30 percent are realized at the study NG price of $4.42/MMBtu (i.e., comparing the Dec-18 values for CM95-B6 to CM95-B or CM95-B8 to CM95-B1 in Exhibit G-3). Conversely, heat integration benefits are not realized in a November 2022 basis. Additionally, the increase in COC associated with increasing false air ingress is more notable when capital costs hold more weight in the total COC (i.e., comparing the rate of COC change with increasing false air ingress in Exhibit G-4). These comparisons highlight the importance of properly characterizing financial assumptions based on project-specific conditions when performing higher fidelity cost estimates.

Exhibit G-3. Dec-2108 vs. Nov-2022 comparison of COC (excl. T&S)

Exhibit G-4. Dec-2108 vs. Nov-2022 comparison of COC with false air ingress (excl. T&S)



The cost and performance summaries of all study cases are repeated in tabular and graphical form in Exhibit G-5 through Exhibit G-27, with costs shown on a December 2018 basis.

Exhibit G-5. Summary of base cases COC (excl. T&S) (Dec-2018)

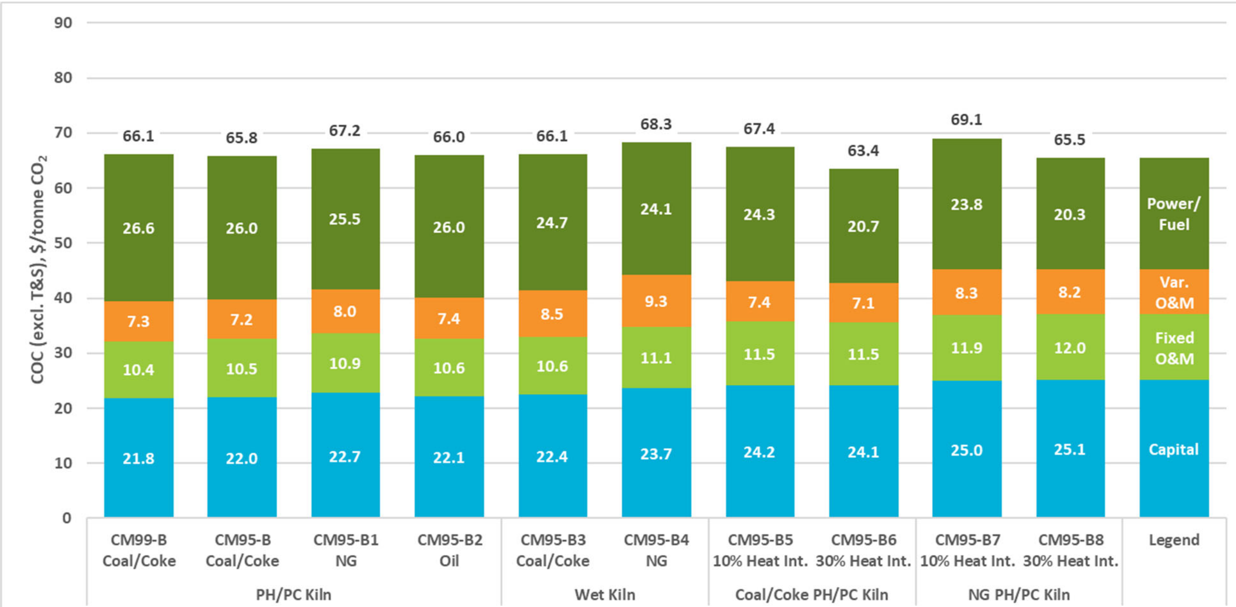


Exhibit G-6. Summary of base cases COC and COA (excl. T&S) (Dec-2018)

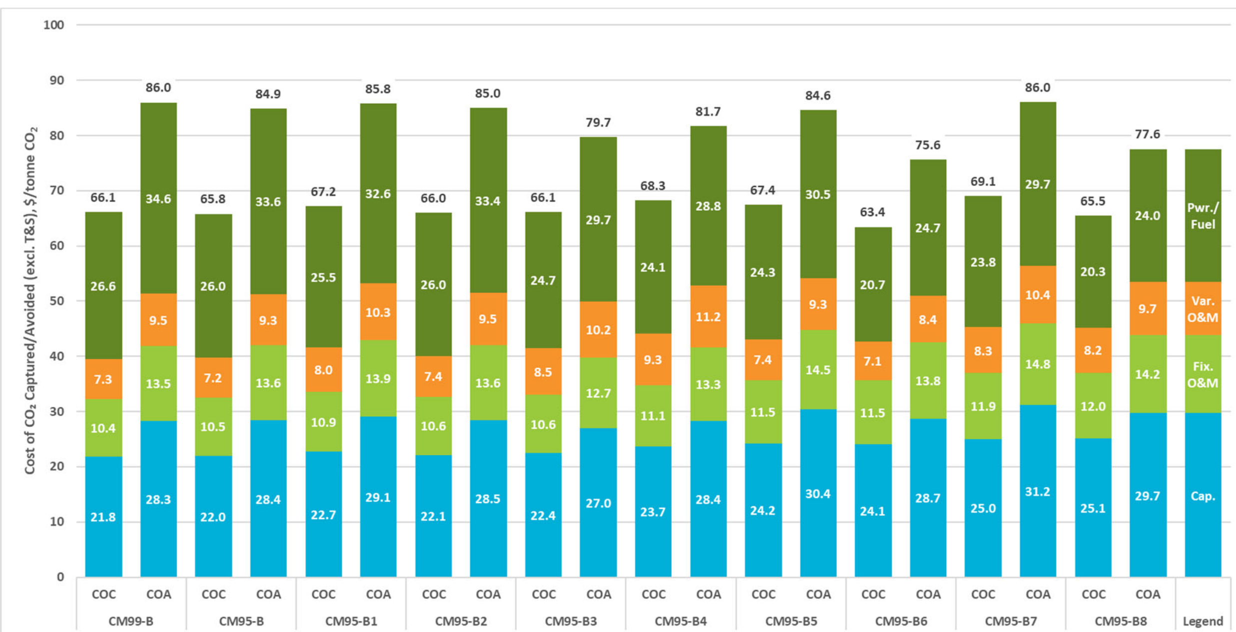
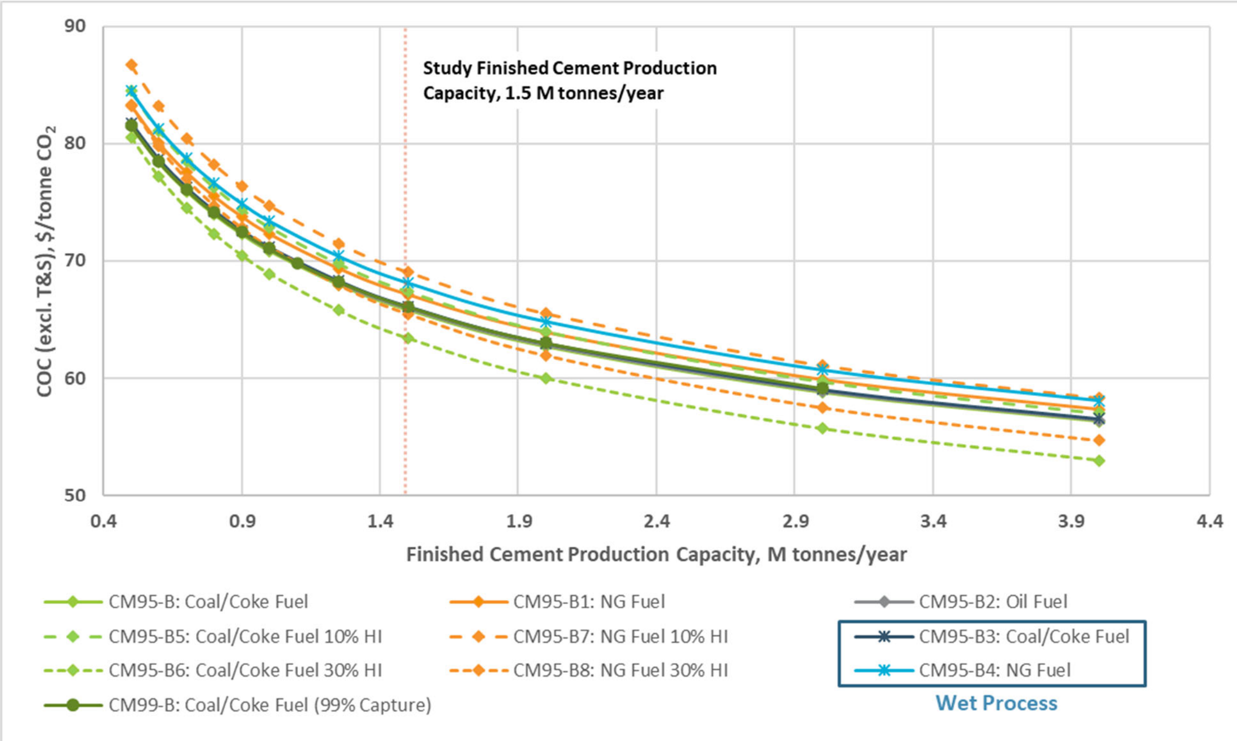


Exhibit G-7. Summary of plant capacity sensitivity analyses for base cases (Dec-2018)



Note: HI = heat integration

Exhibit G-8. Summary of cases with potential heat integration opportunities (Dec-2018)

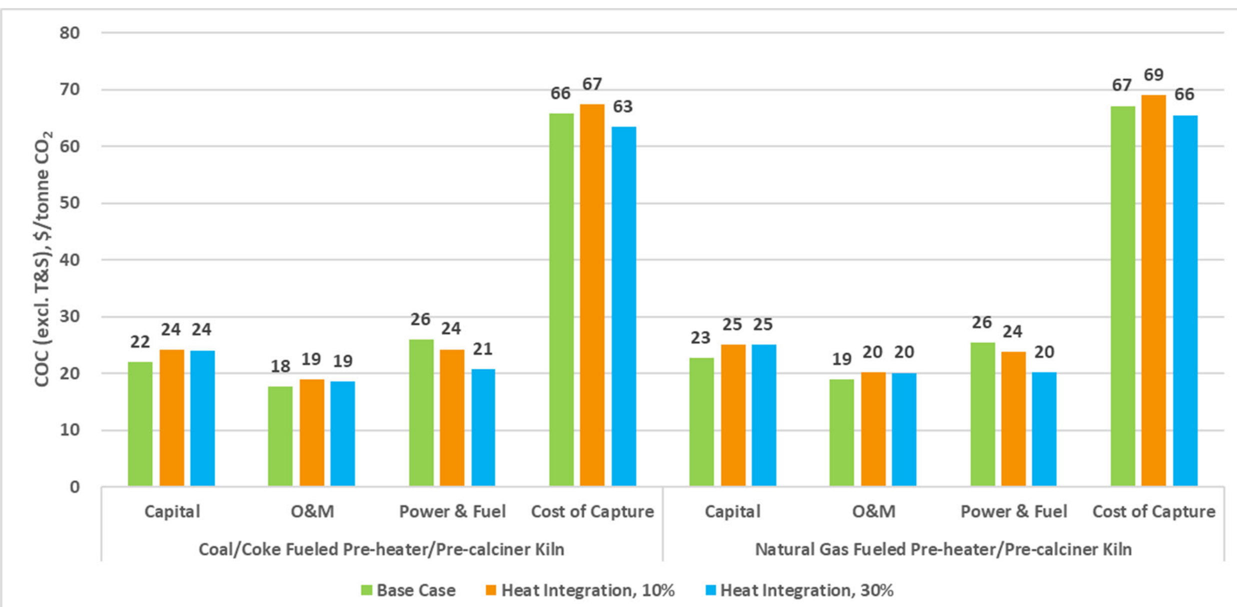


Exhibit G-9. COC and COA for cases with heat integration potential (Dec-2018)

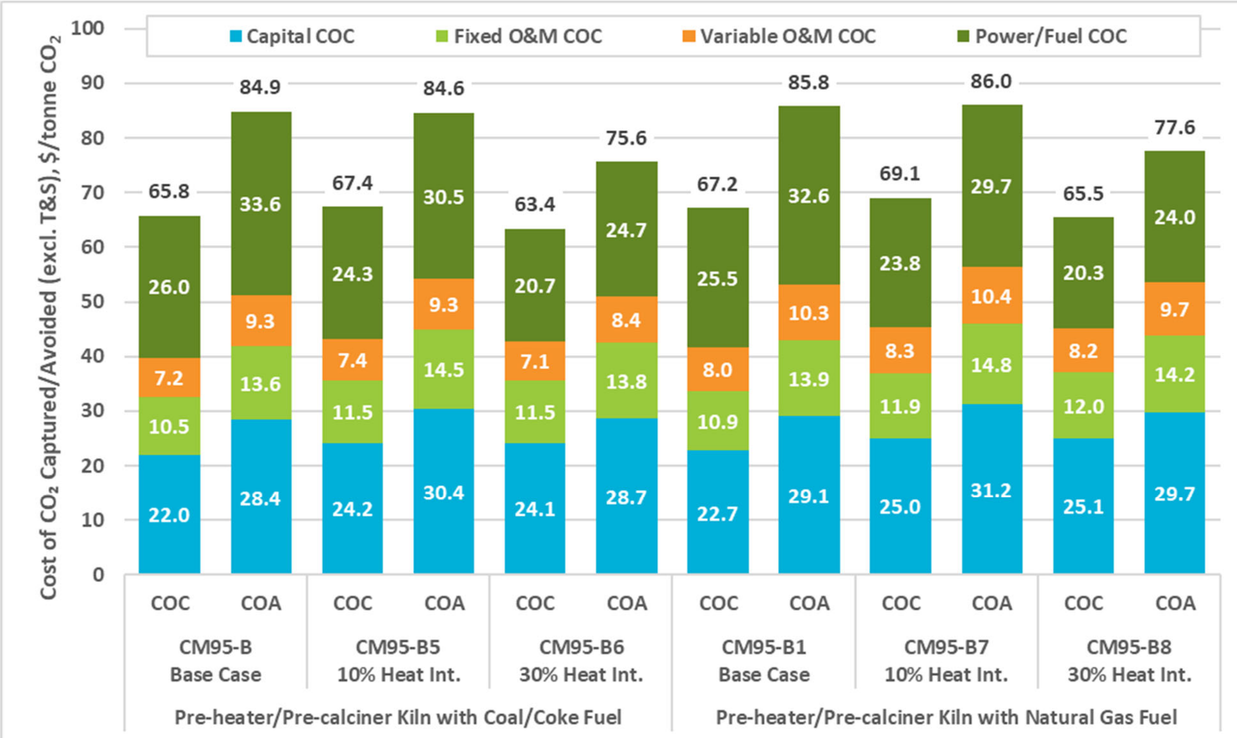
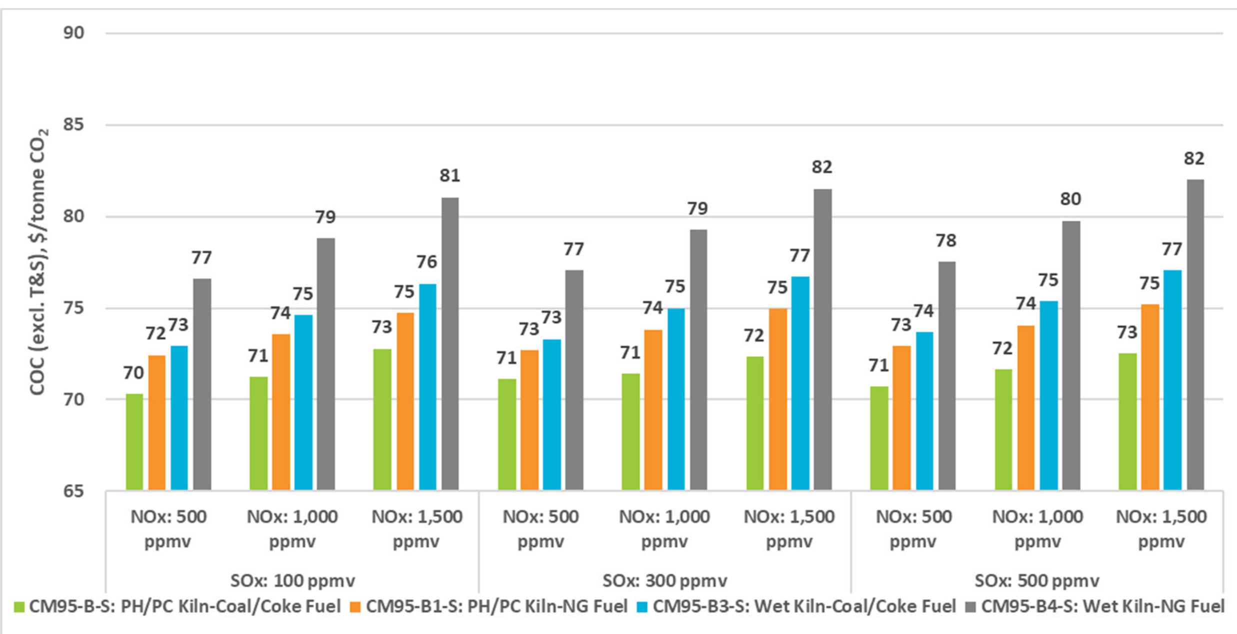
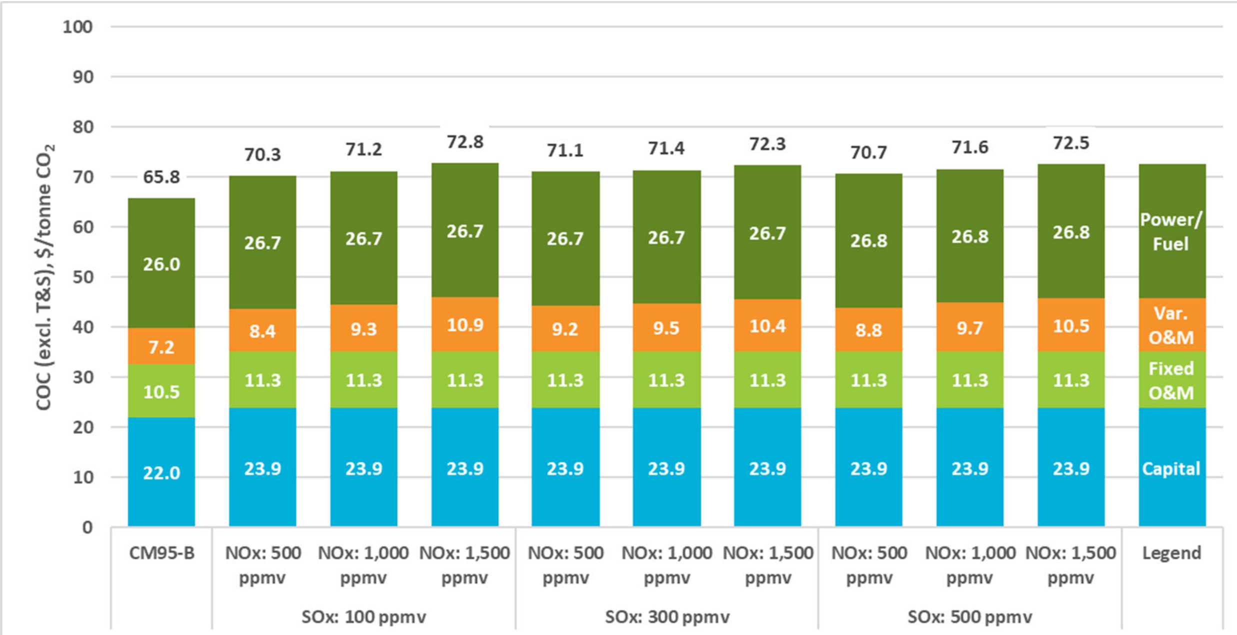


Exhibit G-10. Summary of COC for sensitivity cases with FGD and SCR (Dec-2018)



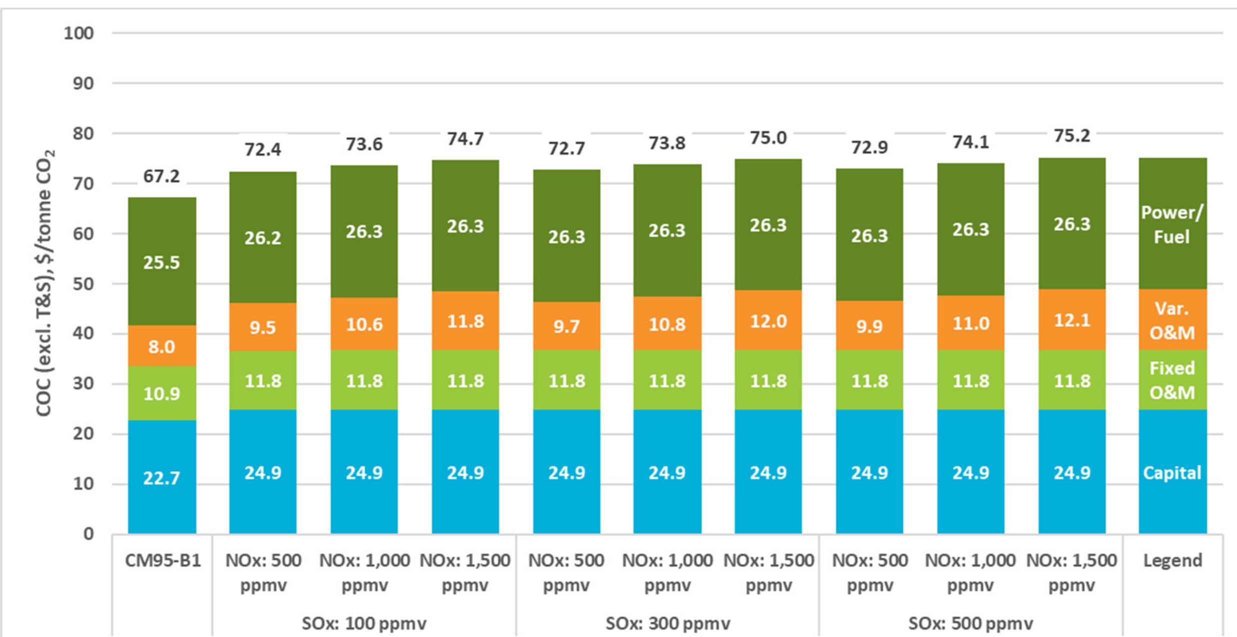
Note: The SO_x and NO_x values shown on the abscissa of are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

Exhibit G-11. COC comparison of sensitivity case CM95-B-S and base case CM95-B (Dec-2018)



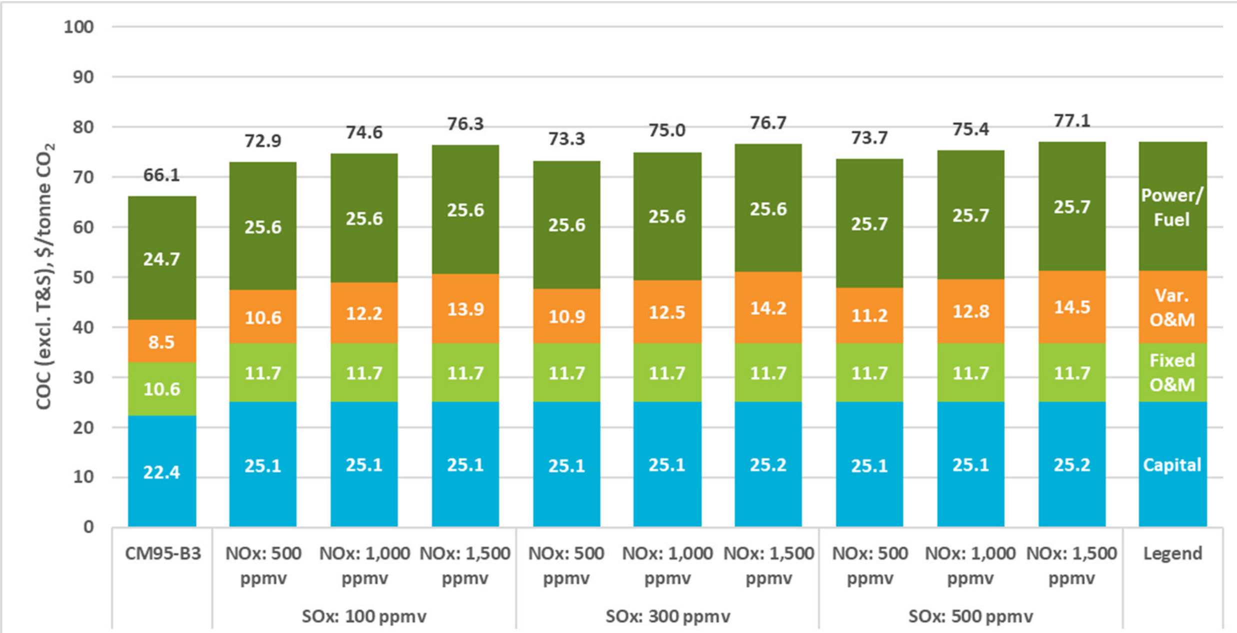
Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

Exhibit G-12. COC comparison of sensitivity case CM95-B1-S and base case CM95-B1 (Dec-2018)



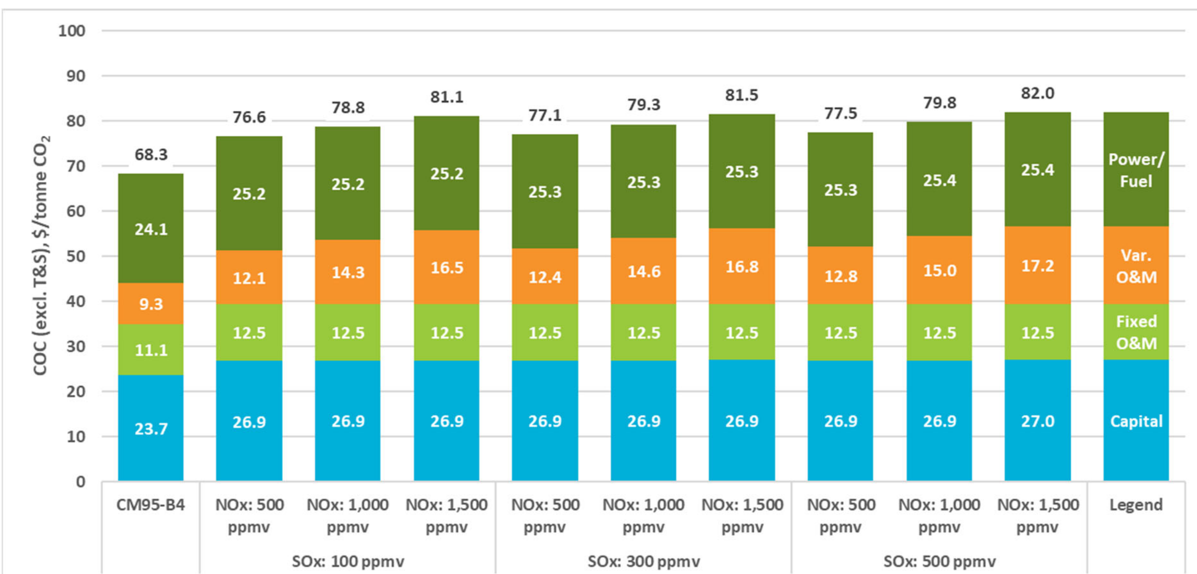
Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

Exhibit G-13. COC comparison of sensitivity case CM95-B3-S and base case CM95-B3 (Dec-2018)



Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

Exhibit G-14. COC comparison of sensitivity case CM95-B4-S and base case CM95-B4 (Dec-2018)



Note: The SOx and NOx values shown on the abscissa are concentrations in the kiln emissions stream requiring pretreatment prior to CO_2 scrubbing

Exhibit G-15. COC comparison of air in-leakage scenarios (Dec-2018)

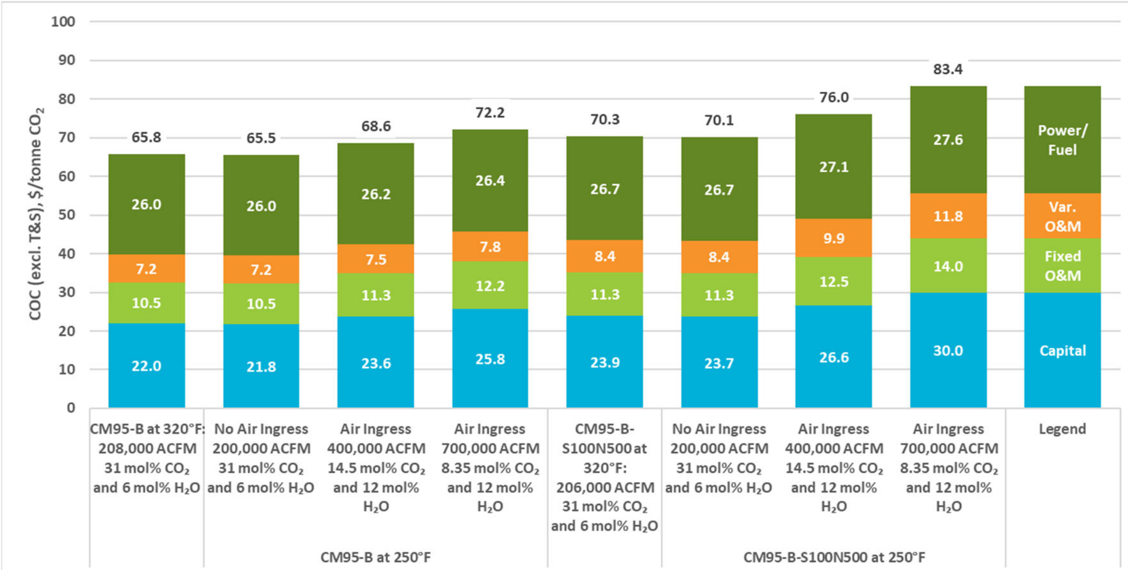


Exhibit G-16. Cost and performance summary comparison – base cases

Case Number	CM99-B	CM95-B	CM95-B1	CM95-B2	CM95-B3	CM95-B4	CM95-B5	CM95-B6	CM95-B7	CM95-B8
PERFORMANCE										
Capture Rate	99 percent	95 percent								
Kiln Type	Pre-heater/Pre-calciner				Wet Process		Pre-heater/Pre-calciner			
Kiln Fuel	Coal/Coke		Nat. Gas	Oil	Coal/Coke	Nat. Gas	Coal/Coke		Natural Gas	
Kiln Off-gas CO_2 Concentration, mol%	31	31	25	30	17	13	31	25	31	31
Heat Integration Potential, %	N/A						10	30	10	30
Combined Stream CO_2 Conc., mol%	21	21	19	21	15	12	22	23	19	20
CO_2 Captured, tonnes/year	1,516,106	1,426,677	1,415,169	1,424,904	1,688,297	1,673,262	1,391,847	1,325,543	1,381,155	1,316,892
CO_2 Captured, tonnes/hour	173	163	162	163	193	191	159	151	158	150
CO_2 Compressor Load, kW	13,270	12,490	12,390	12,470	14,780	14,650	12,180	11,600	12,090	11,530
Cooling Water Flowrate, gpm	72,800	67,058	65,439	66,974	75,927	73,552	65,774	63,216	64,217	61,563
Cooling Tower Duty, MMBtu/hour	728	671	654	670	759	736	658	632	642	616
COST										
TPC, $/1,000	433,334	411,590	421,675	412,759	496,430	519,639	441,543	419,230	453,504	433,066
BEC, $/1,000	281,467	267,528	273,782	268,251	321,890	336,545	287,018	272,570	294,449	281,180
Home Office Expenses	49,257	46,817	47,912	46,944	56,331	58,895	50,228	47,700	51,529	49,206
Project Contingency	72,222	68,598	70,279	68,793	82,738	86,606	73,590	69,872	75,584	72,178
Process Contingency	30,388	28,647	29,702	28,771	35,471	37,592	30,707	29,089	31,942	30,502
TOC, $M	525	499	511	500	602	630	535	508	549	525
TOC, $/1,000	525,036	498,682	511,094	500,131	601,820	630,101	534,756	507,655	549,453	524,662
Owner's Costs	91,702	87,092	89,419	87,372	105,390	110,462	93,213	88,425	95,949	91,596
TASC, $/1,000	553,308	525,536	538,616	527,062	634,228	664,031	563,552	534,992	579,041	552,914
Capital Costs, $/tonne CO_2	21.8	22.0	22.7	22.1	22.4	23.7	24.2	24.1	25.0	25.1
Fixed Costs, $/tonne CO_2	10.4	10.5	10.9	10.6	10.6	11.1	11.5	11.5	11.9	12.0
Variable Costs, $/tonne CO_2	7.3	7.2	8.0	7.4	8.5	9.3	7.4	7.1	8.3	8.2
Purchased Power and Fuel, $/tonne CO_2	26.6	26.0	25.5	26.0	24.7	24.1	24.3	20.7	23.8	20.3
COC (excl. T&S), $/tonne CO_2	**66.1**	**65.8**	**67.2**	**66.0**	**66.1**	**68.3**	**67.4**	**63.4**	**69.1**	**65.5**
COC (incl. T&S), $/tonne CO_2	**76.1**	**75.8**	**77.2**	**76.0**	**76.1**	**78.3**	**77.4**	**73.4**	**79.1**	**75.5**

Exhibit G-17. Cost and performance summary comparison – CM95-B-S sensitivity cases

SOx Concentration	100 ppm_v			300 ppm_v			500 ppm_v		
NOx Concentration	**500 ppm_v**	**1,000 ppm_v**	**1,500 ppm_v**	**500 ppm_v**	**1,000 ppm_v**	**1,500 ppm_v**	**500 ppm_v**	**1,000 ppm_v**	**1,500 ppm_v**
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Pre-heater/Pre-calciner								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,426,477								
CO_2 Captured, tonnes/hour	163								
CO_2 Compressor Load, kW	12,480								
Cooling Water Flowrate, gpm	66,994								
Cooling Tower Duty, MMBtu/hour	670								
COST									
TPC, $/1,000	445,993	445,997	446,001	446,076	446,080	446,084	446,169	446,173	446,177
BEC, $/1,000	292,193	292,196	292,199	292,250	292,253	292,256	292,313	292,316	292,319
Home Office Expenses	51,134	51,134	51,135	51,144	51,144	51,145	51,155	51,155	51,156
Project Contingency	74,332	74,333	74,333	74,346	74,347	74,347	74,362	74,362	74,363
Process Contingency	28,334	28,334	28,334	28,336	28,336	28,336	28,339	28,339	28,339
TOC, $M	541	541	541	541	541	541	541	541	542
TOC, $/1,000	540,655	540,980	541,381	540,887	541,136	541,461	540,980	541,305	541,629
Owner's Costs	94,662	94,983	95,380	94,810	95,056	95,377	94,811	95,132	95,452
TASC, $/1,000	569,769	570,112	570,533	570,013	570,276	570,619	570,111	570,453	570,795
Capital Costs, $/tonne CO_2	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9
Fixed Costs, $/tonne CO_2	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Variable Costs, $/tonne CO_2	8.4	9.3	10.9	9.2	9.5	10.4	8.8	9.7	10.5
Purchased Power and Fuel, $/tonne CO_2	26.7	26.7	26.7	26.7	26.7	26.7	26.8	26.8	26.8
COC (excl. T&S), $/tonne CO_2	**70.3**	**71.2**	**72.8**	**71.1**	**71.4**	**72.3**	**70.7**	**71.6**	**72.5**
COC (incl. T&S), $/tonne CO_2	**80.3**	**81.2**	**82.8**	**81.1**	**81.4**	**82.3**	**80.7**	**81.6**	**82.5**

Exhibit G-18. Cost and performance summary comparison – CM95-B1-S sensitivity cases

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Pre-heater/Pre-calciner								
Kiln Fuel	Natural Gas								
CO_2 Captured, tonnes/year	1,414,977								
CO_2 Captured, tonnes/hour	162								
CO_2 Compressor Load, kW	12,380								
Cooling Water Flowrate, gpm	65,377								
Cooling Tower Duty, MMBtu/hour	654								
COST									
TPC, $/1,000	461,305	461,310	461,315	461,407	461,411	461,416	461,509	461,513	461,518
BEC, $/1,000	302,133	302,136	302,140	302,202	302,205	302,209	302,272	302,275	302,278
Home Office Expenses	52,873	52,874	52,874	52,885	52,886	52,887	52,898	52,898	52,899
Project Contingency	76,884	76,885	76,886	76,901	76,902	76,903	76,918	76,919	76,920
Process Contingency	29,415	29,415	29,415	29,418	29,418	29,418	29,421	29,421	29,421
TOC, $M	559	560	560	560	560	560	560	560	561
TOC, $/1,000	559,467	559,869	560,271	559,658	560,060	560,462	559,849	560,251	560,653
Owner's Costs	98,161	98,559	98,956	98,251	98,648	99,046	98,341	98,738	99,135
TASC, $/1,000	589,593	590,017	590,441	589,794	590,218	590,642	589,996	590,420	590,844
Capital Costs, $/tonne CO_2	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9
Fixed Costs, $/tonne CO_2	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
Variable Costs, $/tonne CO_2	9.5	10.6	11.8	9.7	10.8	12.0	9.9	11.0	12.1
Purchased Power and Fuel, $/tonne CO_2	26.2	26.3	26.3	26.3	26.3	26.3	26.3	26.3	26.3
COC (excl. T&S), $/tonne CO_2	**72.4**	**73.6**	**74.7**	**72.7**	**73.8**	**75.0**	**72.9**	**74.1**	**75.2**
COC (incl. T&S), $/tonne CO_2	**82.4**	**83.6**	**84.7**	**82.7**	**83.8**	**85.0**	**82.9**	**84.1**	**85.2**

Exhibit G-19. Cost and performance summary comparison – CM95-B3-S sensitivity cases

SOx Concentration	100 ppm_v			300 ppm_v			500 ppm_v		
NOx Concentration	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v	500 ppm_v	1,000 ppm_v	1,500 ppm_v
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Wet Process								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,688,081								
CO_2 Captured, tonnes/hour	193								
CO_2 Compressor Load, kW	14,770								
Cooling Water Flowrate, gpm	75,855								
Cooling Tower Duty, MMBtu/hour	759								
COST									
TPC, $/1,000	554,448	554,456	554,463	554,602	554,610	554,617	554,757	554,764	554,772
BEC, $/1,000	363,273	363,278	363,283	363,378	363,384	363,389	363,484	363,490	363,495
Home Office Expenses	63,573	63,574	63,575	63,591	63,592	63,593	63,610	63,611	63,612
Project Contingency	92,408	92,409	92,411	92,434	92,435	92,436	92,459	92,461	92,462
Process Contingency	35,195	35,195	35,195	35,199	35,199	35,199	35,203	35,203	35,203
TOC, $M	673	673	674	673	674	674	673	674	675
TOC, $/1,000	672,765	673,477	674,188	673,072	673,784	674,495	673,381	674,092	674,803
Owner's Costs	118,317	119,021	119,725	118,470	119,174	119,878	118,624	119,328	120,032
TASC, $/1,000	708,993	709,743	710,492	709,316	710,066	710,816	709,642	710,391	711,141
Capital Costs, $/tonne CO_2	25.1	25.1	25.1	25.1	25.1	25.2	25.1	25.1	25.2
Fixed Costs, $/tonne CO_2	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
Variable Costs, $/tonne CO_2	10.6	12.2	13.9	10.9	12.5	14.2	11.2	12.8	14.5
Purchased Power and Fuel, $/tonne CO_2	25.6	25.6	25.6	25.6	25.6	25.6	25.7	25.7	25.7
COC (excl. T&S), $/tonne CO_2	**72.9**	**74.6**	**76.3**	**73.3**	**75.0**	**76.7**	**73.7**	**75.4**	**77.1**
COC (incl. T&S), $/tonne CO_2	**82.9**	**84.6**	**86.3**	**83.3**	**85.0**	**86.7**	**83.7**	**85.4**	**87.1**

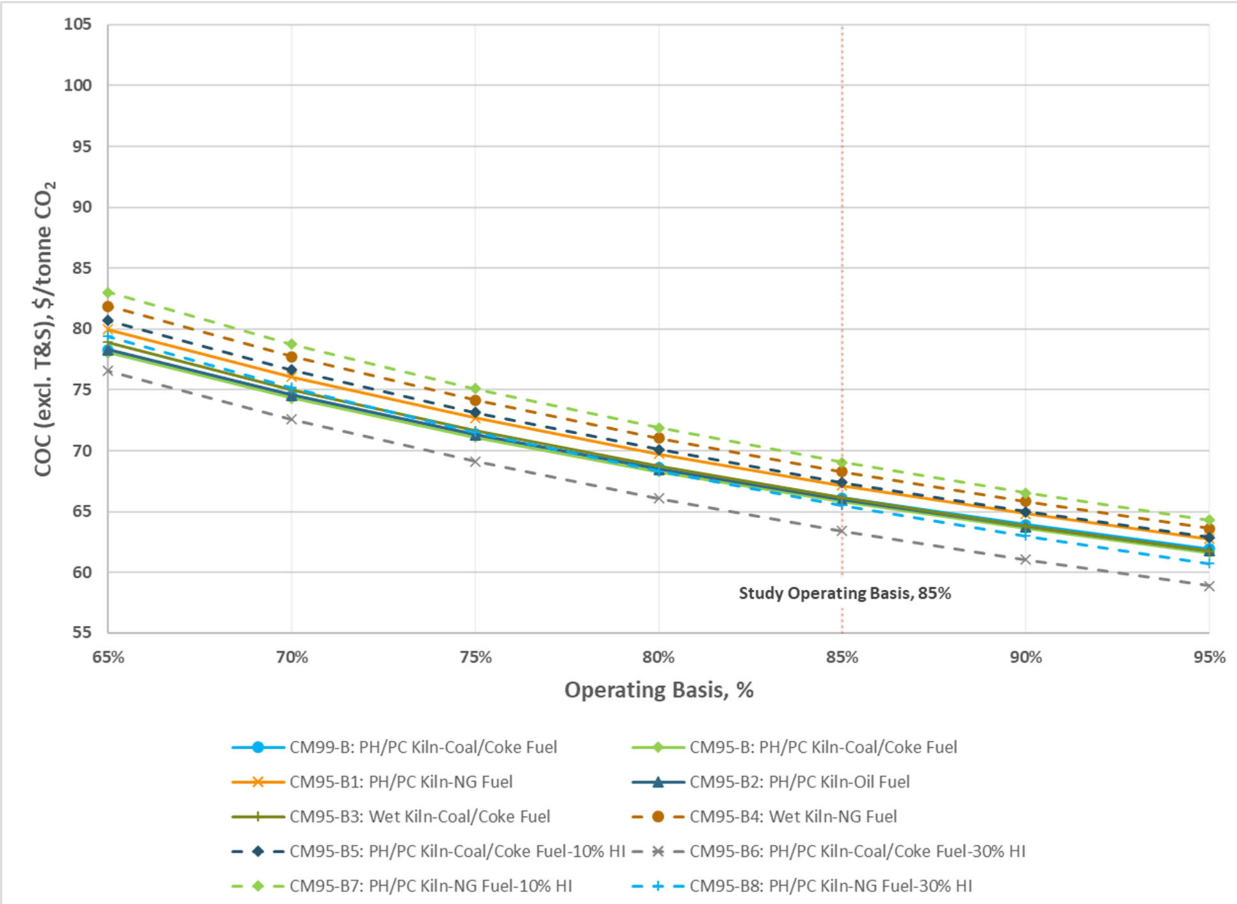
Exhibit G-20. Cost and performance summary comparison – CM95-B4-S sensitivity cases

SOx Concentration	100 ppm$_v$			300 ppm$_v$			500 ppm$_v$		
NOx Concentration	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$	500 ppm$_v$	1,000 ppm$_v$	1,500 ppm$_v$
PERFORMANCE									
Capture Rate	95 percent								
Kiln Type	Wet Process								
Kiln Fuel	Coal/Coke								
CO_2 Captured, tonnes/year	1,673,056								
CO_2 Captured, tonnes/hour	191								
CO_2 Compressor Load, kW	14,640								
Cooling Water Flowrate, gpm	73,482								
Cooling Tower Duty, MMBtu/hour	735								
COST									
TPC, $/1,000	587,976	587,986	587,996	588,165	588,174	588,184	588,363	588,372	588,382
BEC, $/1,000	385,299	385,305	385,312	385,428	385,435	385,442	385,564	385,571	385,578
Home Office Expenses	67,427	67,428	67,430	67,450	67,451	67,452	67,474	67,475	67,476
Project Contingency	97,996	97,998	97,999	98,027	98,029	98,031	98,060	98,062	98,064
Process Contingency	37,254	37,254	37,254	37,259	37,259	37,259	37,264	37,264	37,264
TOC, $M	714	715	716	714	715	716	715	715	716
TOC, $/1,000	713,761	714,690	715,619	714,146	715,076	716,005	714,544	715,473	716,402
Owner's Costs	125,784	126,704	127,623	125,982	126,901	127,821	126,182	127,101	128,021
TASC, $/1,000	752,196	753,175	754,154	752,602	753,582	754,561	753,022	754,001	754,980
Capital Costs, $/tonne CO_2	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	27.0
Fixed Costs, $/tonne CO_2	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Variable Costs, $/tonne CO_2	12.1	14.3	16.5	12.4	14.6	16.8	12.8	15.0	17.2
Purchased Power and Fuel, $/tonne CO_2	25.2	25.2	25.2	25.3	25.3	25.3	25.3	25.4	25.4
COC (excl. T&S), $/tonne CO_2	**76.6**	**78.8**	**81.1**	**77.1**	**79.3**	**81.5**	**77.5**	**79.8**	**82.0**
COC (incl. T&S), $/tonne CO_2	**86.6**	**88.8**	**91.1**	**87.1**	**89.3**	**91.5**	**87.5**	**89.8**	**92.0**

Exhibit G-21. Cost and performance summary comparison – air in-leakage cases

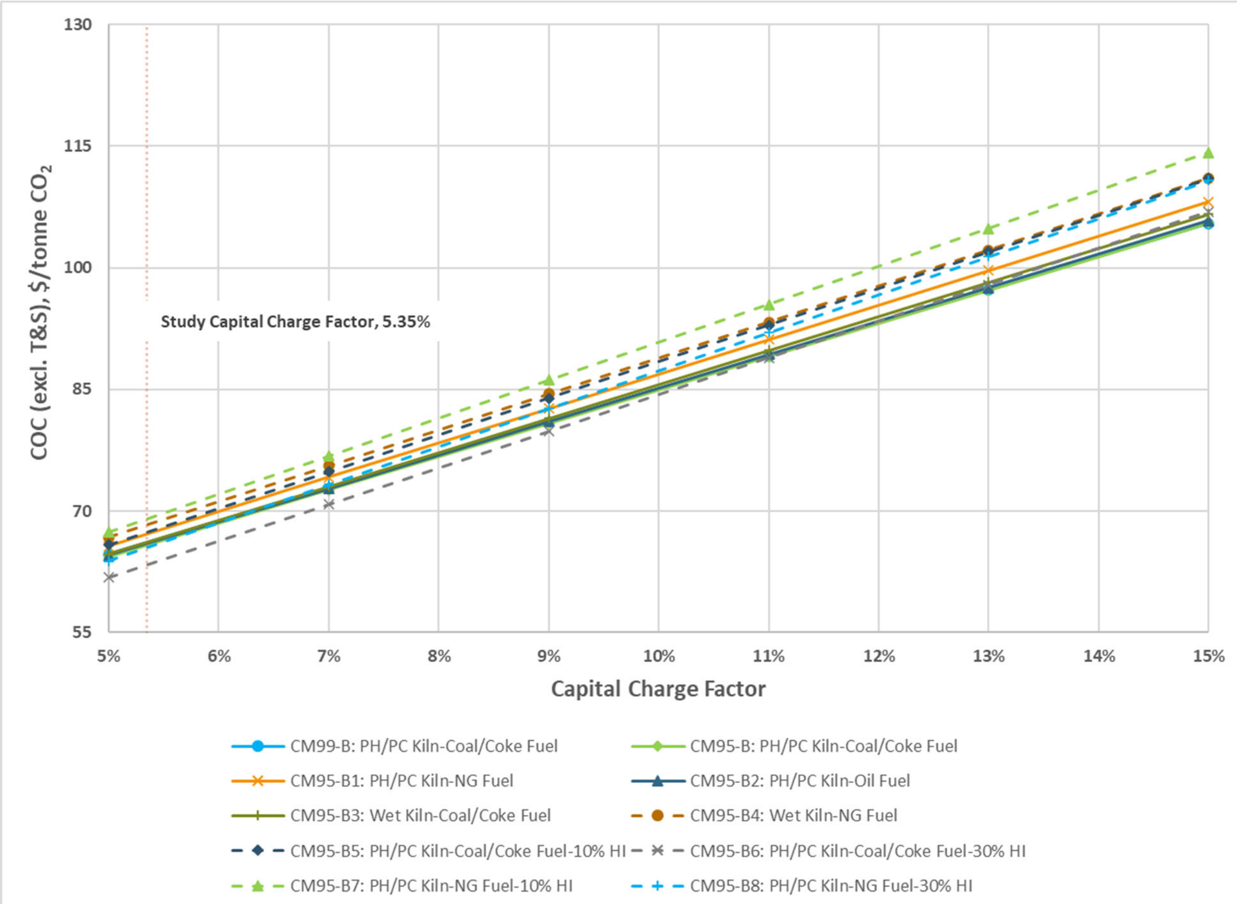
	CM95-B				CM95-B-S100N500			
	Base Case at 320°F	Emissions Stream at 250 °F			Base Case at 320°F	Emissions Stream at 250 °F		
		No Air In-leakage	Air In-leakage 400,000 ACFM	Air In-leakage 700,000 ACFM		No Air In-leakage	Air In-leakage 400,000 ACFM	Air In-leakage 700,000 ACFM
PERFORMANCE								
Capture Rate	95 percent							
Kiln Type	Pre-heater/Pre-calciner							
Kiln Fuel	Coal/Coke							
CO_2 Captured, tonnes/year	1,426,677	1,426,677	1,428,082	1,430,220	1,426,477	1,426,477	1,427,786	1,429,911
CO_2 Captured, tonnes/hour	163	163	163	163	163	163	163	163
CO_2 Compressor Load, kW	12,490	12,490	12,500	12,520	12,480	12,480	12,490	12,510
Cooling Water Flowrate, gpm	67,058	67,058	67,124	67,224	66,994	66,994	67,056	67,155
Cooling Tower Duty, MMBtu/hour	671	671	671	672	670	670	671	672
COST								
TPC, $/1,000	411,590	408,405	442,812	483,822	445,993	443,192	497,314	560,851
BEC	267,528	265,539	287,232	313,054	292,193	290,295	325,997	367,918
Home Office Expenses	46,817	46,469	50,266	54,784	51,134	50,802	57,049	64,386
Project Contingency	68,598	68,068	73,802	80,637	74,332	73,865	82,886	93,475
Process Contingency	28,647	28,329	31,513	35,346	28,334	28,230	31,382	35,072
TOC, $M	499	495	536	586	541	537	603	680
TOC, $/1,000	498,682	494,839	536,366	585,863	540,655	537,271	603,033	680,343
Owner's Costs	87,092	86,433	93,554	102,041	94,662	94,079	105,720	119,492
TASC, $/1,000	525,536	521,485	565,249	617,411	569,769	566,202	635,506	716,979
Capital Costs, $/tonne CO_2	22.0	21.8	23.6	25.8	23.9	23.7	26.6	30.0
Fixed Costs, $/tonne CO_2	10.5	10.5	11.3	12.2	11.3	11.3	12.5	14.0
Variable Costs, $/tonne CO_2	7.2	7.2	7.5	7.8	8.4	8.4	9.9	11.8
Purchased Power and Fuel, $/tonne CO_2	26.0	26.0	26.2	26.4	26.7	26.7	27.1	27.6
COC (excl. T&S), $/tonne CO_2	**65.8**	**65.5**	**68.6**	**72.2**	**70.3**	**70.1**	**76.0**	**83.4**
COC (incl. T&S), $/tonne CO_2	**75.8**	**75.5**	**78.6**	**82.2**	**80.3**	**80.1**	**86.0**	**93.4**

Exhibit G-22. COC (excl. T&S) vs. operating basis (Dec-2018)



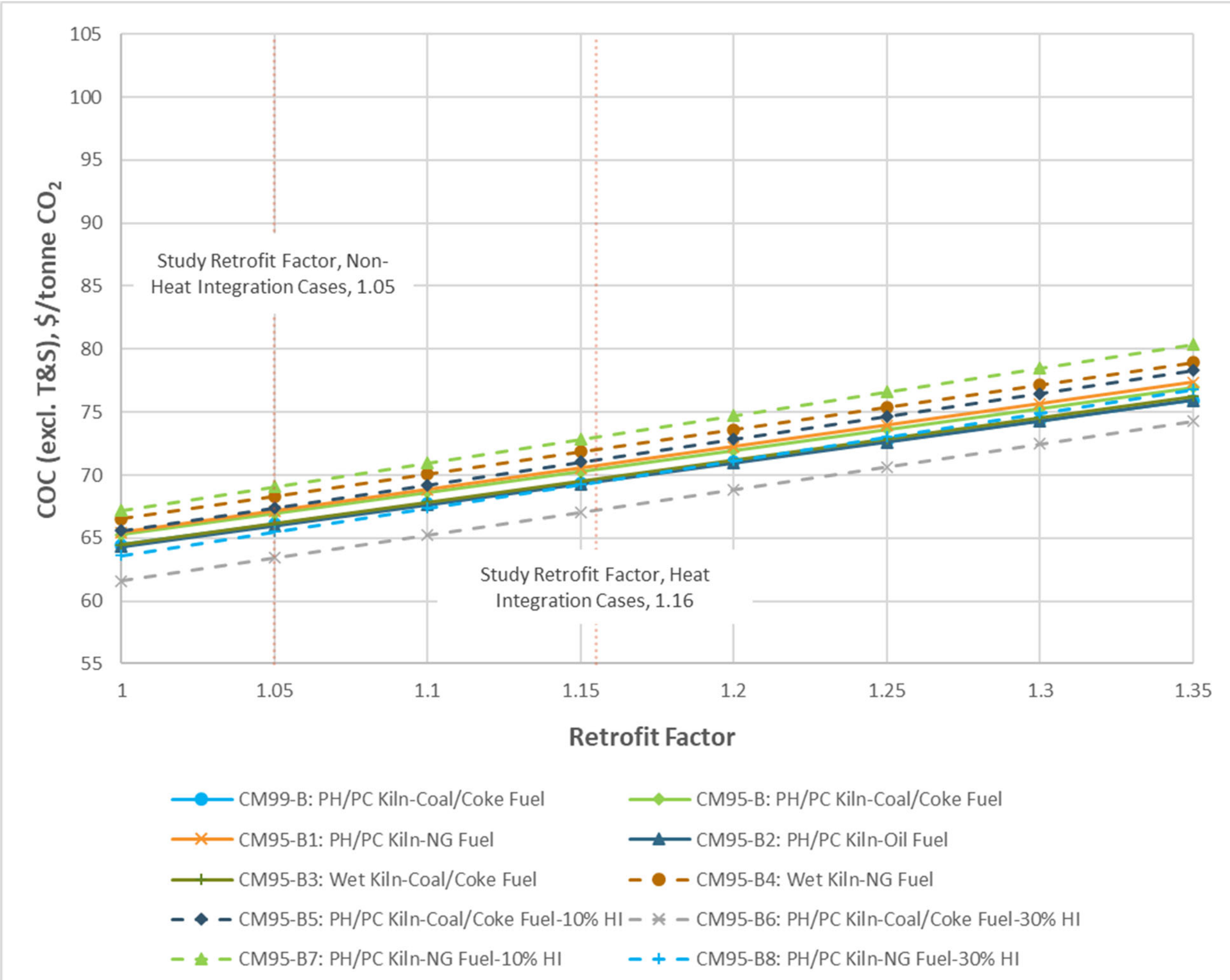
Note: HI = heat integration

Exhibit G-23. COC (excl. T&S) vs. CCF (Dec-2018)



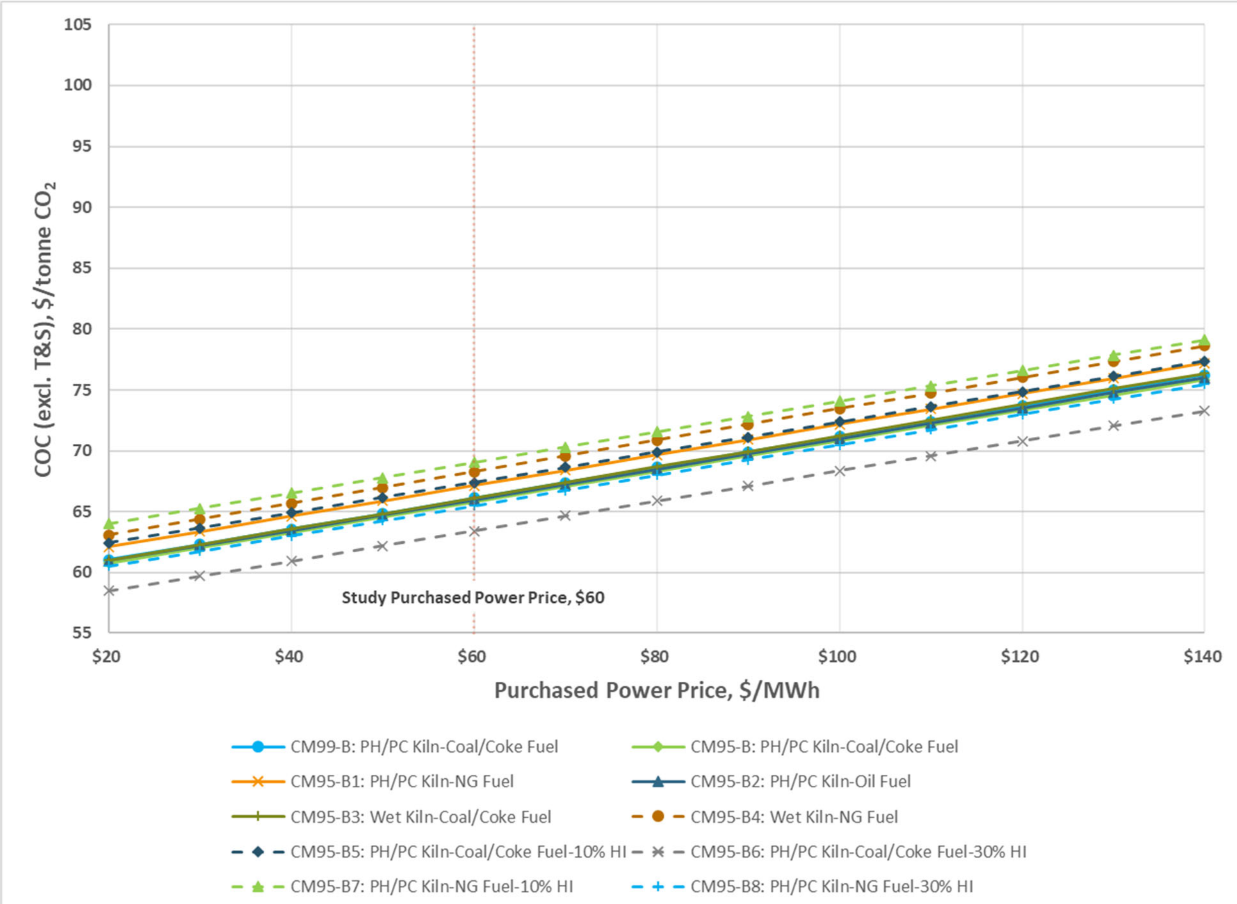
Note: HI = heat integration

Exhibit G-24. COC (excl. T&S) vs. retrofit factor (Dec-2018)



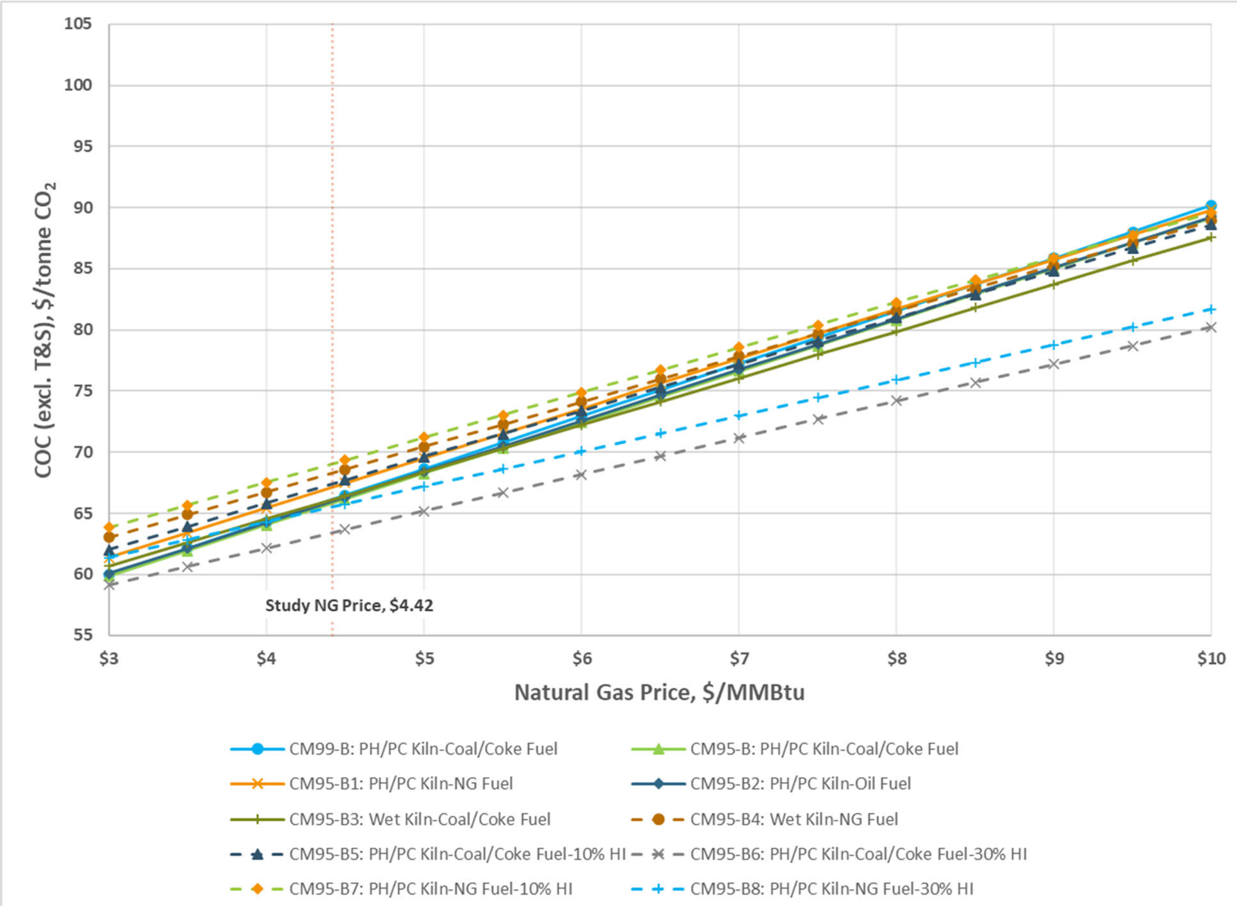
Note: HI = heat integration

Exhibit G-25. COC (excl. T&S) vs. purchased power price (Dec-2018)



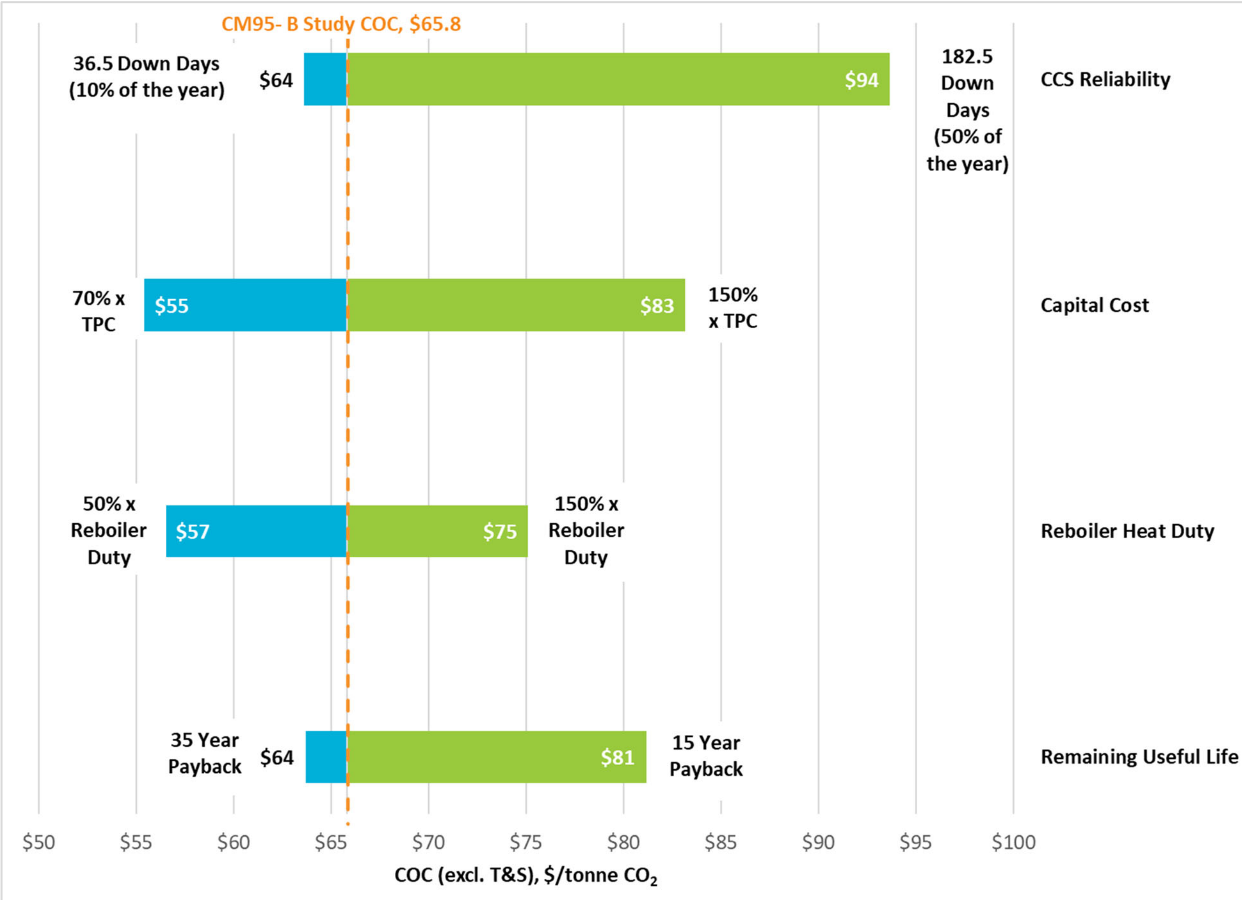
Note: HI = heat integration

Exhibit G-26. COC (excl. T&S) vs. NG price (Dec-2018)



Note: HI = heat integration

Exhibit G-27. COC vs. select study assumptions



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