CO_2 COMPRESSION REPORT
American Electric Power
Mountaineer CCS II Project
Phase 1

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Disclaimers

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1. SYNOPSIS

The purpose of this report is to explain the results of a technology study that evaluated options for compressing the full CO_2 product stream from the proposed nominal 235 MWe commercial scale application of Alstom's chilled ammonia process (CAP) at American Electric Power's Mountaineer generating station, in New Haven, West Virginia.

The study focused on commercially available, integrally-geared, inter-cooled, gas compression systems. The scope of the study included all of the equipment required to compress and condition the captured CO_2 for sequestration. Geologic characterization information and actual operating data from the Mountaineer Chilled Ammonia Product Validation Facility (PVF), which operated from 2009 to 2011 provided injection parameters on which to base the design for the commercial scale compression system. Equipment arrangements, auxiliary power demands, balance of plant integration, and capital and operating costs were considered in the evaluation of each compression system.

In the end, two arrangements were considered technically and economically feasible for implementation on the commercial scale system. Further technical investigation in Phase II of the project would determine which arrangement would ultimately be selected. Both utilize compression of the CO_2 to an intermediate condition, followed by variable-speed pumping to the final desired injection conditions. The compressor-pump arrangement allows for greater flexibility and higher operating efficiency throughout the life of the well, which is important based on the expected variability in injection pressure over the life of the injection wells – a key takeaway from the PVF operation effort, and design basis driver for the commercial scale project.

1.1 EXECUTIVE SUMMARY

Five basic configuration options to pressurize CO_2 from a nominal 300 psia (20.7 bar) to 3,000 psig (207 bar) were identified. Two of the five options evaluated were an emerging compression technology and are not discussed in this report due to intellectual property concerns with the technology supplier. The remaining three alternatives are:

- Option 1 – Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 1,320 psig (91 bar) followed by pump and after-cooler to 3,000 psig (207 bar).

- Option 3 – Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 860 psig (59 bar) followed by cooling with cooling water and liquefaction via heat exchange with a refrigerant. Liquid CO_2 then pumped to 3,000 psig (207 bar).

- Option 4 - Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 3,000 psig (207 bar).

Process Flow Diagrams (PFD's) were developed for each option. Based on the PFD's developed, equipment suppliers and OEMs were contacted in order to procure budgetary proposals, performance data and cost estimates for the equipment defined by the configuration descriptions given above.

A summary of the auxiliary power requirements to pressurize CO_2 to 3,000 psig (207 bar) for each of the options is presented in Table 1 below.

It should be noted that the refrigeration auxiliary load for Option 3 is assessed at the peak summer condition, thus the value in the table is a worst-case auxiliary load. During other seasons, especially winter, this value would be less since at lower ambient temperatures, the refrigeration system could be bypassed and the water-cooled after-cooler would provide the necessary cooling.

Table 1: Summary of Auxiliary Power Requirements

LOAD	1	3	4
COMPRESSION, kWe	5,980	4,630	8,996
PUMP, kWe	1,321	1,440	0
REFRIGERATION, kWe	0	1,233*	0
COOLING WATER PUMP, kWe	160	55	165
SUBTOTAL, kWe	7,461	7,358	9,161
TOTAL, kWe	7,461	7,358	9,161

* - Peak condition; considerably less during winter months. Calculated annual average is 440 kWe.

A summary of the cooling water service requirements for each of the options is presented in Table 2 below. This cooling water is assumed to be available from Alstom's cooling tower and would be piped from the Direct Contact (DC) cooling water circuit. Alstom has verified that they can provide cooling water at the temperature required by the compression equipment.

Table 2: Summary of Cooling Water Requirements

OPTION	1	3	4
COOLING WATER, GPM (m^3/min)	6,800 (25.7)	2,340 (8.9)	7,000 (26.5)

Process equipment costs were either estimated by WorleyParsons or obtained from equipment suppliers' budgetary proposals. Compressor cost data for Options 1 and 3 are from Alstom's "CO_2 Compression Study Report Summary". A summary of the equipment costs for the various CO_2 compression options is shown in Table 3.

It should also be noted that each of the options could be configured for heat recovery with the CAP system or the main Mountaineer unit. However, cursory analyses indicated that the CAP and plant processes would benefit little from the heat available from integrally geared machines with inter-stage cooling. Other compression technologies or heat recovery means may have been implemented, but since this was a commercial demonstration project treating a slipstream of flue gas, the plant and the engineering team had little appetite for adding additional complexity and over-integration of systems with the CO_2 compression system. Furthermore, the reduced injection pressures as experienced on the Mountaineer CCS validation facility suggested that available heat of compression would be reduced from initial expectations. Finally, the additional capital costs for equipment to recoup the available heat (pumps, heat exchangers, piping, etc) would be significant. For these reasons the team chose not to focus its efforts in Phase I on recovering the heat of compression.

As shown in Table 3, Option 1 – compression in an integrally-geared centrifugal compressor to an intermediate supercritical condition followed by cooling and pumping to final pipeline pressure (most flexible operating condition), is the most economical solution from an equipment cost perspective followed by Option 3, which uses sub-critical compression with liquefaction. Although Option 3 is penalized from a CAPEX perspective due to the high cost of the refrigeration equipment, the lower operating costs associated with this option offset a significant portion of the capital.

In Table 3 and all other cost tables throughout the report, estimated costs are presented in the following manner:

- Option 1 is held as the “Base” cost option.
- All other costs for the other options identified will be represented as a percentage difference (+/-) from the Base.

Table 3: Summary of Equipment Cost

OPTION	**1**	**3**	**4**
EQUIPMENT ITEM	**Integrally-Geared Compressor/ Pump**	**Integrally-Geared Compressor/ Liquefaction/ Pump**	**Integrally-Geared Compressor/ No Pump**
CO_2 KO DRUM	BASE	0%	0%
COMPRESSOR AND MOTOR	BASE	-2.5%	+107.4%
INTER-/AFTER-COOLER	BASE	-35.8%	+27.0%
REFRIGERATION, USD	N/A	+$2.9M	N/A
CO_2 RECEIVER	BASE	+44.7%	N/A
PUMP AND MOTOR	BASE	+12.9%	N/A
PUMP VFD	BASE	+9.0%	N/A
PUMP AFTER-COOLER	BASE	N/A	N/A
TOTAL EQUIPMENT COST	BASE	+47.3%	+25.7%

The total evaluated costs indicate that, over the long term, Option 1, integrally-geared compression followed by supercritical CO_2 pumping is the least cost option with Option 3, sub-critical compression, cooling and CO_2 liquefaction followed by pumping, being the next least cost option.

Table 4: Total Evaluated Cost Summary

OPTION	1	3	4
	Integrally-Geared Compressor/ Pump	Integrally-Geared Compressor/ Liquefaction	Integrally-Geared Compressor/No Pump
TOTAL EQUIPMENT COST	BASE	+47.3%	+25.7%
AUXILIARY POWER COST (FIRST YEAR)	BASE	-12.0%	+22.8%
TOTAL OPERATING COST, NET PRESENT VALUE (NPV), OVER 10 YEARS	BASE	-12.0%	+22.8%
TOTAL EVALUATED COST (TOTAL OF EQUIPMENT AND NPV COSTS)	BASE	+6.5%	+23.7%

The study evaluation presented in this report generated the following key takeaways:

- All options evaluated are technically feasible
- Based on experience with injection at Mountaineer, pressures below 3000 psig (207 bar) are likely to be sufficient to inject CO_2 into the targeted underground reservoirs, which would result in additional power savings and reduced total evaluated costs for options having the flexibility to produce lower injection pressures. Compression to an intermediate pressure, followed by variable speed pumping to the final injection pressure offers greater flexibility and efficiency over the life of the system as compared to full compression to the maximum expected injection pressure.
- Performance and total evaluated cost for Option 1, compression with an integrally-geared compressor to an intermediate supercritical condition followed by cooling and pumping to final pipeline pressure, and Option 3, subcritical compression, cooling and CO_2 liquefaction followed by pumping to final pipeline pressure, are similar. Detailed engineering and design in Phase II of the project, focusing on these options, is recommended to determine the best option for Mountaineer plant.

2. INTRODUCTION

The proposed CO_2 capture facility at AEP's Mountaineer Plant would utilize Alstom's CAP technology to capture approximately 1.5 million metric tons of CO_2 annually. This is based on a design target of 90 percent CO_2 capture from a 235-MWe equivalent flue gas slipstream of the 1,300-MWe Mountaineer Power Plant. The captured CO_2 would be transported by pipeline to injection sites located up to approximately 12 miles (approx. 19 kilometers) from the plant, and injected in its supercritical state into deep geologic formations.

The existing Mountaineer Plant began commercial operation in 1980. The plant consists of a 1,300-MW pulverized coal-fired electric generating unit, a hyperbolic cooling tower, material handling and unloading facilities, and various ancillary facilities required to support plant operation. The plant uses (on average) approximately 10,000 tons of coal per day. Coal is delivered to the plant by barge (on the Ohio River), rail, and conveyors from a nearby coal mine located west of the site. The plant is equipped with air emissions control equipment, which includes: (1) an electrostatic precipitator for particulate control; (2) selective catalytic reduction for nitrogen oxides (NO_x) control; (3) a wet flue gas desulfurization (FGD) unit for sulfur dioxide (SO_2) control; and (4) a Trona injection system for sulfur trioxide (SO_3) control.

The existing Mountaineer Plant Product Validation Facility (PVF) was a demonstration of Alstom's CAP system and treats approximately 20 MW of flue gas, or 1.5 percent of the total plant flue gas flow. The PVF started capturing CO_2 in September 2009 and initiated injection in October 2009. The PVF is designed to capture and store approximately 100,000 metric tons of CO_2 annually. Captured CO_2 from the PVF is injected via two onsite wells into two geologic formations (Rose Run and Copper Ridge) located approximately 1.5 miles below the plant site. The PVF also includes three deep monitoring wells used for monitoring geologic conditions and assessing the suitability of the geologic formations for future storage. The PVF supplied data to support the design and engineering of the MT CCS II project.

The CO_2 capture system proposed for the Mountaineer CCS II Project is similar to the Alstom CAP system currently operating at the Mountaineer Plant PVF, but approximately 12 times larger in scale. As with the PVF, the process uses an ammonia-based reagent to capture CO_2 and convert it to a form suitable for geologic storage. The captured CO_2 stream is cooled and compressed to a supercritical state for storage. In general terms, supercritical CO_2 exhibits properties of both a gas and a liquid. The process is designed to remove approximately 90 percent of the CO_2 from the 235-MW slipstream of flue gas.

The CAP uses an ammonia-based reagent to remove CO_2 from the flue gas. The first step in the process is to cool or chill the flue gas. The capture process involves CO_2 reacting with ammonia (NH_3) ions to form a solution containing ammonia-CO_2 salts. These reactions occur at relatively low temperatures and pressures within the absorption vessels. The solution of ammonia-CO_2 salts would then be pumped to a regeneration vessel. In the regeneration vessel, the solution is heated and the reactions are reversed, resulting in a high-purity stream of CO_2. The regenerated reagent is then recycled back to the absorption vessel to repeat the process. The CO_2 stream is scrubbed to remove excess ammonia, then compressed, and transported via pipeline to injection wells for geologic storage.

The purpose of this study is to evaluate options for compressing the CO_2 product stream from Alstom's chilled ammonia process (CAP) discharge sufficient to transport and inject the supercritical CO_2 into remotely located injection wells. Options evaluated include (1) full compression directly to the design injection pipeline pressure (3,000 psig or 207 bar), and, (2) compression to an intermediate pressure with pumping of CO_2, in either the liquid or supercritical state, to the required final pipeline injection pressure (3,000 psig or 207 bar). All options will have the ability to deliver CO_2 to the pipeline inlet at 3000 psig (207 bar), however, they will also be evaluated based on their ability to deliver CO_2 at a reduced pressure (approx. 1500 psig or 103 bar) in the event the required well injection pressure is lower, as has been experienced at Mountaineer's Product Validation (PVF) facility.

The scope of this study considers all of the equipment required to compress and condition CO_2 for sequestration. The equipment area covered begins with the CO_2 discharge from the CAP process and ends with the CO_2 transport pipeline inlet.

Process flow diagrams (PFD's) and process descriptions were generated for each option, and equipment vendors were contacted in order to procure budgetary proposals for process equipment.

3. DISCUSSION

3.1 Design Basis

Due to the fact that the Mountaineer CCS system is treating a 235 MWe equivalent flue gas slipstream, changes in operating load on the main steam generating unit load were not expected to impact the inlet flow rate to the chilled ammonia process (CAP). The design basis for the capture plant was to operate at full capture capacity for all main unit loads 55 – 100% of full rated capacity (1300 MWe). Certainly there would be impacts at a larger scale, but they were not considered in this phase of the project.

The compression systems evaluated were designed to handle a 50% turndown of the CAP, and the process design included the capability of bypassing the CO_2 compression system to return captured CO_2 back to the outlet flue gas stream for greater operations flexibility during start-up, shutdown, and upset conditions when captured CO_2 might be out of specification limits. The team did not thoroughly investigate the potential impacts of operating the compression system at reduced capacities for extended periods during this phase of the project. For Phase I, verification that the compression system suppliers could accommodate CO_2 flow rates between 50% and 100% of the expected volume was most important. Further investigation into the impacts of operating at reduced CO_2 flow rates, start-up, shutdown, etc. would be explored in later phases of the project.

The CO_2 compression system will be designed and sized based on the CO_2 product specification given below in Table 5.

Table 5: CO_2 Specification

Parameter	Unit	Nominal Value
Carbon dioxide (CO_2)	vol %	> 99.50
Water (H_2O)	ppmv	2400
Oxygen (O_2)	ppmv	< 100
Nitrogen (N_2)	ppmv	< 250
Ammonia (NH_3)	ppmv	< 50
Total Mass flow	lb/hr (kg/hr)	445,000 (201,849)
CAP Discharge Pressure	psia (bara)	296 (20.4)
Injection Pressure Range	psia (bara)	1,500 – 3,000 103 – 207
Temperature @ CAP Discharge	°F (^oC)	99.14 (37.3)

This CO_2 product specification was initially derived for the PVF at Mountaineer from several sources since there were no specifications which dealt with the specifics of the CAP process. Alstom provided the basic constituent specifications (O_2, N_2, and NH_3) based upon process modeling, analyses and performance of their lab scale and pilot facilities. The high CO_2 purity was an inherent output of the Alstom Chilled Ammonia process and while the team did investigate how process modifications might alter the CO_2 purity, the specification above did not differ significantly from validation experience and was determined to be the design basis for the commercial scale demonstration. Compression system selection was not expected to require alteration of the CO_2 product specification, and any impacts from the CO_2 product constituents would likely be handled with readily available materials of construction.

Moisture content (2400 ppmv) was the only parameter that differed from the PVF moisture specification of <600 ppmv. The PVF moisture specification, based in part on the Kinder-Morgan pipeline moisture specification of 30 lbs H_20 per million SCF, was accepted due to pipeline corrosion concerns brought up by AEP's deep injection well contractor, Battelle. Allowing for an increased moisture specification meant less equipment in the CAP for dehydrating and a reduced energy demand. The increased moisture did prompt for more attention to materials of construction, ultimately driving the decision to line the CO_2 transport pipeline to mitigate corrosion concerns.

The 3000 psi (207 bar) maximum expected injection pressure has its origins in the geologic characterizations and actual injection operating experiences of the PVF. Initial estimates by Battelle indicated that both target injection formations, Rose Run and Copper Ridge, would have to be initially injected at some value over 1,800 psi and this value would likely increase depending on the formation and how much was injected over the course of operation. Alstom, as part of their PVF scope had agreed to an industry standard of 1,500 psi (their interpretation of what the pipelines generally were receiving). AEP and Alstom considered other options, but after consulting with a CO_2 pipeline consultant it was decided to use the 1,500 psi as the low side of the target injection pressure range and boost the pressure with a standard booster pump and variable speed drive to higher pressures of the formation as necessary.

Per the Underground Injection Control (UIC) permit with the state of West Virginia, the injection could not exceed the fracture pressure of the formations, or a bottom-hole pressure of 0.8psi/ft of depth. Compliance with this permit established a maximum injection pressure into the target formations.

For Copper Ridge:

8,300 ft depth x 0.8 psi/ft = **6,640 psi max bottom hole pressure**
Subtracting the hydrostatic head [calculated to be 2,880 psi]
6,640 psi - 2,880 psi = **3760 psi max top hole pressure**
85% safety factor = **3196 psi**.

For Rose Run:

7,800 ft depth x 0.8 psi/ft = **6,240 psi max bottom hole pressure**
Subtracting the hydrostatic head [calculated to be 2,707 psi]
6,240 psi - 2,707 psi = **3,533 psi max top hole pressure**
85% safety factor = **3,003 psi**.

3.2 Compression Options

There are two broad classifications of compressors: positive displacement and dynamic or turbo compressors. The only applicable positive displacement type compressor would be reciprocating; rotary and diaphragm types are not appropriate for this application. Applicable turbo compressors are centrifugal or radial compressors; axial flow compressors are not applicable due to their limited pressure ratio.

Reciprocating compressors generate increased pressure via volume reduction. They are available from a variety of equipment manufacturers including Cameron and Ariel. Reciprocating compressors have been successfully used for several decades to compress CO_2 for Enhanced Oil Recovery (EOR). A table summarizing the advantages and disadvantages of these compressors is shown in Table 6 below.

Table 6: Advantages and Disadvantages of Reciprocating Compressors

ADVANTAGE	DISADVANTAGE
HIGH PRESSURE RATIOS	MULTIPLE MACHINES REQUIRED
MULTI-STAGED WITH INTER-COOLING	MAINTENANCE PRONE
SIMPLE TO OPERATE/REPAIR	RELATIVELY EXPENSIVE

There are two types of centrifugal compressors frequently employed for service of the type evaluated here. The first type is single-shaft radial centrifugal compressors offered by companies such as Dresser-Rand. These compressors have also been used successfully to compress CO_2 for EOR. Compressors of this type convey kinetic energy to the motive fluid then convert that energy into pressure. A table of the advantages and disadvantages of single-shaft centrifugal compressors is summarized in Table 7 below.

Table 7: Advantages/Disadvantages of Single-Shaft Centrifugal Compressors

ADVANTAGE	DISADVANTAGE
HIGH PRESSURE RATIOS	SENSITIVE TO ENTRAINED LIQUID
MULTI-STAGED WITH INTER-COOLING	HIGH NOISE LEVELS
HIGH EFFICIENCY	LIMITED PRESSURE RATIO
VARIABLE SPEED DRIVE (VSD) APPLICABLE	

The second type of centrifugal compressor frequently employed for the service of EOR and CO_2 compression is the integrally-geared centrifugal compressors. These compressors use a bull gear to power multiple "shafts" thereby providing the capability to efficiently compress a large amount of CO_2 in a single machine. A table of the advantages and disadvantages of integrally-geared centrifugal compressors is summarized in Table 8 below.

Table 8: Advantages/Disadvantages of Integrally-Geared Compressors

ADVANTAGE	DISADVANTAGE
HIGH PRESSURE RATIOS	NO VSD
MULTI-STAGED WITH INTER-COOLING	COMPLEX MAINTENANCE/REPAIR
HIGH EFFICIENCY	HIGHER GEAR LOSSES
	LARGE FOOTPRINT

3.3 CO_2 Compression Configurations Evaluated

Five configuration options to pressurize CO_2 from 296 psia (20.7 bara) to 3,000 psig (207 bar) were identified for the MT CCS II project. Two of the five options evaluated were an emerging compression technology and are not discussed in this report due to intellectual property concerns with the technology supplier. The remaining three alternatives are:

- Option 1 – Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 1,320 psig (91 bar) followed by pump and after-cooler to 3,000 psig (207 bar).
- Option 3 – Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 860 psig (59 bar) followed by cooling with cooling water and liquefaction via heat exchange with a refrigerant. Liquid CO_2 then pumped to 3,000 psig (207 bar).
- Option 4 - Integrally-geared, inter-cooled, centrifugal compressor with after-cooler to 3,000 psig (207 bar).

Process Flow Diagrams (PFD's) were developed for each of the five basic options. ASPEN models were generated in order to estimate preliminary performance data, and heat recovery options were further analysed utilizing ALPRO steam cycle simulations developed for the project by Alstom.. Based on this information, equipment suppliers and OEMs were contacted in order to procure budgetary proposals, performance data, and cost estimates for the equipment defined by the configuration descriptions given above. The PFDs, basic process descriptions, equipment arrangements, and results of OEM inquires are discussed below.

3.3.1 Option 1

In this configuration, CO_2 from Alstom's CAP would be routed to a knock out drum before being directed to an integrally-geared centrifugal compressor. This compressor would be inter-cooled to some extent and it is possible that some condensate would be formed during inter-stage cooling. Supercritical CO_2 would exit the machine at 1300 – 1500 psig (90 to 103 bar) and be cooled with cooling water to approximately 105 ^{o}F (40.6 ^{o}C) before being routed to a CO_2 buffer tank. The buffer tank is sized for 5 minutes of CO_2 storage at the maximum flow rate. A pump would draw supercritical CO_2 from the buffer tank and pump the CO_2 stream to 3000 psig (207 bar). A pump after-cooler would be used to cool the high pressure CO_2 stream in order to ensure the pipeline temperature specification (110 ^{o}F or 43.3 ^{o}C max) is met. A simplified PFD of this option can be seen in Appendix A. Also contained on the PFDs are key performance parameters in regards to temperature, pressure, and flowrate.

Alstom provided the equipment costs and performance results for Option 1 with the exclusion of the pump and pump after-cooler, which was estimated by WorleyParsons. The compressor discharge pressure is 1,339 psia (92 bar). Compressor power is estimated at 5,980 kWe while the estimated auxiliary load due to the pump is 1,321 kW.

Cooling water requirements for the inter- and after-cooler are estimated at 5,600 gpm (21 m^3/min) assuming a 20^{o}F temperature rise across the coolers. The estimated pump after-cooler cooling water requirement is 1,200 gpm for a total option cooling water requirement of 6,800 gpm (26 m^3/min).

An equipment list for this option is shown in Table 9. Instrument air compression and drying for the CAP is also housed in the compressor building. The overall compressor building footprint is estimated as 91 feet (27.7 m) by about 100 feet (30.5 m).

TABLE 9: Equipment List for Option 1

EQUIPMENT NAME	QTY	TYPE OF EQUIPMENT	MATERIAL SPECIFICATION
FEED KNOCK OUT DRUM	1	SHOP FABRICATED VERTICAL PRESSURE VESSEL	304 SS CLAD CS
CO_2 COMPRESSOR	1	INTER-COOLED, INTEGRALLY-GEARED CENTRIFUGAL COMPRESSOR	
COMPRESSOR AFTER-COOLER	1	SHELL AND TUBE HEAT EXCHANGER	
CO_2 BUFFER TANK	1	SHOP FABRICATED HORIZONTAL PRESSURE VESSEL	304 SS CLAD CS
CO_2 PUMP	1	MULTISTAGE, AXIALLY SPLIT, CENTRIFUGAL PUMP	
PUMP AFTER-COOLER	1	SHELL AND TUBE HEAT EXCHANGER	304SS TUBES/CS SHELL

3.3.2 Option 3

In Option 3, CO_2 from Alstom's CAP would be routed to a knock out drum before being directed to an integrally-geared centrifugal compressor. It is expected that the compressor would be cooled with cooling water service and that a small amount of condensate could be removed from the intercooler effluent. Subcritical gaseous CO_2 would exit the machine at approximately 870 psig (60 bar)and then be cooled to 60^{o}F (15.5 ^{o}C) and liquefied via refrigerant in a kettle-type shell and tube heat exchanger before being routed to a receiving vessel. The CO_2 receiver vessel would be sized for 10 minutes of liquid CO_2 storage at the maximum flow rate. As per discussions with Alstom and AEP, a greater storage time is required for the subcritical liquid pump arrangement than for the supercritical pumping options. A pump would draw off liquid CO_2 from the receiver and pump the CO_2 stream to 3,000 psig (207 bar). A simplified PFD of this option can be seen in Appendix A.

Alstom provided complete equipment costs and performance evaluation for Option 3. Compressor power is estimated at 4,630 kWe. It is assumed that the after-cooler utilizes cooling water service and that the CO_2 effluent from the cooler is around 100°F (38 °C). The dew point for the CO_2 stream at 870 psig (60 bar) was estimated to be between 70 and 75 °F (21 – 24 °C). WorleyParsons chose to liquefy and subcool the CO_2 to 68°F (20 °C). The duty required for this operation is estimated at approximately 36.5 MMBtu/hr (3,040 tons of refrigeration) or 38.3 GJ/hr. The auxiliary load required to provide this refrigeration load is 1,080 kWe. Liquid CO_2 flows to a receiver before being routed to the pump suction. The pump elevates the liquid CO_2 pressure to 3,000 psig (207 bar). The estimated auxiliary load due to the pump is 1,440 kW. Due to the cool pump suction temperature, no pump after-cooler is required to meet the pipeline temperature specification (110°F or 43 °C max). The final CO_2 delivery temperature is estimated as 92°F. An equipment list for Option 3 is shown in Table 10.

TABLE 10: Equipment List for Option 3

EQUIPMENT NAME	QTY	TYPE OF EQUIPMENT	MATERIAL SPECIFICATION
FEED KNOCK OUT DRUM	1	SHOP FABRICATED VERTICAL PRESSURE VESSEL	304 SS CLAD CS
CO_2 COMPRESSOR	1	INTER-COOLED, INTEGRALLY-GEARED CENTRIFUGAL COMPRESSOR	
COMPRESSOR AFTER-COOLER	1	SHELL AND TUBE HEAT EXCHANGER	
CO_2 LIQUEFACTION	1	SHELL AND TUBE HEAT EXCHANGER 36.5 MMBTU/HR (38.3 GJ/HR)	
REFRIGERATION UNIT	1	CHILLER UNIT	
CO_2 RECEIVER	1	SHOP FABRICATED HORIZONTAL PRESSURE VESSEL	304 SS CLAD CS
CO_2 PUMP	1	MULTISTAGE, AXIALLY SPLIT, CENTRIFUGAL PUMP	

3.3.3 Option 4

CO_2 from Alstom's CAP would be routed to a knock out drum before being directed to an integrally-geared centrifugal compressor. Supercritical CO_2 would exit the machine at 3,000 psig (207 bar) and 105^{o}F (41 ^{o}C). This compressor would be inter-cooled to some extent and it is possible that some condensate would be formed during inter-stage cooling. A simplified PFD of this option can be seen in Appendix A. The PFD illustrates the main process equipment and a few key operating state points.

It is assumed that the compressor has five stages and would operate at an approximate 10:1 overall pressure ratio with a compressor inlet pressure of 296 psia (20.4 bar). The first two compressor stages are cooled with cooling water service; approximately 1,420 gpm (5.4 m^3/m) of cooling water would be required for inter-cooling). The remaining stages are not cooled. This compressor requires an estimated 8,996 kW of electrical power.

An after-cooler would be needed to cool the high-pressure CO_2 down to pipeline conditions. An ASPEN model was used to determine the cooling required to lower the CO_2 compressor exhaust temperature (326^{o}F or 163 ^{o}C) to 105^{o}F (41 ^{o}C). An estimated 55.8 MMBtu/hr (58.6 GJ/hr) is required. This corresponds to a cooling water service flow of 5,580 gpm (21 m^3/m) assuming a 20 degree temperature rise across the exchanger. Heat exchanger fabricators were contacted to develop basic equipment design data and provide a budgetary cost estimate for the exchanger.

An equipment list for this option is shown in Table 11. The compressor building, which also holds the CAP instrument air compressor, dryers, and receivers, is estimated to have a footprint of 90 feet (27 m) by 76 feet (23 m).

TABLE 11: Equipment List for Option 4

EQUIPMENT NAME	QTY	TYPE OF EQUIPMENT	MATERIAL SPECIFICATION
FEED KNOCK OUT DRUM	1	SHOP FABRICATED VERTICAL PRESSURE VESSEL	304 SS CLAD CS
CO_2 COMPRESSOR	1	INTEGRALLY-GEARED INTER-COOLED	
COMPRESSOR AFTER-COOLER	1	SHELL AND TUBE HEAT EXCHANGER	304SS TUBES/CS SHELL

3.4 RESULTS SUMMARY

A summary of the auxiliary power requirements to pressurize CO_2 to 3,000 psig for each of the options is presented in Table 12 below. Note that the refrigeration auxiliary power load for Option 3 is assessed at the peak summer condition. During other seasons, especially winter, this value would be less since at lower ambient temperatures the refrigeration system would be bypassed and the water cooled after-cooler would provide the necessary cooling. The total auxiliary power values shown in the table represent worst-case power requirements for each option. The average annual power consumption for Option 3 is calculated to be 6,565 kW; compared to 7,358 kW as shown in Table 12. This average annual power consumption is based on an average annual refrigeration load of 440 kW. The refrigeration load shown in the table for Option 3 represents a worst-case (Summer peak) condition.

Table 12: Summary of Auxiliary Power Requirements (CO_2 to 3,000 psig (207 bar))

LOAD	1	3	4
COMPRESSION, kWe	5,980	4,630	8,996
PUMP, kWe	1,321	1,440	0
REFRIGERATION, kWe	0	1,233*	0
COOLING WATER PUMP, kWe	160	55	165
SUBTOTAL, kWe	7,461	7,358	9,161
TOTAL, kWe	7,461	7,358	9,161

* - Peak condition; considerably less during winter months. Calculated annual average is 440 kWe.

Table 13 shows an estimated auxiliary power summary to pressurize CO_2 to 1,500 psig (103 bar). In this case, for Option 4 which utilizes a compressor sized and designed to pressurize CO_2 to 3,000 psig (207 bar), supercritical CO_2 would be throttled down in pressure to 1,500 psig (103 bar) at the CO_2 injection well. The Joule-Thompson affect is not significant at this pressure range (as CO_2 is a supercritical fluid) so there would only be a minimal (10 degree) temperature drop due to throttling the CO_2. For cases where high pressure CO_2 pumps are used, the pumps would either be bypassed, or run at a lower speed as in Options 1 and 3.

Table 13: Summary of Auxiliary Power Requirements (CO_2 to 1,500 psig (103 bar))

LOAD	1	3	4
COMPRESSION, kWe	5,980	4,630	8,996
PUMP, kWe	210	440	0
REFRIGERATION, kWe	0	1,233*	0
COOLING WATER PUMP, kWe	160	55	165
SUBTOTAL, kWe	6,350	6,358	9,161
TOTAL, kWe	6,350	6,358	9,161

* - Peak condition; considerably less during winter months. Calculated annual average is 440 kWe.

None of the options evaluated utilize variable speed or multiple speed compressor drives. The CO_2 pump in Options 1 and 3, however, would be equipped with a variable speed drive to enable efficient attainment of intermediate CO_2 pipeline pressures, between 1,500 psig (103 bar) and 3,000 psig (207 bar). This gives the low pressure compression options (1 through 3) greater flexibility in efficiently attaining a "moving" pipeline pressure, which will likely be the case over the life of the injection wells. Pipeline pressure requirements are expected to change as the volume of stored CO_2 increases over the operating life.

The pump variable speed drives would offer rapid payback over the project life. Using Option 1 as an example (compression to 1,320 psig (91 bar), with pumping to 3,000 psig (207 bar)), the pump power is 1,321 kWe. If the desired injection pressure were 2,500 psig (172 bar), instead of 3,000 psig (207 bar), a pump with a variable speed drive could be turned down to produce CO_2 at 2,500 psig (172 bar). The corresponding pump power would drop to approximately 950 kW. This power savings would correspond to a net present value of $777,000 for ten years of operation, more than adequate to cover the cost of the variable speed drive. The savings would be much larger if the required injection pressure were less.

The auxiliary power analysis confirmed that given a fixed mass of CO_2 with assumed relative purity greater that 99.5%, a competing technology (e.g. amine, etc.) delivering CO_2 for compression at atmospheric pressure would be inherently more energy intensive. Technologies producing CO_2 at approximately 1 atm would require an additional two stages of compression to reach the inlet conditions of the compression system following the CAP. In addition, the determination and validation that it was possible to utilize a variable speed pump to pressurize and transport CO_2 once it was liquefied or in the supercritical state, provided even more opportunity to eliminate stages of compression, optimize overall energy demand and achieve the minimum pressure required to deliver CO_2 to the storage reservoirs.

A summary of cooling water requirements for each of the options is presented in Table 14 below. This cooling water would be supplied from Alstom's process cooling tower. WorleyParsons verified with Alstom that their design could accommodate the needed cooling water temperature. Option 3 has significantly lower cooling water requirements due to its use of refrigeration cooling. Note that Option 5B has zero cooling water requirements.

Table 14: Summary of Cooling Water Requirements

OPTION	1	3	4
COOLING WATER, GPM (m^3/min)	6,800 (25.7)	2,340 (8.9)	7,000 (26.5)

Heat recovery from the compression system was considered for the options evaluated. However, cursory analyses indicated that the CAP and plant processes would benefit little from the heat available from integrally geared machines with inter-stage cooling. Lower injection pressures as experienced on the Mountaineer CCS validation facility also suggested that available heat of compression would be reduced from initial expectations (in the 3000 psig, 207 bar range). Furthermore, the additional capital and maintenance costs for equipment to recoup the available heat (pumps, heat exchangers, piping, etc), would be significant and therefore the team did not focus its efforts in Phase I on recovering the heat of compression. Further discussion of AEP's approach toward systems integration on the project can be found in AEP's CCS Integration Report, on the Global CCS Institute website.

3.5 Cost Evaluation

3.5.1 Equipment Cost

A summary of the equipment costs for the various CO_2 compression options is shown below in Table 21. Process equipment costs were either estimated by WorleyParsons or solicited from equipment vendors. Option 1 is held as the "base" option, with all other option costs represented as +/- percentages from that base.

Reviewing Table 15, Option 1 – compression in an integrally-geared centrifugal machine to an intermediate supercritical condition followed by cooling and pumping to final pipeline pressure (most flexible operating condition), is clearly the most economical solution from an equipment cost perspective. Although Option 3 is penalized from a CAPEX perspective as compared to Option 4, due to the high cost of the refrigeration system, the lower operating costs associated with this option offset a significant portion of the capital as will be seen later in the total evaluated costs.

Table 15: Summary of Equipment Cost

OPTION	1	3	4
EQUIPMENT ITEM	**Integrally-Geared Compressor/ Pump**	**Integrally-Geared Compressor/ Liquefaction/ Pump**	**Integrally-Geared Compressor/ No Pump**
CO_2 KO DRUM	BASE	0%	0%
COMPRESSOR AND MOTOR	BASE	-2.5%	+107.4%
INTER-/AFTER-COOLER	BASE	-35.8%	+27.0%
REFRIGERATION, USD	N/A	+$2.9M	N/A
CO_2 RECEIVER	BASE	+44.7%	N/A
PUMP AND MOTOR	BASE	+12.9%	N/A
PUMP VFD	BASE	+9.0%	N/A
PUMP AFTER-COOLER	BASE	N/A	N/A
TOTAL EQUIPMENT COST	BASE	+47.3%	+25.7%

3.5.2 Total Cost Evaluation

To get a clearer picture and assess the impact of power consumption, heat recovery, refrigeration, etc, operating costs were calculated to provide a total cost evaluation for each of the options. Operating costs were calculated for auxiliary power consumption. The power was levelized at an 85 percent overall capacity factor to provide the average annual power consumption. The average annual refrigeration power for Option 3 was calculated to be 440 kW at average ambient conditions. Power costs were calculated using economic factors specific to Mountaineer Plant, provided by AEP for a 10-year evaluation period. Maintenance costs were not evaluated since they were not considered to be appreciably different between the options.

The total net present value costs for the 10-year evaluation period are summarized in Table 16. These are added to the equipment capital cost for a total evaluated cost for each option.

The results in Table 16 indicate that, over the 10 year evaluation period, Option 1, integrally-geared compression followed by supercritical CO_2 pumping is the least cost option with Option 3, sub-critical compression, cooling and CO_2 liquefaction followed by pumping, being the next least cost option.

Table 16: Total Evaluated Cost Summary

OPTION	**1**	**3**	**4**
	Integrally-Geared Compressor/ Pump	**Integrally-Geared Compressor/ Liquefaction**	**Integrally-Geared Compressor/No Pump**
TOTAL EQUIPMENT COST	BASE	+47.3%	+25.7%
AUXILIARY POWER COST (FIRST YEAR)	BASE	-12.0%	+22.8%
TOTAL OPERATING COST, NET PRESENT VALUE (NPV), OVER 10 YEARS	BASE	-12.0%	+22.8%
TOTAL EVALUATED COST (TOTAL OF EQUIPMENT AND NPV COSTS)	BASE	+6.5%	+23.7%

4. KEY TAKEAWAYS

The CO_2 Compression study produced the following key takeaways:

- All options evaluated are technically feasible
- Based on experience with injection at Mountaineer, pressures below 3000 psig are likely to be sufficient to inject CO_2 into the targeted underground reservoirs, which would result in additional power savings and reduced total evaluated costs for options having the flexibility to produce lower injection pressures. Compression to an intermediate pressure, followed by variable speed pumping to the final injection pressure offers greater flexibility and efficiency over the life of the system as compared to full compression to the maximum expected injection pressure.
- Performance and total evaluated cost for Option 1, compression with an integrally-geared compressor to an intermediate supercritical condition followed by cooling and pumping to final pipeline pressure, and Option 3, subcritical compression, cooling and CO_2 liquefaction followed by pumping to final pipeline pressure, are similar. Detailed engineering and design in Phase II of the project, focusing on these options, is recommended to determine the best option for Mountaineer plant.

5. CONCLUSION

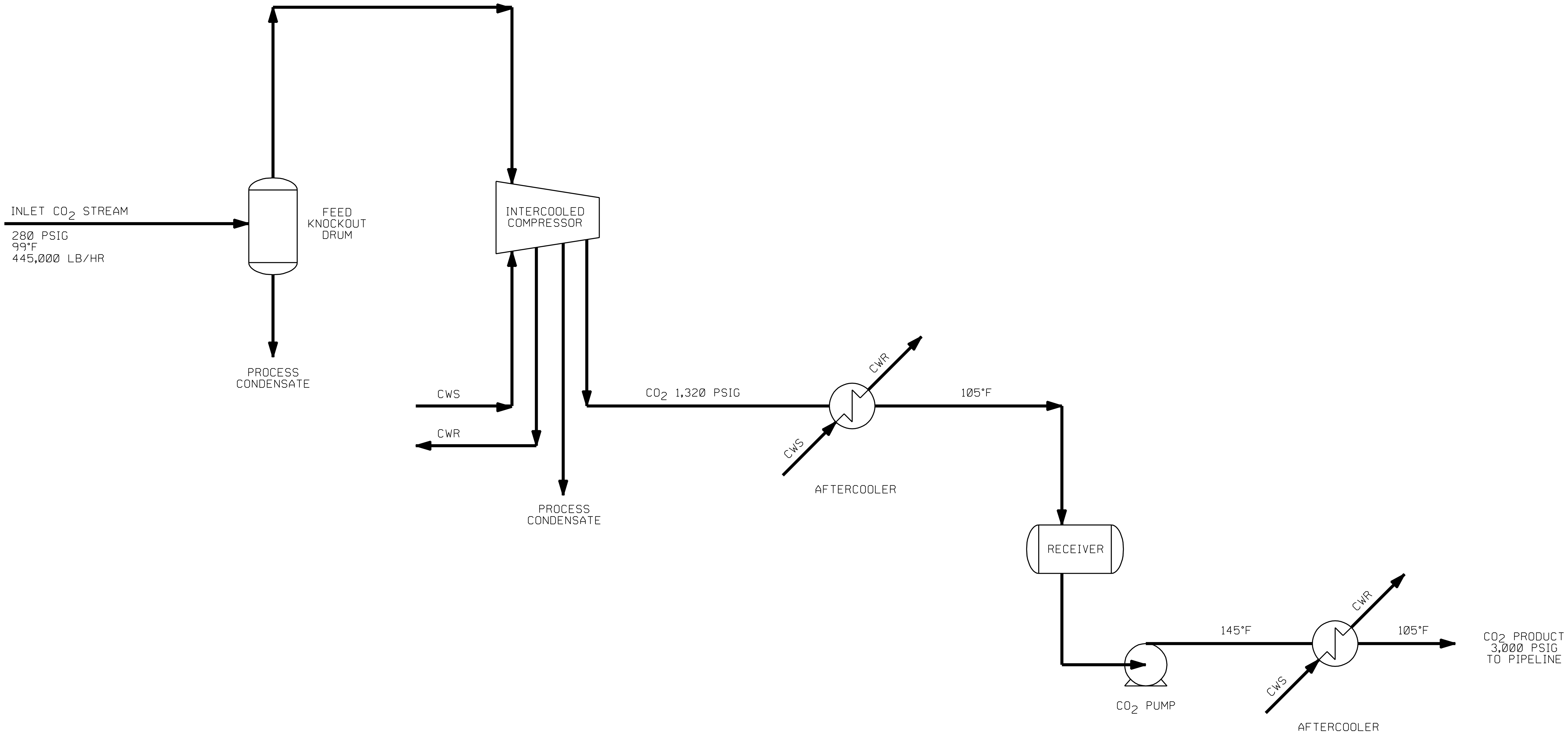
Based on the results of the evaluation and the key takeaways discussed above, AEP determined that integrally-geared centrifugal compression to either a subcritical or supercritical condition (Options 3 and 1, respectively) followed by cooling and pumping to final CO_2 pipeline pressure were both practical and feasible technology options for the MT CCS II installation. The integrally-geared technology is proven, and the CO_2 pump equipped with variable speed drive offers large-range outlet pressure flexibility over the other options; particularly compression to 3,000 psig (207 bar). Estimated performance and total evaluated cost values for these two options are similar. Thus it was determined that further evaluation in Phase II be carried out for Options 1 & 3 in order to determine the optimal solution for Mountaineer Plant.

6. REFERENCES

1. “CO_2 Compression Study Report Summary” Issued by Alstom Carbon Capture GmbH, November 26, 2010 (CONFIDENTIAL).

2. AEPMT-1-LI-1.01.01.01.03-0001 REV. 3 CO_2 Compression Study – Issued by WorleyParsons, July 2011.

APPENDIX A – CONCEPTUAL PROCESS FLOW DIAGRAMS



NOTE:

CWS: COOLING WATER SUPPLY
CWR: COOLING WATER RETURN

AEP MOUNTAINEER CCS II
PROCESS FLOW DIAGRAM
INTERCOOLED COMPRESSOR WITH PUMP
ALTERNATE 1

SCALE NONE

DRAWING NUMBER FS-1.01.01.01.03-001

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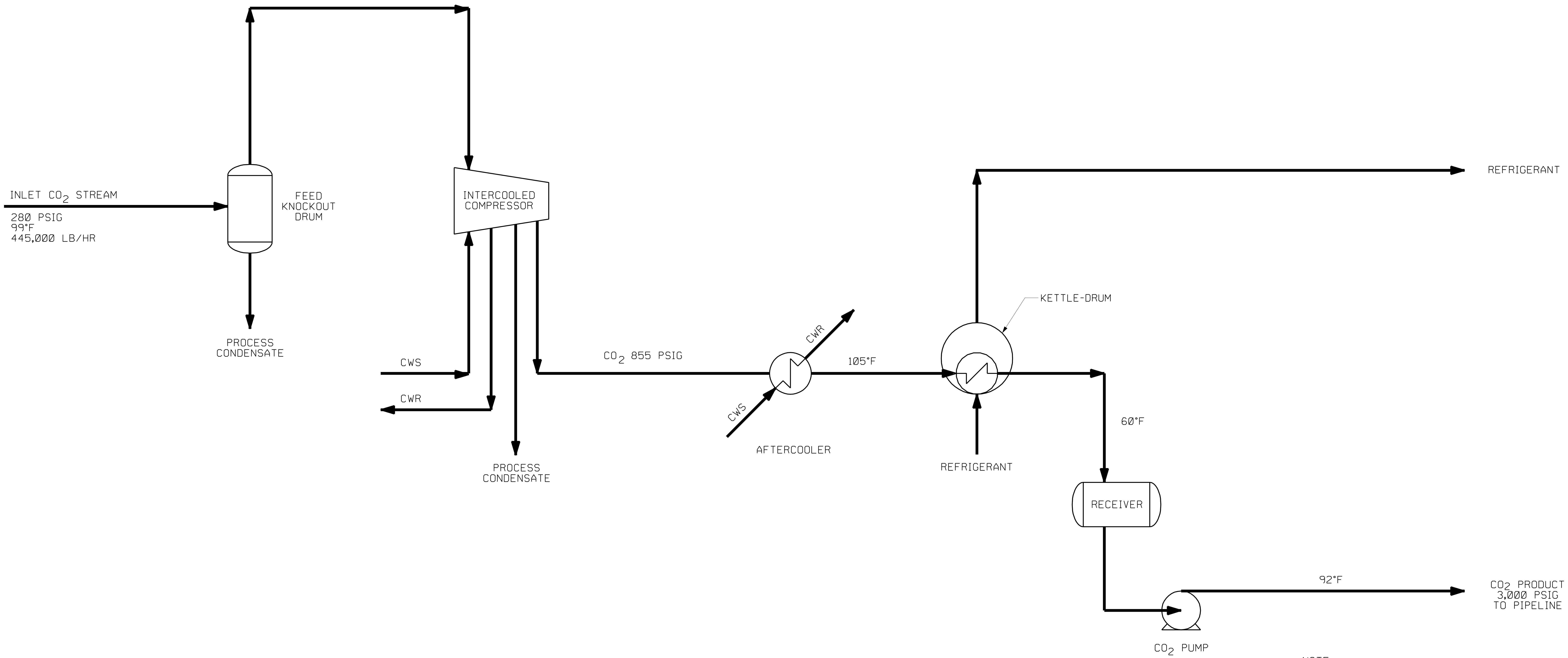

NOTE:

CWS: COOLING WATER SUPPLY
CWR: COOLING WATER RETURN

AEP MOUNTAINEER CCS II
PROCESS FLOW DIAGRAM
INTERCOOLED COMPRESSOR
WITH REFRIGERATION ALTERNATE 3

SCALE	DRAWING NUMBER
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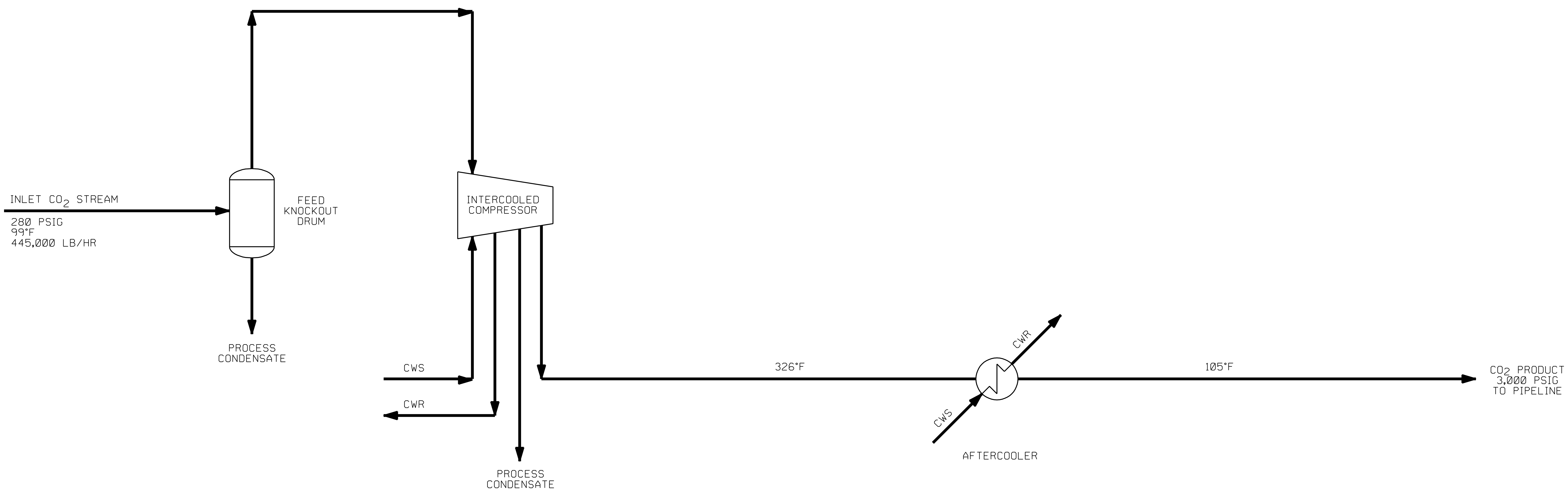

NOTE:

CWS: COOLING WATER SUPPLY
CWR: COOLING WATER RETURN

AEP MOUNTAINEER CCS II
PROCESS FLOW DIAGRAM
INTERCOOLED COMPRESSOR
ALTERNATE 4

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