RED TRAIL ENERGY CO_2 CAPTURE AND SEQUESTRATION PROJECT

CO_2 SURFACE FACILITY DESIGN REPORT

This document has been revised as indicated below and described in the revision record on the following page. Please destroy all previous revisions.

Rev N°	Date	Originator's Name & Initials	Reviewed/Checked By Name & Initials	Description	Pages
0	05/08/2017	B. Piggott (BDP)	R. McKaskle (RWM)	Preliminary	ALL

ISSUED FOR : ☒ Comment ☐ Approval ☐ Design

Table of Contents

1 Executive Summary and Conclusions

The Red Trail Energy (RTE) ethanol facility in Richardton, ND produces ethanol through the fermentation of corn. In addition to ethanol, the fermentation process produces a large quantity of carbon dioxide (CO_2). RTE produces a maximum amount of 587 metric tonnes (11.2 MMSCF) of CO_2 per day in the fermentation process. The CO_2 from the fermentation process is normally vented to the atmosphere after it is scrubbed with water to remove any entrained ethanol and other chemicals. RTE is working with the University of North Dakota's Energy and Environmental Research Center (EERC) to develop a basic CO_2 recovery facility design and injection well design for capturing the CO_2 that is vented to atmosphere. Trimeric contracted with EERC to develop a concept-phase estimate for the surface equipment for the CO_2 recovery facility. This report details the work completed by Trimeric to estimate the size, capital cost, and operating costs for the surface equipment.

Trimeric presented three initial designs for the CO_2 recovery facility; each facility produced CO_2 at different purification levels so that the CO_2 could be used in different ways. The most basic facility produced CO_2 that was suitable for injection, a second design produced CO_2 that was suitable for enhanced oil recovery (EOR) operations, and the final design produced CO_2 that met established specifications for food and beverage grade CO_2. Table 1 below shows the estimated capital and operating costs for each facility design. Block flow diagrams for each facility design are provided in Appendix A.

Table 1. Estimated Total Installed Capital and Power Requirements for CO_2 Recovery Facilities.

Facility Design	Total Installed Capital Cost (Millions)	Power Requirement (kWh/Tonne)
Facility to Inject CO_2 in Sequestration Well	$13.1	111.8
EOR CO_2 Facility	$14.7	152.1
Food/Beverage Grade CO_2 Facility	$15.7	152.5

The costs in Table 1 assume no sparing of major rotating equipment, that the process will be cooled with cooling water from a new cooling tower, and that the CO_2, if injected into the ground, would be injected on RTE's existing property (pipeline distance would be minimized). These costs are based on scaling of costs for completed projects elsewhere in the United States and from Trimeric internal resources.

The project team decided to move forward with a design and cost estimate for a CO_2 recovery facility that produced CO_2 intended for injection only. As a result, the facility is only designed to compress and dehydrate the source CO_2. Water is the only component that will be removed from the source CO_2. The project team also decided to install spare equipment for the major rotating equipment, which has a large impact on the overall facility cost. The decision to spare major rotating equipment did not impact the facility design chosen for this project, but the total installed cost is estimated to be much higher than what is shown in Table 1.

The facility will compress the CO_2 with two different compression technologies. Primary compression will occur in a multistage centrifugal blower located next to the existing fermentation tanks at the RTE facility. This equipment will compress the CO_2 from the PK-3801 CO_2 Scrubber from near atmospheric pressure up to a nominal pressure of 17 psig.

The compressed CO_2 is cooled and condensed water is separated from the gas stream before it flows to a four stage reciprocating compressor. Between each stage of compression the gas stream is cooled and any condensed liquid water is separated from the gas stream. After the 3rd stage of compression, the gas stream flows through a tower where it is contacted with triethylene glycol (TEG) and nearly all of the remaining water vapor in the gas stream is absorbed into the TEG. Rich TEG from the bottom of the tower is regenerated in a small natural gas-fired or electric reboiler that drives water out of the rich TEG as a vapor that is then vented to the atmosphere. Dry CO_2 from the leaves the reciprocating compressor at a pressure of 1,511 psig and travels through a pipeline for a half mile to arrive at the injection wellhead at 1,502 psig. A process flow diagram for this process is provided in Appendix B and a heat and material balance for this process is provided in Appendix C.

Trimeric requested budgetary quotations from vendors for the rotating equipment and the TEG dehydration unit for this project and utilized internal resources to estimate the cost of the cooling tower. Table 2 shows the equipment costs for the compression and dehydration CO_2 recovery facility based on budgetary vendor quotes and Trimeric in-house data as well as the total installed cost for the facility assuming a scaling factor of 2.3 to get from purchased equipment costs to total installed capital costs. The costs shown in Table 2 assume that the blower and reciprocating compressor have installed spares.

Table 2. Estimated Purchased Equipment Costs and Total Installed Capital Costs for CO_2 Recovery Facility.

Equipment Description	Purchased Equipment Cost	Total Installed Cost
Blower B-101 Skid	$1,360,000	$3,128,000
Blower B-102 Skid (Spare)	$1,360,000	$3,128,000
CO_2 Compressor C-201 Skid	$2,680,000	$6,164,000
CO_2 Compressor C-202 Skid (Spare)	$2,680,000	$6,164,000
TEG Dehydration Unit	$625,000	$1,438,000
Cooling Tower	$292,000	$584,000
Total	$8,997,000	$20,606,000

2 Facility Designs Considered

Three different CO_2 recovery facility designs were considered for this project. Each design captured most of the CO_2 but treated the CO_2 to remove varying levels of impurities in order to meet different product CO_2 requirements. A brief description of each facility design follows with some discussion on the reasons for accepting or rejecting the design from consideration. The facility design ultimately chosen for this project is a compression and dehydration facility, which removes only water from the feed stream for CO_2 intended for injection into a subsurface formation for permanent storage.

2.1 Food and Beverage Grade Facility

The first design considered for recovering the CO_2 emitted from the RTE ethanol facility was a food and beverage grade CO_2 plant. This plant design produces the highest value CO_2 in the form of a pressurized and refrigerated liquid that is typically transported from the plant by truck to customers. The CO_2 produced from this plant is suitable for human consumption and as a result, must meet stringent purity requirements that necessitate the installation of additional unit operations to remove trace impurities. A block flow diagram of a typical food grade facility is shown in Appendix A.

In the food grade plant design, CO_2 from the PK-3801 CO_2 Scrubber is compressed by a blower and then in a 2-stage oil-flooded screw compressor from approximately 17 psig to approximately 400 psig. The compressed gas stream is cooled and condensed water is removed from the gas stream before flowing to a series of unit operations designed to remove trace levels of impurities from the CO_2. These unit operations vary depending upon the impurities in the source CO_2 but for an ethanol facility the typical unit operations include:

- Water Wash Column to remove any residual alcohols and aldehydes in the gas stream. The water supplied to this column is usually once-through water to prevent impurities from concentrating in the water.
- Sulfur Guard Beds to remove any trace sulfur compounds from the gas stream.
- Carbon Beds to remove trace large hydrocarbons (C5 and greater) from the gas stream.
- Molecular Sieve Beds to remove essentially all of the water vapor remaining in the gas stream.

Downstream of the Molecular Sieve Beds, the gas stream is condensed to a liquid in a heat exchanger that utilizes a refrigeration unit (typically ammonia, propane, or some other refrigerant) as the medium to liquefy the gas. Liquid CO_2 flows into a distillation column where the remaining inert light gases such as oxygen and nitrogen are stripped out of the liquid and vented to the atmosphere. The purified, liquid CO_2 flows into storage tanks for eventual trucking to customers.

Anticipated total installed capital costs and operating power estimate for the food grade CO_2 recovery plant design are shown in Table 3.

Table 3. Food and Beverage Grade CO_2 Recovery Facility Estimated Total Installed Capital Cost and Power Requirements.

Facility Design	Total Installed Capital Cost (Millions)	Power Requirement (kWh/Tonne)
Food/Beverage Grade CO_2 Facility	\$15.7	152.5

The food grade CO_2 recovery plant design was not selected for this project for the following reasons:

- Uncertain market conditions. The food/beverage grade CO_2 market is highly regional and seasonal. The saleable price for the product CO_2 depends heavily on local demand and the proximity of other surrounding food and beverage grade CO_2 plants. The logistical costs for transporting the liquid CO_2 from the source to customers factors heavily into the anticipated profitability of the facility and no major efforts were undertaken to identify a market for food or beverage grade CO_2 in proximity to the RTE facility.
- High capital costs. The beverage and food grade CO_2 recovery facility has the highest capital cost of the options considered.
- High operating power costs. The compression requirements for the CO_2 are less than other facility designs because the final product is only compressed to approximately 400 psig, but the compression required for the refrigeration unit that liquefies the CO_2 is significant and drives the electrical costs upwards.

2.2 EOR / Pipeline Grade Facility

The second design considered for recovering CO_2 emitted from the RTE facility was an enhanced oil recovery CO_2 plant (EOR plant). The EOR plant produces a middle grade of CO_2 that is suitable for injection into oil producing formations and transportation by common carrier pipelines in the U.S. The CO_2 acts as a solvent in the formation, pressurizing the oil field and allowing for deeper extraction of the residual oil in the formation after water-flood operations. EOR is a widely-practiced method for extracting crude oil from the ground in the United States and is typically delivered to the oil field via pipeline with the CO_2 at dense phase conditions, which is above the critical pressure of 1,070 psia. CO_2 needs to have some impurities removed from it in order to be suitable for injection into oil formations for EOR and common carrier CO_2 pipelines typically impose limits on water content, oxygen, and other components, but these limits are less stringent than for food and beverage grade CO_2. A block flow diagram of a typical EOR grade CO_2 recovery facility is shown in Appendix A.

In the EOR grade plant design, CO_2 from the PK-3801 CO_2 Scrubber is compressed by a blower and then a 2 stage oil-flooded screw compressor from nearly ambient pressure up to approximately 400 psig. The compressed gas stream is cooled and condensed water is removed from the gas stream before flowing to Molecular Sieve Beds to remove essentially all of the remaining water vapor in the gas stream. Downstream of the Molecular Sieve Beds, the gas stream is cooled to the liquefaction point by a heat exchanger that utilizes a refrigeration unit (typically ammonia, propane, or some other refrigerant) as the medium to liquefy the gas. Liquid CO_2 flows into a distillation column where the remaining inert light gases such as oxygen and nitrogen are stripped out of the liquid and vented to the atmosphere. The liquid CO_2 from the bottom of the distillation column is pumped up to delivery pressure and may be slightly heated before entering the EOR pipeline.

Anticipated total installed capital cost and operating power estimates for the EOR grade CO_2 recovery plant design are shown in Table 4.

Table 4. EOR Grade CO_2 Recovery Facility Total Installed Capital Cost and Power Requirement Estimates.

Facility Design	Total Installed Capital Cost (Millions)	Power Requirement (kWh/Tonne)
EOR CO_2 Facility	\$14.7	152.1

The EOR grade CO_2 recovery plant design was not selected for this project for the following reasons:

- Insufficient pipeline infrastructure and low CO_2 product volumes. EOR grade CO_2 is typically transported to the oil field by pipeline in large volumes at high pressures. While North Dakota has significant oil reserves, not many of those reserves are currently at a point where EOR is an attractive option and the existing CO_2 pipeline networks in this area of the country coming into the North Dakota/Montana area such as Denbury's Greencore pipeline travel northwards from Wyoming into the Bell Creek area or head north from the Dakota Gasification Company facility into Canada. As a result, the RTE CO_2 is somewhat isolated from current infrastructure and justifying an additional investment in pipelines would likely require a larger CO_2 source than RTE.
- High capital costs. The EOR grade CO_2 recovery facility has a higher capital cost than the facility that produces CO_2 suitable for injection and produces a product that has less value than the food/beverage grade CO_2.
- High operating power costs. Similar to the food and beverage grade CO_2 recovery facility, the power required for the refrigeration circuit that liquefies the CO_2 in the EOR grade facility is significant and drives the electrical costs upwards.

2.3 Facility for Producing Injection Grade CO_2

The third and final design considered for recovering the CO_2 emitted by the RTE facility was a facility designed to produce CO_2 suitable for injection into an underground storage formation. The CO_2 produced in this process is not suitable for further use beyond injection and other than water, retains most of the impurities present in the source CO_2. This type of facility is what is currently installed at the ethanol plant operated by Archer Daniels Midland in their Decatur, IL complex. A block flow diagram of the facility producing CO_2 suitable for injection can be found in Appendix A.

In this process, CO_2 from the PK-3801 CO_2 Scrubber is compressed by a blower and then further compressed by a four-stage reciprocating compressor to the required injection pressure.

Between stages of the reciprocating compressor, the gas stream is cooled and condensed water is removed from the gas stream. After the 3rd stage of compression, the gas stream flows through a packed tower that contacts the gas with TEG. At this pressure, water content in CO_2 is at a natural minimum which reduces capital and operating costs of the dehydration unit, but solubility of TEG in CO_2 is still low enough for economic operation. TEG losses would be too high in the CO_2 at the outlet of the fourth stage. The TEG absorbs water vapor present in the gas stream and dehydrates the gas to an extent that it is suitable for downstream equipment to be constructed from carbon steel.

Anticipated capital costs and operating power estimate for the CO_2 recovery plant design producing CO_2 for injection are shown in Table 5.

Table 5. Total Installed Capital and Power Requirement Estimates for CO_2 for Injection.

Facility Design	Total Installed Capital Cost (Millions)	Power Requirement (kWh/Tonne)
Facility to Inject CO_2 to Sequestration Well	$13.1	111.8

The CO_2 recovery facility design that produces CO_2 for injection was selected for this project for the following reasons:

1. Low capital costs and operating cost requirements. The facility design has the lowest capital and operating power requirements of the designs considered for this project.
2. This approach has been proven on several other projects.
3. Limited exposure to additional markets. In this design, RTE benefits from the CO_2 injection through incentives tied to the sale of their ethanol in markets that encourage minimizing CO_2 production. There is no need to sell the produced CO_2 itself.
4. Limited infrastructure requirements. The CO_2 injection well will likely be located on RTE's existing property, which will minimize the distance for a pipeline and limit the costs required to route a pipeline through private or public land that RTE does not control. Similarly, there will be no costs associated with trucking liquid CO_2 product off

site for this design. The CO_2 will be captured, processed, measured, and disposed of on RTE's property limits.

3 Facility Design Requirements

The capture facility will receive CO_2 that is currently vented to the atmosphere from the PK-3801 CO_2 Scrubber. This is the only tie-point to the existing RTE facility's process stream. Further details regarding the utilities required and the ambient conditions for the CO_2 recovery facility can be found in the Process Design Basis, issued on March 9, 2017.

3.1 Inlet CO_2 Conditions

The inlet composition for the feed stream to the CO_2 recovery facility is shown in Table 6.

Table 6. Inlet Composition for Feed Stream to CO_2 Recovery Facility.

Species	Mole Percent (Dry Basis)
Carbon Dioxide	99.9865
Oxygen	0.0135
Nitrogen	0

The compositions shown in Table 6 are based upon earlier stack sampling analyses completed by RTE and by efforts to characterize the feed stream during this project. This composition is on a dry basis, but the stream is saturated with water vapor. This stream is not considered fully characterized at this point and further work would be necessary to identify all species present in the inlet gas stream if this project moves forward. However, this information is adequate for the current stage of the project.

The conditions and flow rate for the inlet feed stream to the CO_2 recovery facility are shown in Table 7.

Table 7. Inlet Conditions for CO_2 Recovery Facility

Parameter	Min	Max	Normal	Units
Flow Rate	294	587	495	MTD
Flow Rate	5.6	11.2	9.4	MMSCFD
Pressure	3	24	10	in. H_2O
Temperature	37	80	43	°F
PK-3801 Scrubber DP			5.84	in. H_2O

The inlet flow rate, temperature, and Scrubber differential pressure are based upon historical operating data from the RTE facility. The minimum flow rate is the assumed turndown of the facility (approximately 50%), which is based upon the ability to deactivate the reciprocating compressor’s head ends and reduce the energy consumption of the compressor. The minimum and maximum pressures are based on the set points of the PV/RV valves on the RTE fermenter tanks.

3.2 Product CO_2 Specifications

The specifications for the CO_2 produced by the facility will depend upon the use of the CO_2. For this project, the CO_2 for injection has minimal purity requirements and as a result, the only component removed from the inlet gas stream is water. Table 8 shows the CO_2 purity specification at the discharge of the CO_2 recovery facility.

Table 8. CO_2 Purity Specifications at the CO_2 Recovery Facility Discharge.

Component	Purity Specification
Water	Typical Operation 7-10 lb/MMSCF (147-211 ppmv) Alarm at 15 lb/MMSCF (316 ppmv) Shut Down at 30 lb/MMSCF (633 ppmv)

The conditions and flow rate for the product from the CO_2 recovery facility are shown in Table 9.

Table 9. CO_2 Recovery Facility Delivery Requirements During Normal Operation.

Delivery Parameter	Project Design Requirement
Maximum Flow Rate[1]	Maximum total flow at plant inlet 587 MTD (11.2 MMSCFD)
Minimum Flow Rate[1,2]	Minimum total flow rate at plant inlet 294 MTD (5.6 MMSCFD)
Normal Pressure at Injection Wellhead	1,500 psig (maximum) at normal delivery temperature
Maximum Temperature at Inlet to Pipeline	100 °F (maximum) Assuming cooling water available for process cooling
Minimum Temperature at Injection Wellhead	No minimum temperature specification and cannot be controlled without additional unit operations.

1. *Maximum and minimum flow rates based on the total inlet stream containing CO_2, water, and any trace contaminants.*
2. *Minimum flow rate assumes reciprocating compressor head end deactivation. Lower rates may be possible but could result in recycle and/or local venting with higher than normal injection electricity costs on a kWh/tonne basis.*

4 Design of Chosen Facility

The CO_2 recovery facility that produces CO_2 for injection is a straight-forward design that has been implemented successfully in several different locations in the United States. The main equipment for the facility includes a multistage centrifugal blower, a four-stage reciprocating compressor, and a dehydration unit. This equipment configuration yields a facility that is easy to operate, easy to start up and shut down, and has a low operating cost relative to the other facility designs considered for this project.

Trimeric completed an early phase process simulation of this facility in VMGSim, utilizing the APR for Natural Gas equation of state, which has been shown to accurately predict CO_2 behavior above and below the critical point. A process flow diagram of this simulation is shown in Appendix B and the accompanying heat and material balance for this simulation can be found in Appendix C.

4.1 Major Equipment Design

This section details some of the high level design considerations for the major equipment in the CO_2 recovery facility that produces CO_2 suitable for injection. Trimeric obtained budgetary quotes from some vendors as part of this initial design effort in order to bolster the confidence in the overall cost estimate for the CO_2 recovery facility.

4.1.1 Blower, B-101

The Blower B-101 is a multistage centrifugal blower that compresses CO_2 from the PK-3801 CO_2 Scrubber from near-ambient pressure up to approximately 17 psig. The blower is a skid-mounted piece of rotating equipment that has an inlet separator, aftercooler, and discharge separator associated with it. The inlet separator operates at or near ambient pressure so disposing of liquid that collects in the bottom of the separator requires a small pump to generate enough head to drain the vessel. The gas stream heats up as it is compressed by the blower and the aftercooler cools the gas stream down by exchanging heat with cooling water. Any water condensed out of the gas stream as it cools is removed in the discharge separator. Table 10 shows some key parameters of the blower and associated equipment.

Table 10. Blower B-101 Operating Details.

Parameter	Value
Blower B-101 Brake Horsepower	642 hp
Blower B-101 Discharge Pressure	17 psig
Blower B-101 Discharge Temperature	220 °F
Blower Aftercooler E-101-01 Cooling Water Required	158 gpm

4.1.2 CO_2 Compressor, C-201

From the Blower skid, the gas stream flows into the CO_2 Compressor, C-201 and its associated equipment. The CO_2 Compressor is a four-stage reciprocating compressor that is a skid-mounted piece of equipment that has associated separators and heat exchangers for each stage of compression. The separators may or may not be mounted on the compressor skid, depending upon their size while the heat exchangers are typically shipped loose. After each stage of compression, the hot discharge gas is cooled in a heat exchanger and any condensed water is removed in a separator before the gas stream is compressed by the next stage. Table 11 shows some key process parameters of the CO_2 Compressor and its associated equipment; the total estimated brake horsepower for the compressor is 2,465 hp.

As shown in Table 11, the CO2 leaving each stage of compression is very hot. It is well above the water dew point, which often allows use of carbon steel from the outlet of the compression stage to the inlet of the cooler. Stainless steel or other corrosion resistant materials are typical on the process side of the cooler up to the inlet of the next stage of compression until the CO_2 goes through the dehydration unit. Proper purging following shutdowns is important for management of corrosion issues. Reciprocating compressor skids require sturdy foundations and adequate supporting of piping and other components in order to avoid vibration and stress issues. A pulsation study and a torsional analysis are often required to properly design and construct these units.

Table 11. CO_2 Compressor C-201 Operating Details.

Parameter	Stage 1	Stage 2	Stage 3	Stage 4
Inlet Pressure (psia)	35.5	88	243	608
Inlet Temperature (°F)	85	85	85	85
Outlet Pressure (psia)	90	245	620	1527
Outlet Temperature (°F)	243	244	237	241
Stage Brake Horsepower (hp)	706	678	586	495
Cooling Water Required (gpm)	179	202	180	452

4.1.3 TEG Dehydration Unit

The dehydration unit included in the design for this project is a triethylene glycol (TEG) dehydration unit that brings the wet gas stream into the bottom of a countercurrent absorber and a stream of lean (low water content) TEG into the top of the absorber. The liquid TEG flows down the absorber and absorbs water vapor from the gas as it flows up through the absorber, thereby drying the gas stream well below its saturation point. The TEG that has absorbed the water from the gas stream (referred to as rich TEG) flows from the bottom of the contactor to a regeneration system where the pressure is reduced and the TEG is heated to about 375 °F to liberate the water from the TEG. Water vapor from the regeneration system is vented to atmosphere. A process flow diagram for a typical TEG dehydration unit is provided in Appendix D. The regeneration equipment is skid-mounted while the contactor and, if necessary, an inlet separator would be shipped loose and mounted on their own foundations. Table 12 shows some key process parameters of the TEG dehydration unit.

Table 12. TEG Dehydration Unit Operating Details.

Parameter	Value
TEG Circulation Rate	1.85 gpm
Required Reboiler Duty	78,000 Btu/hr
Required Reboiler Energy	175 SCFH (Natural Gas for Fired Heater) 50 kW (Electric Heater, Technology Recommended by Vendor)
Outlet Gas Water Content	10 lb/MMSCF

4.1.4 Cooling Tower

The RTE facility has an existing cooling tower for the ethanol process, but after discussion with RTE personnel, it was determined that the existing cooling tower does not have excess water flow or heat capacity to handle the additional cooling requirements of the CO_2 recovery facility. As a result, this project assumes that a new cooling tower and cooling water pumps will be required for the CO_2 recovery facility. The cooling tower details shown below assume that the blower and CO_2 compressor will have installed spares with cooling water available for them. See Section 4.3 for the discussion regarding sparing of major rotating equipment. Table 13 shows some key operating parameters for the cooling tower.

Table 13. Cooling Tower Operating Details.

Parameter	Value
Cooling Water Circulation Rate	2,370 gpm
Cooling Water Make Up Rate	40 gpm
Cooling Water Temperature Rise	13 °F

4.2 Equipment Location

Due to the low operating pressure of the fermenter tanks (typically less than 1 psig), it will be necessary to locate at least a part of the CO_2 recovery facility close to the fermenter tanks and CO_2 Scrubber PK-3801. There is sufficient space at the RTE site directly to the west for the entire CO_2 recovery facility, but RTE is saving this space for additional fermentation tanks if the facility decides to expand in the future. As a result, only the blower skid will be located by the fermentation tanks. The reciprocating compressor skid and the dehydration unit will be located to the east of the heat medium building, in the area between the coal processing building and the existing cooling tower. The new cooling tower may be located next to the existing cooling tower; however a final location for this equipment is not known at this time, nor is it critical at this stage of the project.

The estimated piping distance between the blower skid and the reciprocating compressor skid is 1,000 feet. A new, 16” Sch. 10S pipe will be run through the RTE facility’s existing main east/west pipe rack between the two skids. Additional cooling water lines may be run through this pipe rack as well, or buried underground. The suitability of the existing pipe rack for this new line will be assessed in a later phase of the project.

The estimated piping distance between the CO_2 recovery facility and the injection well is 0.5 miles, or 2,640 feet. A new, 4” Sch. 80 carbon steel pipe will be run from the facility to the injection wellhead to transport the compressed, dehydrated CO_2. This pipe can be installed aboveground or underground, as RTE prefers but Trimeric would recommend insulating the pipeline if it is installed aboveground. CO_2 at 1,500 psig will be very sensitive to ambient temperature changes since the density of the high pressure CO_2 fluid is strongly influenced by the temperature of the fluid. Pressure variations in the well from the surface to the point of injection could otherwise result from CO_2 density changes in an uninsulated above-ground pipeline and these pressure variations may be detrimental to the long-term stability of well casing cement.

Trimeric recommends that the CO_2 recovery facility be installed indoors in a building that can maintain a temperature of at least 60 °F in the winter months. Any equipment installed outdoors should be insulated and heat-traced. The formation of hydrates in the process or even liquid CO_2 is a possibility at cold ambient temperatures, and formation of these compounds or liquids can lead to plugging or even catastrophic equipment damage.

4.3 Sparing of Major Equipment

RTE has requested that the CO_2 recovery facility be designed for less than 10 days of downtime per year. This corresponds to an equipment uptime of 97% and this will be difficult to achieve, particularly for the reciprocating compressor, C-201. Planned maintenance for the compressor exceeds seven days of downtime annually and additional unplanned shutdowns and maintenance requirements make it unlikely that the compressor could reach that level of reliability year after year of operation. The B-101 Blower may also have difficulty achieving this level of reliability if a major component (like the impeller or the electric motor) suffers a catastrophic failure. As a result, Trimeric recommends installing spare equipment for the B-101 Blower and C-201 CO_2 Compressor. Other small pieces of rotating equipment like cooling tower pumps, TEG pumps, and water disposal pumps should be spared as well but this will be a minimal cost.

4.4 Options

There are several options that could be considered if the project moves into the next phase of development. In previous projects, Trimeric has found that the equipment configuration presented above results in a reliable and cost-efficient facility but there are other options to consider if the equipment price increases beyond that anticipated by RTE or if some other site-specific factor dictates that the project make an alternate decision. These options include:

1. Alternative process cooling technology. If make up water is limited or unavailable, it is feasible to change the heat exchangers from water-cooled shell and tube exchangers to air-cooled exchangers. In general, air cooled exchangers require more surface area for heat transfer and more space in the facility than shell and tube heat exchangers and since the tubes for the exchangers and at least some of the interconnecting piping need to be constructed of stainless steel, it is typically more economical to minimize the size of the exchangers. Another option to consider would be to install wet surface air coolers, which can realize better heat transfer than air cooled exchangers alone. Wet surface air coolers can reduce water circulation rates relative to shell and tube heat exchangers and can sometimes operate with lower quality water than in a typical cooling tower.
2. Alternative dehydration unit technology. TEG dehydration units are used in a multitude of applications and have been used with success by Trimeric in previous CO_2 recovery facilities. An emerging alternative to TEG dehydration in some applications similar to the proposed RTE CO_2 recovery facility is a DexPro™ unit, which recycles some of the CO_2 around one or more of the stages of compression to take advantage of the Joule-Thomson effect to cool the recycled CO_2 to a relatively cold temperature and sub cool the main CO_2 gas stream to condense additional water from the gas stream in order to meet a target moisture specification. There are limits to how far the DexPro unit can dehydrate the gas stream, but the DexPro technology may be more cost-competitive than TEG dehydration. Trimeric is aware of at least one commercial application of DexPro technology.
3. Alternative compression technology to increase rotating equipment reliability. Sparing of the major rotating equipment is a major cost in this project. A different compression technology, such as a centrifugal compressor, may have higher reliability than the reciprocating compressor and avoid the need for an installed spare compressor. The flow rate of CO_2 for this project is somewhat smaller than what would usually dictate the

selection of a centrifugal compressor, but the large installed cost of the spare reciprocating compressor may make a centrifugal compressor an option if the project moves forward. On a single machine basis, it is unlikely that the centrifugal compressor would be less expensive than a reciprocating compressor and the centrifugal compressor would likely not be able to turn down as far as a reciprocating compressor.

4. Limit blower installed spare cost. This project's cost estimate includes a full installed spare blower skid for the B-101 Blower, including the associated separators and aftercooler. To limit capital costs, it may be feasible to spare only the blower and blower motor and store them in a local warehouse for quick installation should the operating blower or blower motor have a problem that requires significant maintenance. Assuming that a relatively small crane is either on-site or could be brought to site quickly, it would likely only take 1-2 days to replace the blower and/or blower motor.

4.5 Estimated Facility Costs

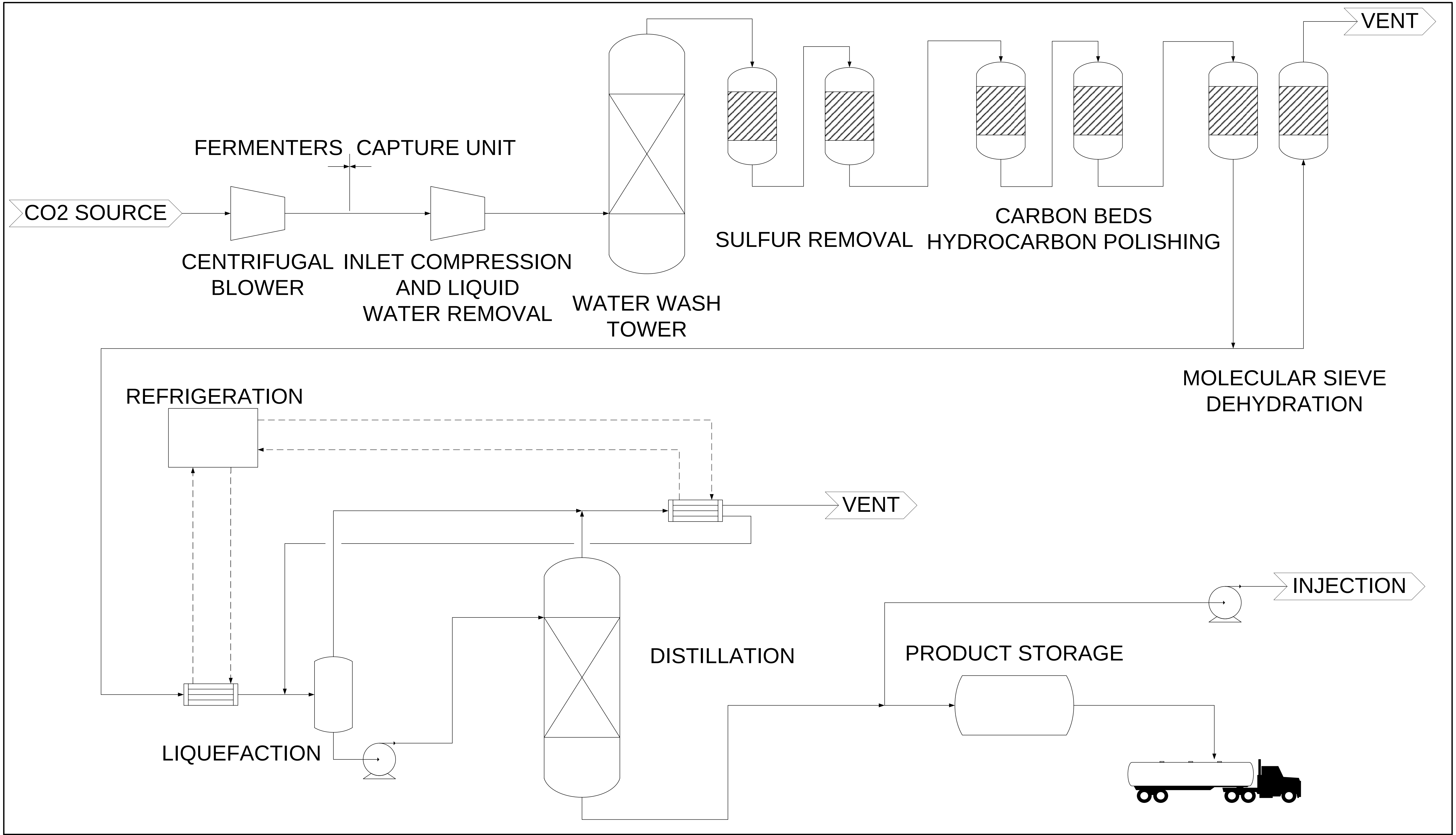
The total installed cost of the CO_2 recovery facility, including spares of the major rotating equipment, is estimated to be $20.6 million +/- 30%. The cost range of +/- 30% incorporates any contingencies and as a result the $20.6 million is a total installed cost for the equipment only. Most of the equipment for the facility would be constructed off-site on skids and then the completed units would be shipped to the site. Table 14 shows the cost breakdown for the facility. The installed cost assumes that the cost installation factor for the skidded equipment would be 2.3, except for the cooling tower, which would be mostly constructed at site and has an installed cost factor of 2.

Table 14. Estimated Purchased Equipment and Total Installed Costs for CO_2 Recovery Facility.

Equipment Description	Purchased Equipment Cost	Total Installed Cost
Blower B-101 Skid	$1,360,000	$3,128,000
Blower B-102 Skid (Spare)	$1,360,000	$3,128,000
CO_2 Compressor C-201 Skid	$2,680,000	$6,164,000
CO_2 Compressor C-202 Skid (Spare)	$2,680,000	$6,164,000
TEG Dehydration Unit	$625,000	$1,438,000
Cooling Tower	$292,000	$584,000
Total	$8,997,000	$20,606,000

APPENDIX A

BLOCK FLOW DIAGRAMS OF CO_2 RECOVERY FACILITIES



REVISIONS						
REV.	DATE	DESCRIPTION	BY	CHECKED	APPROVED	APPROVED
0	12/01/2016	Preliminary Process Flow Sketch for Review	BDP			

FILENAME
EERC_PLANT OPTION
SKETCHES_120116_BIGGIFIED.VSD

DATE
12/01/16

DRAWN BY
BRAD PIGGOTT

TRIMERIC CORPORATION
P.O. Box 826
Buda, Texas 78610

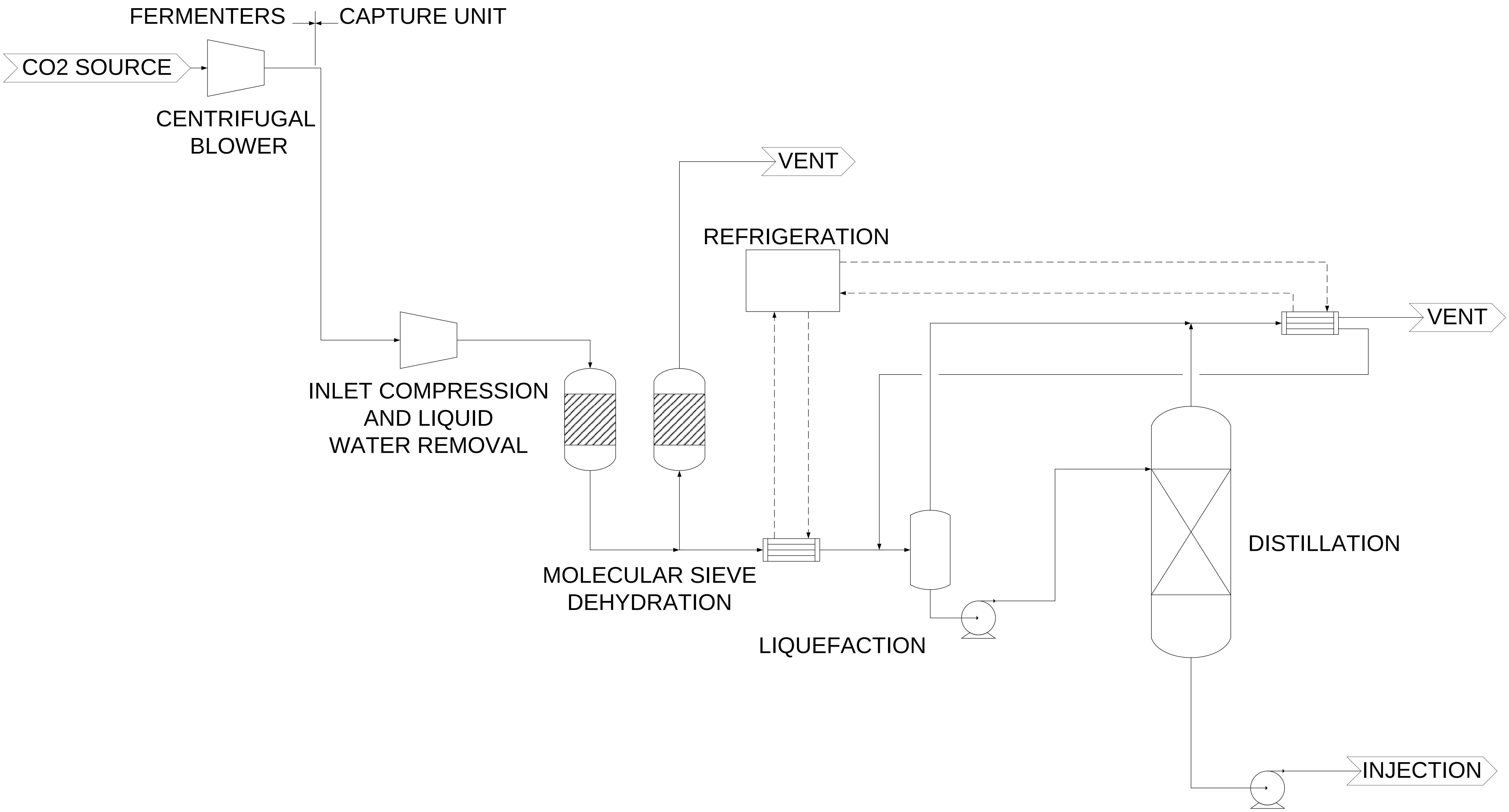
CONCEPTUAL FOOD/BEVERAGE GRADE CO2 PLANT SCHEMATIC

CLIENT/SITE
EERC – RTE FACILITY

JOB NUMBER
50168.01

DRAWING NUMBER
DWG-001

SCALE
NONE



REVISIONS

REV.	DATE	DESCRIPTION	BY	CHECKED	APPROVED	APPROVED
0	12/01/2016	Preliminary Process Flow Sketch for Review	BDP			

FILENAME EERC_PLANT OPTION SKETCHES_120116_BIGGIFIED.VSD

DATE 12/01/16

DRAWN BY BRAD PIGGOTT

TRIMERIC CORPORATION
P.O. Box 826
Buda, Texas 78610

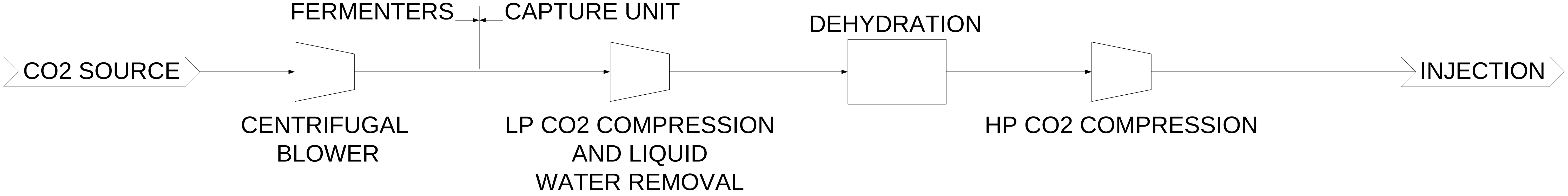
CONCEPTUAL PIPELINE GRADE CO2 PLANT SCHEMATIC

CLIENT/SITE EERC – RTE FACILITY

JOB NUMBER 50168.01

DRAWING NUMBER DWG-002

SCALE NONE



REVISIONS

REV.	DATE	DESCRIPTION	BY	CHECKED	APPROVED	APPROVED
0	12/01/2016	Preliminary Process Flow Sketch for Review	BDP			

FILENAME EERC_PLANT OPTION SKETCHES_120116_BIGGIFIED.VSD	DATE 12/01/16		DRAWN BY BRAD PIGGOTT

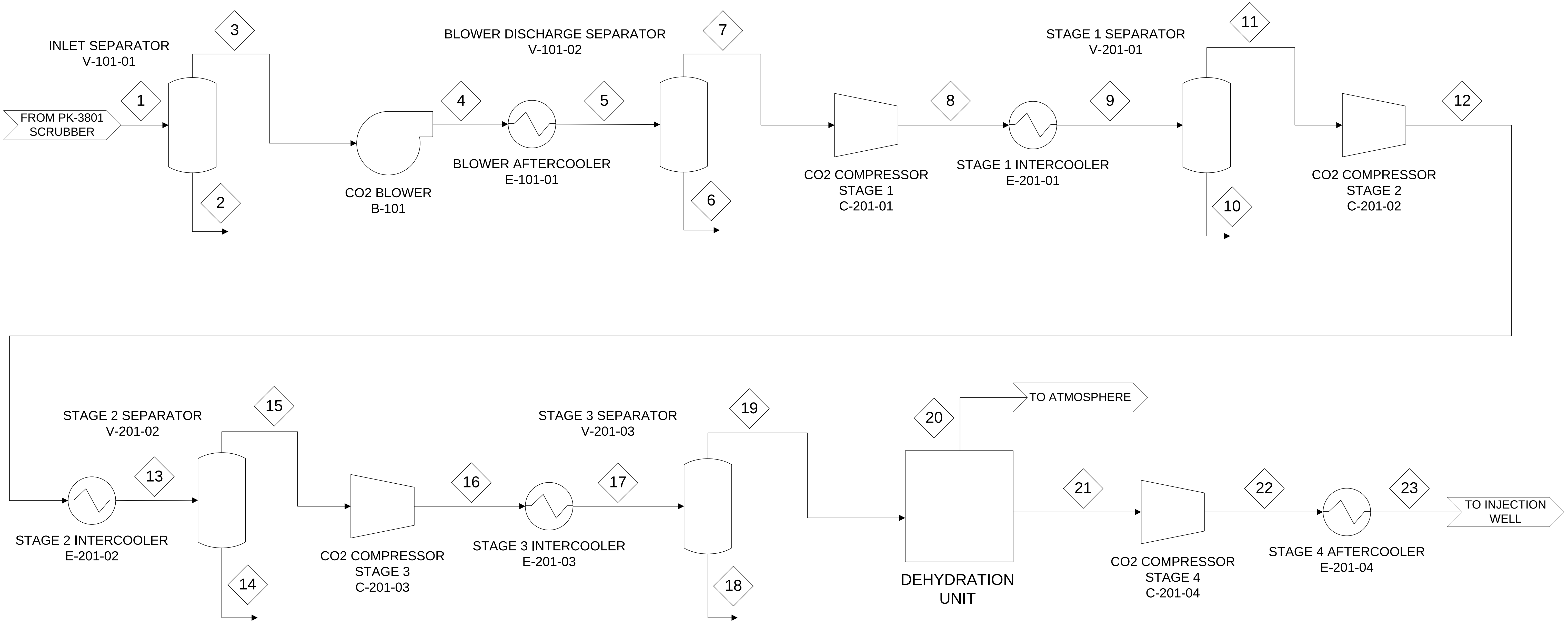
TRIMERIC CORPORATION
P.O. Box 826
Buda, Texas 78610

CONCEPTUAL INJECTION GRADE CO2 PLANT SCHEMATIC

CLIENT/SITE EERC – RTE FACILITY	JOB NUMBER 50168.01
DRAWING NUMBER DWG-003	SCALE NONE

APPENDIX B

PROCESS FLOW DIAGRAM FOR CO_2 RECOVERY FACILITY



REVISIONS

REV.	DATE	DESCRIPTION	BY	CHECKED	APPROVED	APPROVED
0	03/21/2017	For Review	AEV	BDP		

FILENAME
EERC_COMPRESSION TRAIN
PFD_032017.VSD

DATE
03/14/17

DRAWN BY
Austyn Vance

TRIMERIC CORPORATION
P.O. Box 826
Buda, Texas 78610

RTE CAPTURE FACILITY
COMPRESSION TRAIN
PROCESS FLOW DIAGRAM

CLIENT/SITE
EERC / RTE Facility Richardton, ND

JOB NUMBER
50168.01

DRAWING NUMBER
DWG-001

SCALE
NONE

APPENDIX C

HEAT AND MATERIAL BALANCE FOR CO_2 RECOVERY FACILITY

Name	**1**		**2**		**3**		**4**		**5**		**6**	
Description	CO_2 from PK-3801 Scrubber		Liquid from Blower Inlet Separator		CO_2 Blower Feed		CO_2 Blower Discharge		CO_2 Blower Aftrcooler Outlet		Liquid from Blower Discharge Separator	
VapFrac	1.00		0.00		1.00		1.00		0.98413		0.00	
T [F]	80.0		80.0		80.0		220.2		85.0		85.0	
P [psia]	13.80		13.80		13.80		**30.80**		28.80		28.80	
MoleFlow/Composition	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**
WATER	0.03607	45.85	0.99958	0.00	0.03607	45.85	0.03607	45.85	0.03607	45.85	0.99917	20.15
CARBON DIOXIDE	0.9638	1225.09	0.00042	0.00	0.9638	1225.09	0.9638	1225.09	0.9638	1225.09	0.00083	0.02
OXYGEN	0.00013	0.17	0.00	0.00	0.00013	0.17	0.00013	0.17	0.00013	0.17	0.00	0.00
Total	1.00	1271.11	1.00	0.00	1.00	1271.11	1.00	1271.11	1.00	1271.11	1.00	20.17
Mass Flow [lb/h]	54747		0		54747		54747		54747		364	
Metric Tonnes per day [MTD]	596		0		596		596		596		4	
Volume Flow [gal(US)/min]	66152		0		66152		37324		31314		1	
Std Liq Volume Flow [gal(US)/min]	133.631		0.000		133.631		133.631		133.631		0.728	
Std Gas Volume Flow [SCFD]	1.1577E+7		2.0079E-36		1.1577E+7		1.1577E+7		1.1577E+7		1.8372E+5	
Energy [Btu/h]	4.991E+6		-3.257E-36		4.991E+6		6.624E+6		4.642E+6		-2.960E+5	
H [Btu/lbmol]	3926.6		-14771.9		3926.6		5211.0		3651.9		-14675.6	
S [Btu/lbmol-F]	35.614		17.003		35.614		36.141		33.670		17.172	
MW	43.07		18.03		43.07		43.07		43.07		18.04	
Mass Density [lb/ft3]	0.1032		62.1763		0.1032		0.1829		0.2180		62.1356	
Cp [Btu/lbmol-F]	8.933		18.172		8.933		9.631		9.171		18.184	
Thermal Conductivity [Btu/h-ft-F]	0.0097		0.3521		0.0097		0.0137		0.0122		0.3541	
Viscosity [cP]	1.4948E-2		8.5812E-1		1.4948E-2		1.8238E-2		1.6900E-2		8.0836E-1	
Molar Volume [ft3/lbmol]	417.428		0.290		417.428		235.521		197.592		0.290	
Z Factor	0.9947		0.0008		0.9947		0.9944		0.9738		0.0017	

Name	**7**		**8**		**9**		**10**		**11**		**12**	
Description	CO_2 Compressor Stage 1 Feed		CO_2 Compressor Stage 1 Discharge		CO_2 Compressor Stage 1 Intercooler Outlet		Liquid from Stage 1 Separator		CO_2 Compressor Stage 2 Feed		CO_2 Compressor Stage 2 Discharge	
VapFrac	1.00		1.00		0.98778		0.00		1.00		1.00	
T [F]	84.9		249.2		85.0		85.0		85.0		277.9	
P [psia]	28.20753		**74.00**		72.00		72.00		72.00		**245.00**	
MoleFlow/Composition	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**
WATER	0.02054	25.70	0.02054	25.70	0.02054	25.70	0.99791	15.26	0.00845	10.44	0.00845	10.44
CARBON DIOXIDE	0.97933	1225.08	0.97933	1225.08	0.97933	1225.08	0.00209	0.03	0.99142	1225.04	0.99142	1225.04
OXYGEN	0.00013	0.17	0.00013	0.17	0.00013	0.17	0.00	0.00	0.00013	0.17	0.00013	0.17
Total	1.00	1250.94	1.00	1250.94	1.00	1250.94	1.00	15.29	1.00	1235.65	1.00	1235.65
Mass Flow [lb/h]	54383		54383		54383		276		54107		54107	
Metric Tonnes per day [MTD]	592		592		592		3		589		589	
Volume Flow [gal(US)/min]	31972		15844		12171		1		12171		4812	
Std Liq Volume Flow [gal(US)/min]	132.904		132.904		132.904		0.553		132.351		132.351	
Std Gas Volume Flow [SCFD]	1.1393E+7		1.1393E+7		1.1393E+7		1.3924E+5		1.1254E+7		1.1254E+7	
Energy [Btu/h]	4.938E+6		6.825E+6		4.583E+6		-2.241E+5		4.807E+6		6.938E+6	
H [Btu/lbmol]	3947.4		5455.9		3663.5		-14659.0		3890.2		5614.8	
S [Btu/lbmol-F]	33.977		34.499		31.639		17.174		31.818		32.163	
MW	43.47		43.47		43.47		18.07		43.79		43.79	
Mass Density [lb/ft3]	0.2121		0.4279		0.5571		62.1812		0.5543		1.4018	
Cp [Btu/lbmol-F]	9.023		9.868		9.311		18.227		9.201		10.332	
Thermal Conductivity [Btu/h-ft-F]	0.0099		0.0146		0.0118		0.3534		0.0101		0.0160	
Viscosity [cP]	1.5189E-2		1.9068E-2		1.6663E-2		8.1061E-1		1.5350E-2		2.0040E-2	
Molar Volume [ft3/lbmol]	205.001		101.592		78.039		0.291		79.001		31.237	
Z Factor	0.9896		0.9886		0.9617		0.0042		0.9736		0.9681	

Name	**13**		**14**		**15**		**16**		**17**		**18**		**19**	
Description	CO_2 Compressor Stage 2 Intercooler Outlet		Liquid from Stage 2 Separator		CO_2 Compressor Stage 3 Feed		CO_2 Compressor Stg 3 Discharge		CO_2 Compressor Stage 3 Intercooler Outlet		Liquid from Stage 3 Separator		Dehydration Unit Feed	
VapFrac	0.99431		0.00		1.00		1.00		0.99865		0.00		1.00	
T [F]	85.0		85.0		85.0		237.0		85.0		85.0		85.0	
P [psia]	243.00		243.00		243.00		**620.00**		618.00		618.00		618.00	
MoleFlow/Composition	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**
WATER	0.00845	10.44	0.99311	6.99	0.00281	3.45	0.00281	3.45	0.00281	3.45	0.98398	1.63	0.00149	1.82
CARBON DIOXIDE	0.99142	1225.04	0.00689	0.05	0.99706	1225.00	0.99706	1225.00	0.99706	1225.00	0.01602	0.03	0.99838	1224.97
OXYGEN	0.00013	0.17	0.00	0.00	0.00013	0.17	0.00013	0.17	0.00013	0.17	0.00	0.00	0.00013	0.17
Total	1.00	1235.65	1.00	7.04	1.00	1228.61	1.00	1228.61	1.00	1228.61	1.00	1.66	1.00	1226.96
Mass Flow [lb/h]	54107		128		53979		53979		53979		31		53948	
Metric Tonnes per day [MTD]	589		1		588		588		588		0		587	
Volume Flow [gal(US)/min]	3340		0		3340		1659		1063		0		1063	
Std Liq Volume Flow [gal(US)/min]	132.351		0.257		132.094		132.094		132.094		0.062		132.032	
Std Gas Volume Flow [SCFD]	1.1254E+7		6.4081E+4		1.119E+7		1.119E+7		1.119E+7		1.5083E+4		1.1175E+7	
Energy [Btu/h]	4.401E+6		-1.027E+5		4.504E+6		5.995E+6		3.736E+6		-2.397E+4		3.760E+6	
H [Btu/lbmol]	3562.0		-14595.2		3666.0		4879.1		3041.2		-14471.0		3064.9	
S [Btu/lbmol-F]	28.934		17.170		29.001		29.283		26.296		17.146		26.309	
MW	43.79		18.19		43.93		43.93		43.93		18.43		43.97	
Mass Density [lb/ft3]	2.0197		62.3543		2.0151		4.0576		6.3291		62.6820		6.3259	
Cp [Btu/lbmol-F]	10.061		18.389		10.014		11.251		13.764		18.690		13.757	
Thermal Conductivity [Btu/h-ft-F]	0.0118		0.3507		0.0110		0.0165		0.0138		0.3457		0.0136	
Viscosity [cP]	1.6385E-2		8.1908E-1		1.5771E-2		1.9951E-2		1.7399E-2		8.3476E-1		1.7246E-2	
Molar Volume [ft3/lbmol]	21.680		0.292		21.803		10.828		6.942		0.294		6.951	
Z Factor	0.9031		0.0143		0.9082		0.9015		0.7407		0.0364		0.7417	

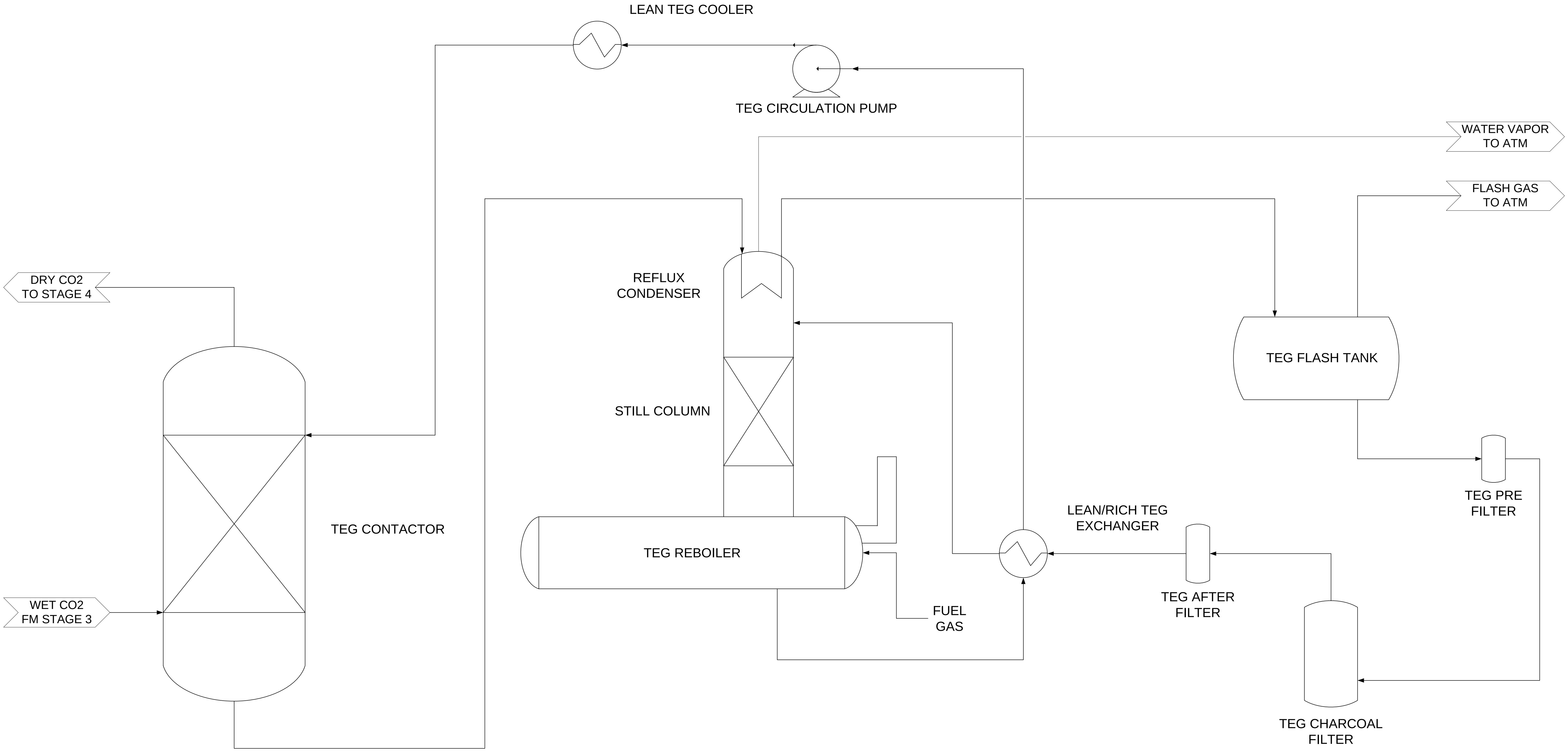
Name	**20**		**21**		**22**		**23**		**24**	
Description	Steam from Dehydration Unit		CO$_2$ Compressor Stage 4 Feed		CO$_2$ Compressor Stage 4 Discharge		Stage 4 Aftercooler Outlet		At Injection	
VapFrac	1.00		1.00		1.00		0.00		0.00	
T [F]	220.0		85.4		240.9		85.0		84.8	
P [psia]	13.80		608.00		**1527.00**		1525.00		1516.09272	
MoleFlow/Composition	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**	**Fraction**	**lbmol/h**
WATER	1.00	1.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE	0.00	0.00	0.99986	1224.97	0.99986	1224.97	0.99986	1224.97	0.99986	1224.97
OXYGEN	0.00	0.00	0.00014	0.17	0.00014	0.17	0.00014	0.17	0.00014	0.17
Total	1.00	1.82	1.00	1225.13	1.00	1225.13	1.00	1225.13	1.00	1225.13
Mass Flow [lb/h]	33		53916		53916		53916		53916	
Metric Tonnes per day [MTD]	0		587		587		587		587	
Volume Flow [gal(US)/min]	0		1090		577		136		136	
Std Liq Volume Flow [gal(US)/min]	0.066		131.967		131.967		131.967		131.967	
Std Gas Volume Flow [SCFD]	1.6597E+4		1.1158E+7		1.1158E+7		1.1158E+7		1.1158E+7	
Energy [Btu/h]	-2.671E+4		3.787E+6		5.047E+6		-6.067E+5		-6.067E+5	
H [Btu/lbmol]	-14655.9		3091.2		4119.8		-495.2		-495.2	
S [Btu/lbmol-F]	17.154		26.343		26.613		18.924		18.927	
MW	18.02		44.01		44.01		44.01		44.01	
Mass Density [lb/ft3]	62.1416		6.1691		11.6569		49.3292		49.2995	
Cp [Btu/lbmol-F]	18.134		13.540		14.864		36.632		36.798	
Thermal Conductivity [Btu/h-ft-F]	0.3549		0.0135		0.0217		0.0528		0.0528	
Viscosity [cP]	8.0644E-1		1.7207E-2		2.3410E-2		7.2548E-2		7.2459E-2	
Molar Volume [ft3/lbmol]	0.290		7.134		3.775		0.892		0.893	
Z Factor	0.0355		0.7480		0.7778		0.2470		0.2459	

APPENDIX D

PROCESS FLOW DIAGRAM FOR TYPICAL TEG DEHYDRATION UNIT

NOTES

1. Example TEG dehydration unit shown. Final configuration to be determined in later project phase.
2. Expected TEG circulation rate less than 5 gpm.
3. Periodic make up TEG required.
4. Estimated fuel gas required 170 SCFH.



REVISIONS

REV.	DATE	DESCRIPTION	BY	CHECKED	APPROVED	APPROVED
0	03/21/2017	For Review	BDP	AEV		

FILENAME
EERC_COMPRESSION TRAIN
PFD_032017.VSD

DATE
03/21/2017

DRAWN BY
Brad Piggott

TRIMERIC CORPORATION
P.O. Box 826
Buda, Texas 78610

RTE CAPTURE FACILITY
DEHYDRATION UNIT EXAMPLE
PROCESS FLOW DIAGRAM

CLIENT/SITE
EERC / RTE Facility Richardton, ND

JOB NUMBER
50168.01

DRAWING NUMBER
DWG-002

SCALE
NONE