

Managing Flammable Species in CO₂ Capture Processes Utilizing Water Scrubbing at Geothermal Power Plants

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ABSTRACT

Non-condensable gas (NCG) from geothermal power plants often contains CO₂, H₂S, H₂, and N₂. Oxygen may also be present in the gas from air ingress due to vacuum conditions in the main condenser of condensing steam turbines. Given the current world-wide emphasis on limiting CO₂ emissions to the atmosphere, there is increasing interest in capturing CO₂ from NCG streams for potential utilization (e.g., in greenhouses, in beverages, for e-fuels, and for enhanced oil recovery), and for sequestration (e.g., subsurface reinjection). In parts of the world where fresh water or seawater is abundant, CO₂ can be captured by contact of the NCG stream with cool water in an absorption column. However, the presence of oxygen in the NCG stream can significantly complicate the capture process. As CO₂ is removed for utilization or sequestration, the remaining species (e.g., most importantly H₂ and O₂) are concentrated in the residual streams. Thus, the process schemes must ensure that dangerous concentrations of fuel (e.g., H₂) and oxidant (e.g., O₂) are avoided. This requirement to limit the concentration of fuel and oxidant in the residual stream can significantly reduce the amount of CO₂ that can safely be recovered. This paper presents a novel concept to use a preabsorber to contact the water and NCG stream upstream of the main absorption column to absorb the bulk of the CO₂ and H₂S into the water phase. The preabsorber concept manages the flammable species at the beginning of the processing scheme, making it easier to make a safe gas product stream (i.e., low in oxygen) for sequestration or utilization later in the processing scheme.

1. Introduction

Geothermal steam contains various non-condensable gas (NCG) species that vary by site depending on the characteristics of the reservoir. NCG often contains CO₂, H₂S, H₂, N₂, CH₄, NH₃, and/or Ar, but other species can also be present at low levels (Energy Sector Management Assistance Program, 2016). In the geothermal power steam turbine condenser, NCG leaves the condenser through ejectors or vacuum pumps. The vacuum conditions in the condenser can lead to air ingress (O₂ and N₂) through seals and glands in the steam turbine or even by flashing air out of the cooling water if the steam turbine condenser is a direct-contact type heat exchanger. The NCG flowing out of the steam turbine condensers may need to be treated for environmental purposes to remove contaminants (e.g., H₂S) down to levels that do not pose a safety or odor risk to nearby public spaces. In addition to environmental compliance, NCG may be further treated to remove CO₂ or purify the CO₂ in the NCG in order to:

- Produce food and beverage grade CO₂ that can be used for freezing foods, carbonating beverages, etc. Human consumption of this CO₂ requires the purity to be very high, which can result in the production of food and beverage grade CO₂ being prohibitively expensive. However, there may be some instances where the cost of procuring a different source of CO₂ is also high and production of food and beverage grade CO₂ from NCG may be economically attractive.
- Produce fuels and other chemicals. Some NCG sources have a substantial amount of H₂ present (or H₂ can be produced via electrolysis or other means) in addition to CO₂ and these can be chemically reacted with one another to form synthetic methane or potentially reacted to form carbon monoxide (CO) to make a syngas mixture that can then be used to produce more complex chemicals.
- Produce CO₂ gas for use in greenhouses. CO₂ can be used in greenhouses to enhance photosynthesis and produce healthier plants at increased growth rates.
- Capture and sequester the CO₂. Governmental bodies like those in the United States and the European Union have incentivized industries that emit CO₂ to capture and store the CO₂ permanently by providing tax credits and low carbon fuel markets to industrial sites that are able to capture and sequester some or all the CO₂ that they produce. In geothermal power areas, sequestration may be an attractive option since it generally does not generate an additional product that is not related to the core business of power production.

Table 1 shows an example of the difference in selected specifications for CO₂ to different destinations. The CO₂ recovery and purification processes must be tailored to the specific application given the variability in NCG composition between different sites and the vast difference in CO₂ purity specifications for potential products.

Table 1: Selected Specifications for CO₂ to Different Destinations.

Requirement	Sequestration	Utilization: Greenhouse	Utilization: E-fuels, Food & Beverage (Finley, Fisher, McKaskle, 2006)
Minimum CO ₂ Content	Not applicable	Not applicable	99.985 volume%
Minimum CO ₂ % captured	None	None	None
Maximum H ₂ S	Not applicable	300 ppmv (~0.3 ppmv in greenhouse)	0.2 ppmv
Water removal	Not applicable (likely dissolve in water)	No free water or ice	-70F (-57C)

There are a number of different processes that might be used for capturing CO₂ from an NCG stream at a geothermal power plant. This might include the use of a chemical absorbent such as alkanolamines, physical solvents like DMPEG, membrane systems, or pressurized water scrubbing. This paper focuses on pressurized water scrubbing for a geothermal power plant in Iceland with an abundance of water that can be used as the solvent for CO₂ removal and where water streams can be easily disposed of by injection.

Table 2 shows a hypothetical NCG composition that may be treated in a pressurized water scrubbing system. This composition does not represent any particular geothermal power site but is used to illustrate the impacts of CO₂ recovery on the flammability of the residue gas.

Table 2: Hypothetical Composition of NCG Flowing to NCG Treatment Systems.

Gas Species in NCG	Mole Fraction of Species in NCG
Carbon Dioxide (CO ₂)	63.91%
Hydrogen (H ₂)	9.91%
Hydrogen Sulfide (H ₂ S)	8.43%
Methane (CH ₄)	0.93%
Ammonia (NH ₃)	0.00%
Nitrogen (N ₂)	13.29%
Oxygen (O ₂)	3.53%

The composition in Table 2 has an elevated concentration of N₂ and O₂, which is indicative of a direct contact condenser and/or mixing of gland steam into the NCG. A geothermal power turbine that uses a surface condenser may have less N₂ and O₂ present in the NCG but may have increased levels of H₂S or NH₃.

In a conventional pressurized water scrubbing system (see Figure 1 in Section 2), NCG from the steam turbine condenser(s) flows to one or more feed gas compressors where the NCG is compressed before flowing into the bottom of a packed tower. As the NCG rises through the packing, it comes into contact with descending water. The water preferentially absorbs polar gases from the NCG (H₂S and CO₂) while absorbing little of the non-polar species (N₂, O₂, H₂, and CH₄). The unabsorbed gases flow out of the top of the packed tower, while the CO₂-and-H₂S-rich water flows out of the bottom of the packed tower. Water for the pressurized water scrubbing may vary

from one site to another but could be supplied from a fresh water source, seawater, or geothermal power loop water (e.g., condensate or brine). The water flowing into the packed tower can be cooled to maximize absorption of CO₂ and H₂S.

In theory most of the CO₂ present in the NCG can be absorbed in a pressurized water scrubber system with a tall enough tower and enough water flowing through the tower. When the CO₂ and H₂S absorb into the water in the packed tower, the concentration of the non-absorbed species in the remaining NCG increases, and it can increase to the point where the remaining NCG becomes an explosive gas mixture.

Note, for the purposes of this discussion, an “explosive gas mixture” is defined as one in which the concentrations of both fuels and oxygen are such that only an ignition source is required for the gas mixture to burn, deflagrate, or explode. In contrast, pure hydrogen is a “flammable” gas, but it is not an “explosive gas mixture,” because there is no oxidant present in pure hydrogen.

Whether or not the remaining NCG is an explosive gas mixture can be determined by calculating the limiting oxygen concentration (LOC), the upper flammability limit (UFL), and the lower flammability limit (LFL) of the gas mixture. The method for calculating these parameters is covered extensively in other papers (Piggott, et al., 2021) and those calculations are not repeated here. If a given gas mixture has an oxygen content above the LOC, then it will be an explosive gas mixture if the fuel in it is also above the LFL and below the UFL.

Table 3 shows the calculated LOC, UFL, and LFL for the NCG stream in Table 2 before entering the pressurized water scrubber system and after 90% of the CO₂ is removed from the stream in the pressurized water scrubber system.

Table 3: LOC, UFL, and LFL for NCG Stream Before and After Carbon Capture.

Stream	LOC, %	UFL, %	LFL, %
NCG Before Pressurized Water Scrubber	8.1	49.3	18.5
NCG After Pressurized Water Scrubber (90% CO ₂ Capture)	6.8	56.4	5.6

Table 3 shows that the pressurized water scrubber NCG treatment processes widen the range of conditions under which the NCG may be an explosive gas mixture by:

- Reducing the fraction of O₂ required for the stream to be flammable from 8.1% down to 6.8%.
- Increasing the UFL from 49.3% to 56.4%.
- Decreasing the LFL from 18.5% to 5.6%.

Table 4 shows the composition of the NCG stream after 90% of the CO₂ is removed in the pressurized water scrubbing system. The preferential absorption of H₂S over CO₂ means that most of the H₂S will be removed from the NCG in the pressurized water scrubbing system as well.

Table 4: NCG Composition After 90% CO₂ Capture (and H₂S Removal) – Based on a Hypothetical Composition of NCG in Table 2.

Gas Species in NCG	Composition of NCG Downstream of CO₂ Removal Unit
Carbon Dioxide (CO ₂)	18.77%
Hydrogen (H ₂)	29.11%
Hydrogen Sulfide (H ₂ S)	0.00%
Methane (CH ₄)	2.72%
Total Fuel + Inerts	50.60%
Ammonia (NH ₃)	0.00%
Nitrogen (N ₂)	39.03%
Oxygen (O₂)	10.37%

In this specific case then, the NCG stream leaving the pressurized water scrubbing system is an explosive gas mixture because the O₂ concentration is above the LOC in Table 3 and the concentration of inerts and fuel is between the LFL and UFL values calculated in Table 3.

The remainder of this paper discusses the design of pressurized water scrubber systems that capture CO₂ from geothermal power processes, the issues and risks that might be encountered when removing CO₂ from NCG, a novel process design to produce a mostly pure CO₂ product from NCG for use, and opportunities for optimization of pressurized water scrubbing systems. This paper was based on a high-level concept design of pressurized water scrubbing for CO₂ recovery from geothermal NCG in Iceland. CO₂ recovery from the NCG at two different sites was considered for a variety of downstream CO₂ uses (sequestration, greenhouse gas, e-fuels / food and beverage).

2. Choice of Capture Technology

The choice of technology for the recovery of CO₂ from NCG streams can take different paths depending upon what fraction of the CO₂ is to be recovered, the composition of the raw NCG, and the intended use, physical form, and purity of the CO₂ product. There is no single technology that can address all situations, and this paper covers technologies that could be applied to a few specific cases. This paper assumes the use of water as the primary solvent for achieving separations; technologies based on this premise may be particularly advantageous in locations where water is plentiful, and acid-gas loaded water can be readily reinjected. Other solvents and other, non-solvent technologies can be used and may be advantageous in other situations.

The intended destination of the recovered CO₂ is a key driver for choosing a particular technology. Some applications consider CO₂ being injected underground (sequestered) only, while others maximize the amount of CO₂ recovered as a liquefied product, and yet others recover CO₂ as a low purity gas. As the fraction of CO₂ being removed from the gas becomes larger, the potential for the residue gas to become an explosive gas mixture becomes greater.

2.1 Conventional Pressurized Water Scrubbing

For cases where carbon capture and sequestration (CCS) is the only goal, conventional pressurized water scrubbing (PWS) may be a reasonable option. In PWS, the NCG is compressed and

contacted with water to absorb the CO₂ into the water. Higher pressure results in more water absorption per volume of water, although the pressure used may be limited by both equipment factors (e.g., cost of compression) and injection limitations (vapor pressure of CO₂ in the water to be injected compared with reservoir pressure and temperature). The preferred compression equipment at many geothermal power plants tends to be liquid ring (water) compressors; these compressors typically have a single unit maximum discharge pressure of around 10 bar, and this pressure is assumed as the pressure at which the PWS is operated. Various contacting devices could be used for absorbing the CO₂ into the water, but the most efficient use of the water is obtained using a conventional counter-current trayed or packed tower; this study assumed the use of packed towers. The solubility of CO₂ in water is higher at lower temperature, so cold water is preferred when it is available.

CO₂ has a higher solubility in water compared to most other components in NCG, thus conditions in the water scrubber are designed to scrub the desired fraction of CO₂ into the water while leaving most of the other components in the residue gas. H₂S has similar, slightly higher, solubility in water compared to CO₂, and will also be scrubbed into the water with the CO₂. Figure 1 shows a process flow diagram of a PWS system applied to scrub CO₂ from geothermal NCG using cold water, with the CO₂-loaded water sent to injection. Table 5 shows the stream data for the system. In this simple process, the NCG is compressed to 10 bara, and contacted with the water in a counter-current packed tower.

A key issue in the design of PWS for CO₂ absorption is flammability of the residue gas. Assuming the presence of both oxygen and flammable species in the feed gas, the fraction of the CO₂ removed from the gas may need to be limited in a PWS system so that the residue gas does not come too close to becoming an explosive gas mixture. In this case, sufficient CO₂ (about 7% of the CO₂ in the feed NCG) is purposefully left such that it inerts the residue gas, keeping the mixture of fuels and inert species greater than 10% above the UFL_{mix}.

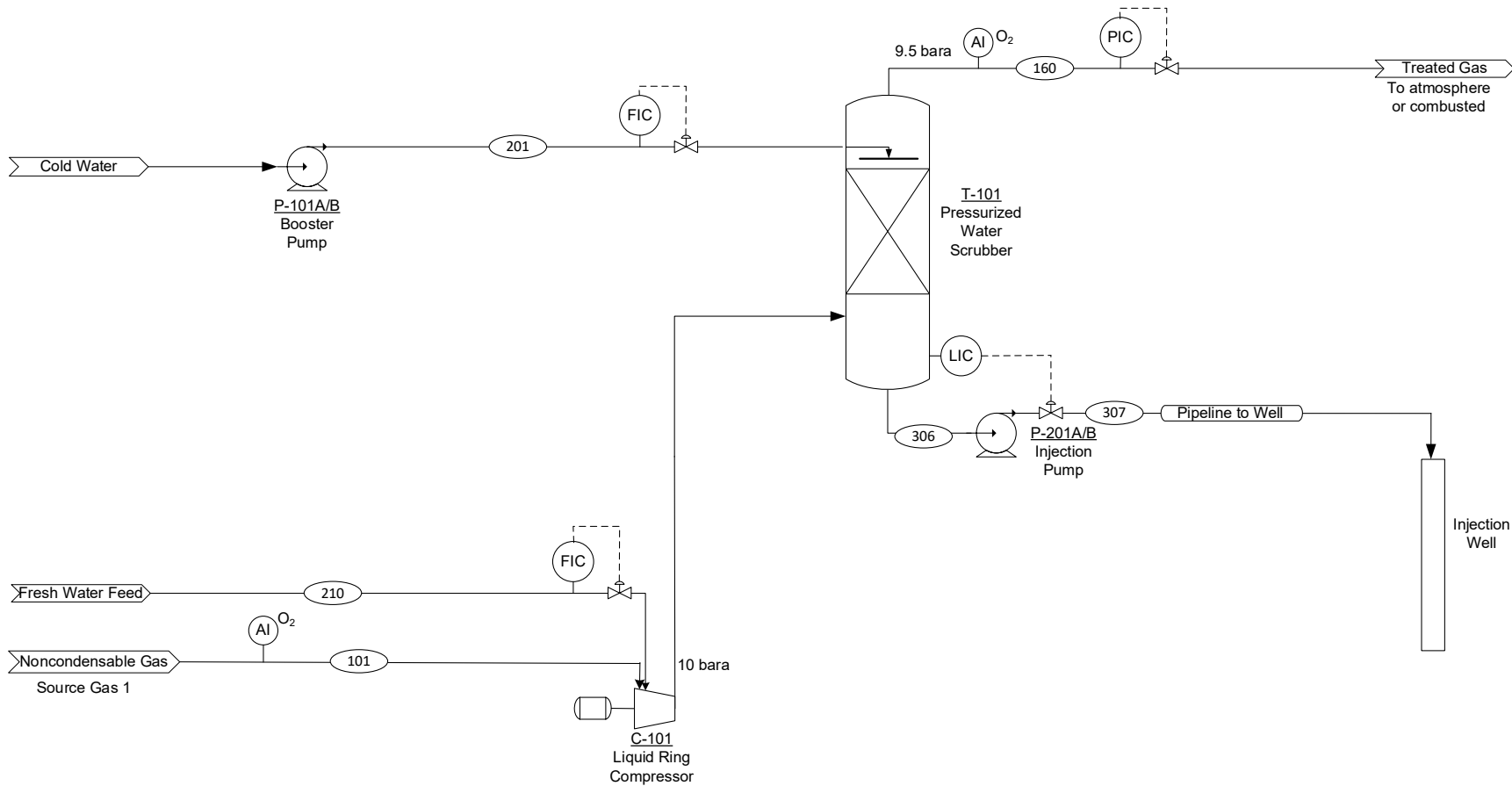


Figure 1: Conventional Pressurized Water Scrubber for Sequestration –Total CO₂ Captured is Limited to Avoid an Explosive Gas Mixture at the Top of the Scrubber.

Table 5: Stream Table for Conventional Pressurized Water Scrubber for Sequestration.

	101	160	201	210	306	307
VapFrac	1	1	0	0	0	0
T [C]	35	9.5	9	8	14	14
P [bar]	1.06	9.5	12	2	9.5	11.4
Mole Flow [kmol/h]	104.3	11.2	10768.6	1665.3	12527.0	12527.0
Mass Flow [kg/s]	1.2	0.1	53.9	8.3	63.3	63.3
MW	40.4	32.5	18.0	18.0	18.2	18.2
Volume Flow [m ³ /h]	2507.0	26.9	194.0	30.0	228.8	228.8
Std Gas Volume Flow [Nm ³ /h]	2338	250	241370	37325	280780	280780
Cp [kJ/kmol-K]	36.9	34.2	76.2	76.2	77.2	77.2
Viscosity [cP]	0.015	0.015	1.342	1.383	1.233	1.233
Mole Fraction [%]						
Carbon Dioxide	79.58	51.39	0	0	0.62	0.62
Hydrogen Sulfide	9.69	0.23	0	0	0.08	0.08
Hydrogen	1.73	15.21	0	0	0	0
Methane	0.03	0.25	0	0	0	0
Nitrogen	2.99	27.4	0	0	0	0
Oxygen	0.56	5.03	0	0	0	0
Argon	0.04	0.34	0	0	0	0
Water	5.39	0.14	100	100	99.3	99.3

2.2 H₂S-Selective Water Scrubbing

For cases where both CO₂ and H₂S are present in the NCG, and it is desired to recover CO₂ as a product, rather than just sequester it, selective water scrubbing can be part of a CO₂ recovery scheme. A selective water scrubber is one that preferentially scrubs H₂S and leaves most of the CO₂ behind. Although H₂S and CO₂ have similar solubility in water, H₂S is slightly more soluble, and this difference can be used to selectively remove H₂S from a CO₂-rich NCG stream. After the H₂S has been removed, CO₂-rich residue gas can conceivably be used directly or further processed as needed (Mamrosh, et al., 2014). The water from the tower would be rich in H₂S, but also contain some CO₂; this water would presumably be reinjected or otherwise treated. Selective water scrubbing uses a packed or trayed tower with a reboiler (or successive flash stages) to enhance the separation of the H₂S and CO₂, maximizing the amount of H₂S (relative to CO₂) removed from the NCG into the water.

The unit can either use a heated reboiler, or it can use a pressure-reduction flash followed by recompression of the flash gas. Multiple flash stages can be used in pressure reduction, with the stages correlated to compressor compression ratio capabilities. See Section 2 in the 2014 GRC paper (Mamrosh, et al., 2014) for detailed description of the selective water scrubber concepts.

In the CO₂ recovery schemes considered here, selective water scrubbing was considered the primary mode of H₂S removal from CO₂, when CO₂ was to be recovered as a product. An example of a recovery scheme using selective water scrubbing is shown in Figure 2 with the associated stream data in Table 6. In this process, water scrubbing is used to achieve two CO₂ goals: 1- sequester the bulk of the CO₂ by absorbing most of it (along with most of the H₂S) into water, and 2- recover a portion of the CO₂ as a gas that is low in H₂S. The CO₂-rich gas product can then be further processed for purification, or may be suited for direct use, such as in a greenhouse. In this case, the fraction of CO₂ that is recovered as the gas-phase product must be high enough such that this gas-phase product is maintained well away from the flammability envelope. Careful control and monitoring of this type of system is essential to avoiding the formation of an explosive gas mixture in the process. The process shown in Figure 2 is based on the use of vapor recompression in the selective scrubber; a reboiler could also be used.

This process has a significant shortcoming, in that the gas-phase product contains nearly all the light gas (H₂, methane, N₂, O₂) species from the NCG. Therefore, this scheme naturally limits the purity of the CO₂ that can be achieved and is also susceptible to the issue of potentially forming an explosive gas mixture. The preabsorber concept covered in the following section is one way of recovering a CO₂ product with higher purity (fewer light gases) and avoiding the formation of an explosive gas mixture.

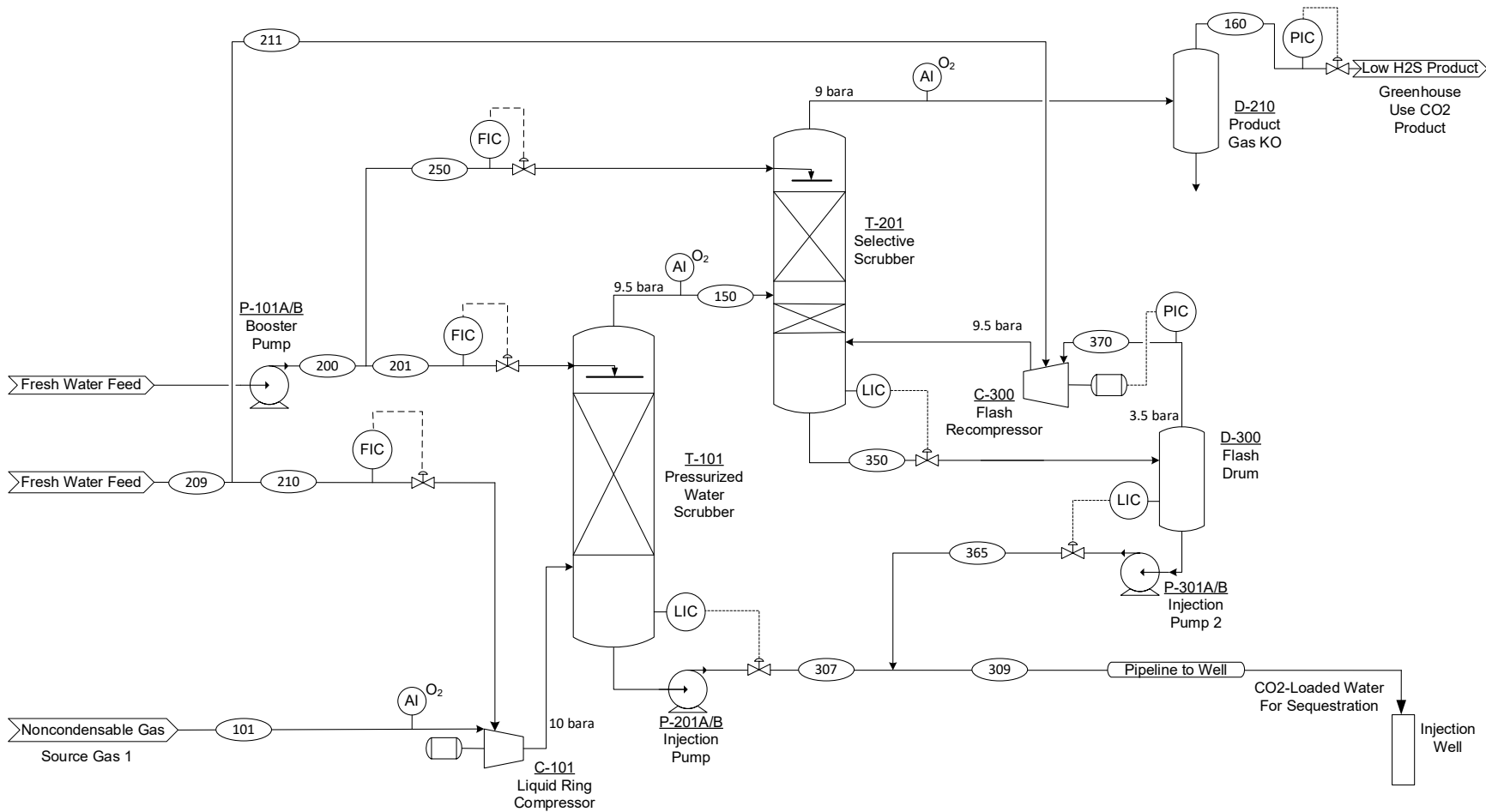


Figure 2: H₂S-Selective Water Scrubbing System for Greenhouse Gas.

Table 6: Stream Table for H₂S-Selective Water Scrubbing System for Greenhouse Gas.

	101	150	160	200	201	209	210	211	250	307	309	350	365	370
VapFrac	1	1	1	0	0	0	0	0	0	0	0	0.0004	0	1
T [C]	35	10.2	10	9	9	8	8	8	9	14.7	13.8	11.7	10.8	10.7
P [bar]	1.06	9.5	9	12	12	5	5	5	12	11.4	11.4	9	11.4	3.5
Mole Flow [kmol/h]	104.3	26.7	18.5	11157.2	8548.3	1887.3	1665.3	222.0	2608.9	10291.1	13130.3	2852.0	2839.2	12.8
Mass Flow [kg/s]	1.2	0.3	0.2	55.8	42.8	9.4	8.3	1.1	13.1	52.0	66.3	14.4	14.3	0.2
MW	40.4	39.1	37.0	18.0	18.0	18.0	18.0	18.0	18.0	18.2	18.2	18.2	18.1	43.8
Volume Flow [m ³ /h]	2507.0	63.2	46.5	201.0	154.0	34.0	30.0	4.0	47.0	188.0	239.4	54.8	51.4	84.2
Std Gas Volume Flow [Nm ³ /h]	2338	599	414	250080	191600	42302	37325	4977	58476	230670	294300	63924	63637	286
Cp [kJ/kmol-K]	36.9	37.1	36.0	76.2	76.2	76.2	76.2	76.2	76.2	77.2	77.1	77.3	76.6	37.5
Viscosity [cP]	0.015	0.015	0.015	1.342	1.342	1.383	1.383	1.383	1.342	1.211	1.230	1.312	1.306	0.014
Mole Fraction [%]														
Carbon Dioxide	79.58	79.11	70.49	0	0	0	0	0	0	0.6	0.53	0.73	0.29	98.92
Hydrogen Sulfide	9.69	0.47	0.03	0	0	0	0	0	0	0.1	0.08	0.01	0	0.56
Hydrogen	1.73	6.43	9.29	0	0	0	0	0	0	0	0	0	0	0.10
Methane	0.03	0.11	0.16	0	0	0	0	0	0	0	0	0	0	0
Nitrogen	2.99	11.48	16.6	0	0	0	0	0	0	0	0	0	0	0.02
Oxygen	0.56	2.12	3.06	0	0	0	0	0	0	0	0	0	0	0.01
Argon	0.04	0.14	0.21	0	0	0	0	0	0	0	0	0	0	0
Water	5.39	0.15	0.16	100	100	100	100	100	100	99.3	99.39	99.27	99.71	0.39

2.3 Preabsorption Concept to Simplify CO₂ Recovery and Purification

The source gas in this case contains over 1 mol% oxygen, which presents significant concerns due to the potential to form explosive gas mixtures once the fuels and this oxygen are concentrated. As a result, the flow scheme with a preabsorber was developed to contact the water and NCG stream upstream of the main absorption column to absorb the bulk of the CO₂ and H₂S into the water phase. The preabsorber concept manages the flammable species at the beginning of the processing scheme, making it easier to make a safe gas product stream (i.e., low in oxygen) for sequestration or utilization later in the process. Without the preabsorber, high levels of oxygen would be present in each of the flash gas streams associated with the selective scrubber. Additionally, oxygen in the vapor CO₂ product from the selective scrubber could be concentrated in downstream processing steps (such as during liquefaction and distillation) causing concerns in those downstream processes.

Figure 3 demonstrates a processing scheme using the preabsorber concept. In this process, the target is to maximize the amount of beverage or e-fuel grade liquid CO₂ that is produced while maintaining safe levels of oxygen in the vapor streams. Table 7 gives the stream data to go with Figure 3. (Note that two sites are considered for CO₂ recovery for this example, so the inlet NCG conditions differ from those presented in Sections 2.1 and 2.2.)

The NCG is compressed and flows into the gas preabsorber in-line mixer (M-101). In the mixer, a very large flow of clean water from the booster pump (P-101) is used to absorb the bulk of the CO₂ and H₂S into the liquid phase at a relatively high pressure, assumed to be about 10 bara for this example. The leftover gases exiting the preabsorption separator (D-101) include most of the light species (e.g., H₂, N₂, O₂). This stream also includes some H₂S as well as enough CO₂ that the stream is at least 10 volume percent higher than the estimated UFL_{mix}. The stream is then vented or combusted. Because most of the light species are removed upstream of the selective scrubber in D-101, another benefit of the preabsorption concept is that a higher purity CO₂ product may be possible. Higher purity CO₂ may require less processing in the downstream purification steps such that smaller equipment could potentially be used to purify the CO₂ for greenhouse gas, e-fuel, and beverage grade products.

The water containing the bulk of the H₂S and CO₂ flows from D-101 to a flash drum (D-200), which operates at a relatively low pressure, assumed to be about 2 bara for this example. This pressure was chosen to selectively flash out most of the CO₂ from the water to feed the subsequent processing steps while maintaining some level of removal of H₂S. The acid-gas-laden water from the bottom of the flash drum is assumed to be pumped (P-201) to an injection well. A higher pressure can be selected for the flash drum if less CO₂ vapor product is required. In the case of a higher flash pressure, more CO₂ would remain absorbed in the water for injection. Similarly, a lower flash pressure would allow more CO₂ vapor to form and leave less in the water phase.

The vapor from the flash drum flows to a flash recompressor (C-400), which compresses the gas to 10 bara so that it can enter the selective scrubber (T-201). A slipstream of fresh water is fed to C-400 as seal water. The seal water flows into T-201 along with the gas.

The purpose of T-201 is to selectively remove H₂S from the gas stream down to below 300 ppmv H₂S; an additional H₂S removal step (e.g., scavengers, liquid redox, etc.) downstream of the

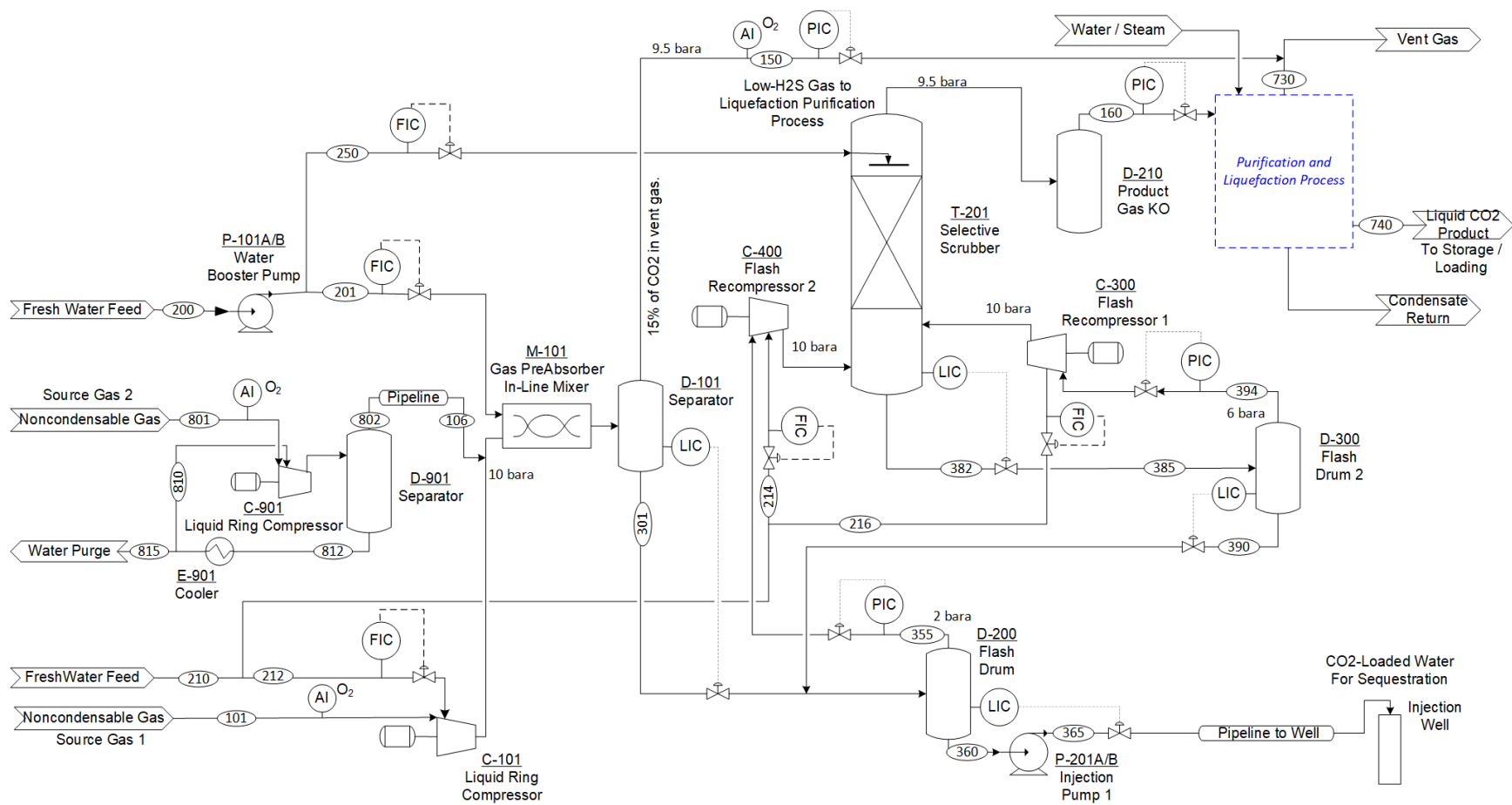


Figure 3: Preabsorption with H₂S-Selective Scrubbing and Purification / Liquefaction for Beverage Grade CO₂.

Table 7: Stream Data for Preabsorption with H₂S-Selective Scrubbing and Purification / Liquefaction for Beverage Grade CO₂.

	101	106	150	160	200	201	210	212	214	216	250	301	355
VapFrac	1	1	1	1	0	0	0	0	0	0	0	0	1
T [C]	35	46.1	11.5	10.2	9	9	8	8	8	8	9	11.5	11.2
P [bar]	1.06	9.88	9.38	9.5	12	12	7	7	7	7	12	9.38	2
Mole Flow [kmol/h]	104.3	176.4	58.2	104.0	57728.8	38855.9	6244.7	1665.3	3552.5	1026.9	18872.9	40743.7	219.9
Mass Flow [kg/s]	1.2	2.1	0.6	1.3	288.9	194.4	31.3	8.3	17.8	5.1	94.4	205.4	2.6
MW	40.4	42.0	37.9	43.4	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.2	43.1
Volume Flow [m ³ /h]	2507.0	454.5	141.1	242.0	1040.1	700.1	112.5	30.0	64.0	18.5	340.0	741.5	2565.7
Std Gas Volume Flow [Nm ³ /h]	2338	3955	1303	2331	1293900	870920	139970	37325	79627	23017	423020	913230	4928
Cp [kJ/kmol-K]	36.9	39.1	36.0	39.1	76.2	76.2	76.2	76.2	76.2	76.2	76.2	77.0	37.0
Viscosity [cP]	0.015	0.016	0.015	0.014	1.342	1.342	1.383	1.383	1.383	1.383	1.342	1.301	0.014
Mole Fraction [%]													
Carbon Dioxide	79.58	88.19	67.07	97.32	0	0	0	0	0	0	0	0.49	93.46
Hydrogen Sulfide	9.69	2.14	1.66	0.02	0	0	0	0	0	0	0	0.03	4.67
Hydrogen	1.73	0.84	4.33	0.72	0	0	0	0	0	0	0	0	0.34
Methane	0.03	0.02	0.1	0.01	0	0	0	0	0	0	0	0	0.01
Nitrogen	2.99	6.17	21.81	1.26	0	0	0	0	0	0	0	0	0.6
Oxygen	0.56	1.48	4.63	0.48	0	0	0	0	0	0	0	0	0.23
Argon	0.04	0.06	0.22	0.02	0	0	0	0	0	0	0	0	0.01
Water	5.39	1.08	0.17	0.15	100	100	100	100	100	100	100	99.47	0.69

Table 7 (Continued): Stream Data for Preabsorption with H₂S-Selective Scrubbing and Purification / Liquefaction for Beverage Grade CO₂.

	360	365	382	385	390	394	730	740	801	802	810	812	815
VapFrac	0	0	0.00002	0.0025	0	1	1	0	1	1	0	0	0
T [C]	11.2	11.3	13.4	12.8	12.8	12.8	10	-20	35	48.1	20	48.1	20
P [bar]	2	12	9.5	6	6	6	25	25	1.06	12	11.5	12	11.5
Mole Flow [kmol/h]	64092.1	64092.1	23626.1	23626.1	23568.2	57.9	33.0	70.9	184.5	176.4	2924.9	2933.0	8.1
Mass Flow [kg/s]	321.5	321.5	119.4	119.4	118.7	0.7	0.4	0.9	2.1	2.1	14.7	14.8	0.04
MW	18.1	18.1	18.2	18.2	18.1	43.6	42.2	44.0	40.9	42.0	18.1	18.1	18.1
Volume Flow [m ³ /h]	1158.8	1158.7	432.7	649.4	428.7	220.7	26.1	3.0	4435.9	373.3	53.2	54.3	0.1
Std Gas Volume Flow [Nm ³ /h]	1436600	1436600	529560	529560	528260	1299	739	1588	4136	3955	65559	65740	181
Cp [kJ/kmol-K]	76.4	76.4	77.3	76.8	76.9	38.2	44.6	97.5	36.9	39.6	76.7	76.6	76.7
Viscosity [cP]	1.278	1.274	1.256	1.244	1.253	0.014	0.015	0.117	0.015	0.016	1.035	0.585	1.035
Mole Fraction [%]													
Carbon Dioxide	0.15	0.15	0.68	0.68	0.44	96.04	92.12	100	84.35	88.19	0.39	0.39	0.39
Hydrogen Sulfide	0.02	0.02	0.05	0.05	0.04	3.58	0	0	2.05	2.14	0.02	0.02	0.02
Hydrogen	0	0	0	0	0	0.05	2.27	0	0.8	0.84	0	0	0
Methane	0	0	0	0	0	0	0.04	0	0.02	0.02	0	0	0
Nitrogen	0	0	0	0	0	0.03	3.99	0	5.9	6.17	0	0	0
Oxygen	0	0	0	0	0	0.02	1.5	0	1.42	1.48	0	0	0
Argon	0	0	0	0	0	0	0.08	0	0.06	0.06	0	0	0
Water	99.83	99.83	99.27	99.27	99.51	0.27	0	0	5.39	1.08	99.59	99.59	99.59

absorber is required to meet e-fuels or beverage grade quality. (Additional H₂S removal may not be required if this were to be for a greenhouse gas quality CO₂ product.)

A slipstream of water (stream 250) from P-101 flows to the top of T-201 and down through the packing where it absorbs CO₂ and H₂S. Selectivity is accomplished by flashing the liquid exiting the bottom of T-201 into a flash drum (D-300), which operates at a lower pressure of roughly 6 bara. At these conditions, more CO₂ than H₂S flashes out of the liquid, and this CO₂ is then recycled via another flash compressor (C-300) back to bottom of T-201 where the CO₂ is available to travel up the tower and on to purification and liquefaction.

The destination of the CO₂ is dependent on the composition of the non-condensable gas, particularly on the amount of oxygen and H₂S. Higher oxygen content in the feed gas requires that more CO₂ is flashed out in the preabsorber separator to sufficiently dilute the oxygen in the vent gas stream to maintain acceptable levels of oxygen. This CO₂ is lost to vent. Higher H₂S content requires a larger flow rate of water in the selective scrubber for removal (for a fixed H₂S concentration in the CO₂ product), which also absorbs additional CO₂. The CO₂ absorbed in the scrubber water is sequestered. Finally, if the low-H₂S gas from the absorber is sent to purification and liquefaction (McIntush, et al., 2022), additional CO₂ will be vented from the distillation column to remove inert gases (e.g., remaining traces of nitrogen, hydrogen, and oxygen).

Table 8 provides an example of the destination of the CO₂ from the feed gas for two different NCG compositions. In both cases, the use of the preabsorber concept limits the amount of CO₂ that must be vented relative to the amount injected with water (sequestered) and relative to the amount of CO₂ converted into liquefied product.

Table 8: Example CO₂ Destination for Two Different NCG Compositions.

	Case 1	Case 2
Gas Composition (dry), mol%		
CO ₂	84.1%	87.3%
H ₂ S	10.2%	5.1%
H ₂	1.8%	1.2%
N ₂	3.3%	5.2%
O ₂	0.6%	1.2%
CO ₂ Vented	15.9%	29.1%
CO ₂ Injected with Water	47.1%	41.2%
CO ₂ Liquefied	37.1%	29.7%

3. Optimization and Options for Implementation

Since this was a high-level study, the water processing schemes were preliminary in nature. Given the many different uses for CO₂ from NCG and the variability in the NCG composition across geothermal facilities, there is no standard water scrubbing scheme for purifying CO₂ from NCG. Thus, the water scrubbing and preabsorption approaches described in this paper could be further tailored to meet the specific objectives of different NCG applications.

Moreover, while the focus of this study was on water scrubbing technologies, it is obvious that the preabsorber concept could readily be adapted for use with other separations techniques, such as alkanolamines, physical solvents, and perhaps other non-solvent technologies (e.g., membranes) as well.

4. Conclusions

This paper presents an overview of pressurized water scrubbing to capture CO₂ from the NCG and a new preabsorption concept to manage the residue gas composition so that an explosive gas mixture is not formed. If the geothermal power plant has an abundance of cool water that can be used on a once-through basis and a suitable well for injection, then water scrubbing at elevated pressure may be a reasonable option for recovering CO₂ from NCG. The preabsorption concept can be used in the water scrubbing process to simplify CO₂ recovery and purification. The preabsorption concept is particularly advantageous when the NCG has high levels of oxygen, significant light ends, and a CO₂ product (greenhouse gas, e-fuel, beverage) is desired.

The inline mixer and separator of the preabsorber are used to dissolve the majority of the CO₂ along with the H₂S into the water while the majority of the light components (e.g., O₂, N₂, CH₄, H₂) exit as vapor from the separator. Enough CO₂ also evolves in the vapor from the separator in order to stay safely away from the formation of an explosive gas mixture. Thus, the preabsorption concept removes most of the oxygen and light ends from the NCG prior to further processing. This makes the downstream purification steps safer to operate since the flammability envelop is avoided. The removal of the bulk of the light ends also results in the recovery of a higher purity CO₂ product from the water scrubbing system.

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