Kent S. Knaebel, Ph.D., P.E.
Adsorption Research, Inc.
6175-D Shamrock Court
Dublin, OH 43016
K.Knaebel@Adsorption.com

AdvanSorb®-CO_2 Capture Process

April 2021

SUMMARY

A process has been developed to capture carbon dioxide (CO_2) from flue gas emitted from power plants, steam generators, and cement plants. It is an "end-of-pipe" process, in that it does not interfere with the source of the flue gas. The process employs *temperature swing adsorption* (TSA), in which adsorbent takes-up CO_2 at low temperature then releases it at high temperature.

In this process, CO_2 is removed from the flue gas at low concentration (typically 5 to 15%). It is released at high concentration (e.g., 95 to 99% - on a dry basis). Thus, this process separates the CO_2 from the flue gas <u>and</u> enriches it. In addition, it also captures H_2O from the flue gas, which may be beneficial in arid climates. Likewise, pollutants such as SO_X and NO_X are captured along with CO_2 and H_2O. Thus, they can be efficiently managed.

The key benefit of this process is: it is driven by heat, which means the hotter the flue gas, the lower the operating cost. Furthermore, the heat in the flue gas is transferred directly to the adsorbent, which makes the process simple and reliable. In contrast, no other CO_2 capture processes directly use the heat available in the flue gas. The process is covered by US patents: 7,594,956 and 8,353,978.

Figure 1 shows the main sections of the Moving Bed Adsorber. Starting at the top, the sections are: Adsorption, Preheater, Regeneration, and Recuperator. Adsorbent flows downwards through each of these, due to gravity. The Adsorbent Conveyer returns the regenerated adsorbent from the bottom of the Recuperator Section to the top of the Adsorption Section.

Here is an overview of how this CO_2 capture process works, starting with the hot flue gas (i.e., near the bottom left corner of Figure 1).

1. The Regeneration Section is essentially a parallel plate heat exchanger. Hot flue gas enters at the bottom, then flows upwards, confined inside metal channels (which are not shown in Figure 1). Simultaneously, adsorbent that is laden with CO_2 and H_2O flows downwards from the Preheater Section, through the gaps between the channels carrying the flue gas. Hence, the flue gas and adsorbent are physically isolated. Heat from the flue gas is transferred through the metal wall of the channel into the adsorbent. As such, heating the adsorbent causes it to release CO_2 and H_2O (and contaminants, if any). That is the essence of TSA.
2. The cooled flue gas exits the top of the Regeneration Section and, is routed to the Quench Tower. That unit further cools the flue gas and, depending on the incoming temperature and water content, it will actually remove water. If the flue gas contains little moisture, a conventional heat exchanger could be used instead of the Quench Tower.
3. From the Quench Tower the flue gas enters the bottom of the Adsorption Section. Simultaneously, the Conveyor delivers cooled, regenerated adsorbent at the top. Hence, the flue gas flows upwards in counter-current contact with the downward flowing adsorbent. The adsorbent picks-up CO_2 and H_2O (and contaminants, if any) from the flue gas. The result is: the flue gas is cleaned, and the adsorbent is loaded. The loaded adsorbent flows downwards into the Preheater Section, while the remaining flue gas, now mostly N_2 and O_2, continues to flow up and out of the Adsorption Section.

4. The Preheater and Recuperator Sections, like the Regeneration Section, are essentially parallel plate heat exchangers. The Preheater Section transfers heat from the heat transfer fluid into the cool adsorbent, while it is flowing downwards from the Adsorption Section. In contrast, the Recuperator Section transfers heat from the hot adsorbent, leaving the Regenerator Section, into the heat transfer fluid. In both of these sections, heat transfer fluid (instead of flue gas) flows upwards inside the channels, and the adsorbent flows downwards, outside the channels. A pump boosts the pressure of the cool heat transfer fluid coming from the top of the Preheater Section propelling into the bottom of the Recuperator Section.

5. The Adsorbent Conveyor merely lifts the cooled adsorbent from the bottom of the Recuperator Section to the top of the Adsorption Section.

In a nutshell, that is how ARI's CO_2 capture process works.

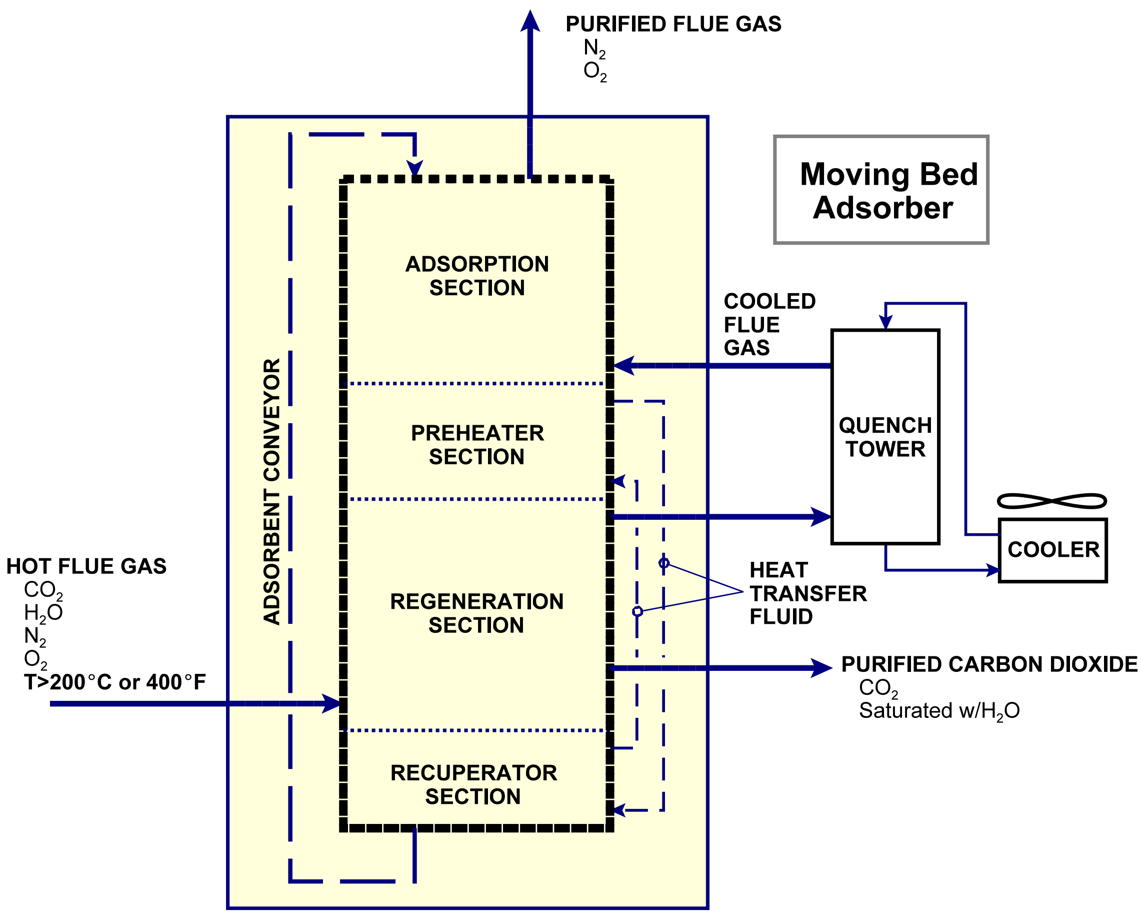

Figure 3. Block-Diagram of ARI's Moving Bed TSA CO_2 Capture Process.

Several variables determine the CAPEX and OPEX of this process. The main ones are: the flue gas flow rate, its temperature, and its composition, and the product purity constraints.

Some of the advantages of ARI's Moving Bed TSA CO_2 Capture Process are:

A. Low pressure drop (about 5 inches-water-column total).

B. The operating pressure is essentially atmospheric. Thus, the vessels can be rectangular rather than cylindrical, and the wall thickness can be relatively thin, which makes them economical to fabricate.

C. The flow directions of the flue gas and adsorbent are counter-current throughout the process. Thus, the required volume of adsorbent is small, and the heat transfer surface areas in the Regeneration, Preheater, and Recuperator Sections are reasonably compact, and the corresponding capital cost is low.

D. The design of this process is inherently modular. Here are some related benefits:

   1. A typical installation will consist of a few to several identical, parallel modules, each of which consists of the above described five sections, plus an adsorbent conveyor.
   2. The speed of the conveyor can be controlled by a variable speed drive. Thus, each module can be operated independently and flexibly.
   3. The modules are practically independent of each other. Thus, any of the modules can be shut-down for maintenance, without affecting the processing capacity of the remaining modules.
   4. These features allow the CO_2 capture system to synchronize with the source of the flue gas. Thus, the process can accept high flow during periods of peak demand, but it can be turned-down when output is reduced.

A pilot-scale moving-bed TSA CO_2 capture process (capacity of 2-tons of CO_2 per day) has been built in Brazil, to evaluate the process under realistic conditions. These tests will yield engineering data and will determine its technical and economic feasibility. For example, tests will be conducted to assess adsorbent life, working capacity, separation performance, and materials compatibility issues, if any. Once those tests are successful, commercial implementation will follow.

DETAILED DESCRIPTION

A more detailed, but still schematic diagram of ARI's CO_2 capture process is shown in Figure 2. In this version, subtle lines indicate the path of the fluid phase in the various Sections. To avoid confusion, the movement of the adsorbent is mostly omitted, because it flows downwards in the Moving Bed Adsorber, on account of gravity. The fluid motion is also mostly counter-current and upwards, but slightly more involved.

For example, in the Adsorption Section, the flue gas from the Quench Tower flows in, horizontally at the bottom, and is distributed to flow upwards vertically. This is depicted by the horizontal line splitting into several parallel lines which represent the flue gas flowing upwards. Likewise, dashed lines in the Preheater and Recuperator Sections schematically represent the mostly upwards, counter-current path of the heat transfer medium through the parallel channels mentioned previously. While, in the Regeneration Section the diagonal lines correspond to the mostly upwards counter-current path that the flue gas follows, again through parallel channels.

Finally, a detail that was not covered in Figure 1 is: the cool, dry, virtually CO_2-free flue gas, does a u-turn at the top of the Adsorption Section, and it flows into the top of the enclosed Bucket Conveyor. It flows downwards (shown as a zig-zag path), counter-current to the adsorbent being lifted. Hence, it cools the adsorbent being conveyed upwards.

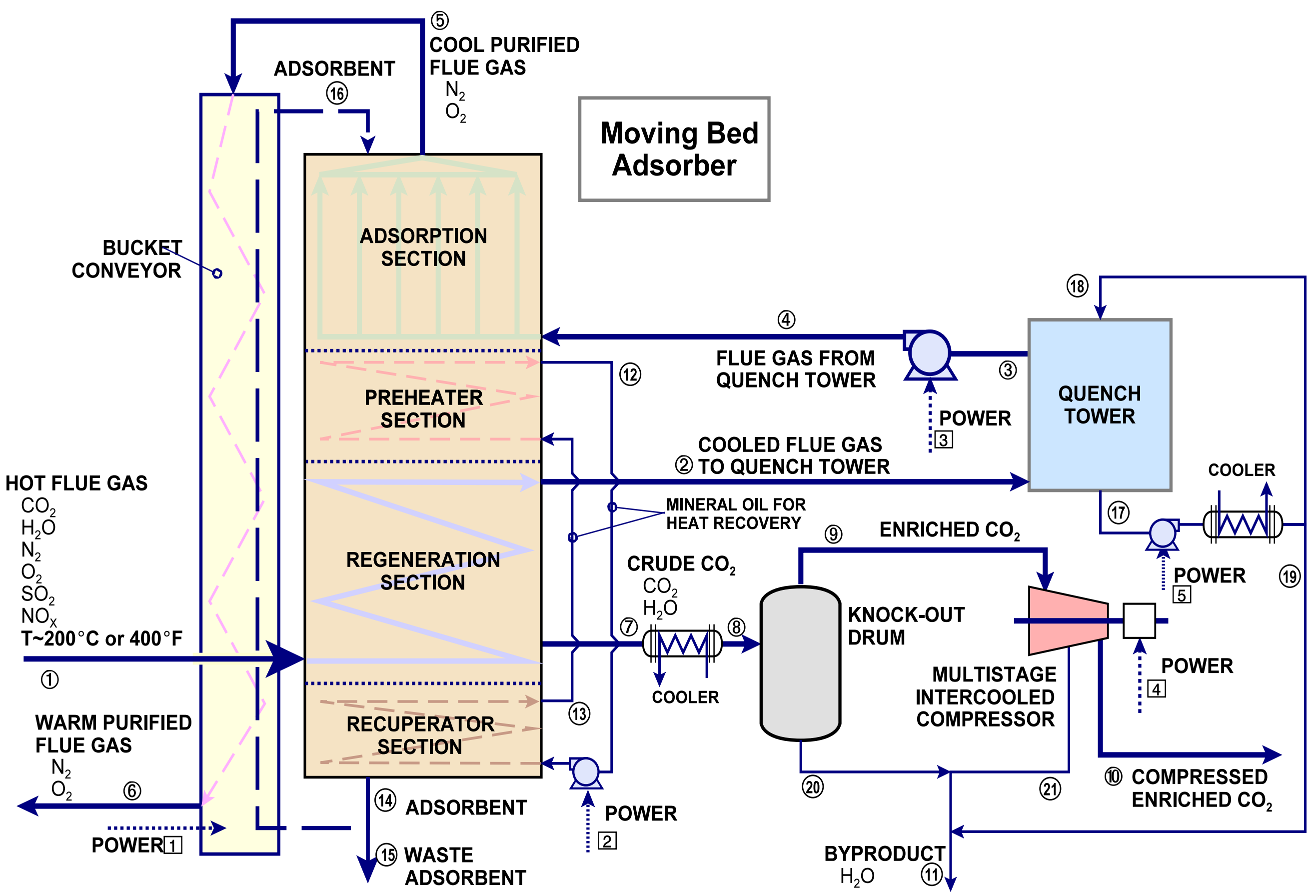

Figure 6. Block-Diagram of ARI's Moving Bed TSA CO_2 Capture Process.

In Figure 2, the streams are numbered, 1 through 21, and the numbers are circled. In addition, five motors consume power, including three pumps and two mechanical drives. Those are also numbered, though they are enclosed in squares. Other differences from Figure 1 are: the streams in which water condenses (or possibly vaporizes) are explicitly shown (Streams 19, 20, and 21, culminating in 11), as is the possible exhaust of Waste Adsorbent (Stream 15).

Each of the Unit Operations, such as the Sections of the Moving Bed Adsorber, and the Knock-Out Drum, Quench Tower, etc. are designed according to conventional engineering principles. Afterwards, their CAPEX and OPEX is estimated in order to determine the cost of the overall operation.

EXAMPLE

Among all the sources of carbon dioxide emissions, steam generators may be the most prevalent, particularly in oil-producing regions. Those areas are also potentially well suited to sequestration of CO_2. Consequently, this example shows how ARI's Moving Bed TSA CO_2 Capture Process can be applied in such an application.

This example is a 500 tonne per day CO_2 Capture Plant which treats the flue gas exhausted from a Steam Generator at 425°F. The basis is 81,542 SCFM of flue gas. The flue gas composition is listed in Table 1, below, along with the compositions of the purified flue gas and enriched CO_2 + H_2O streams. Information about streams 1 to 21, shown in Figure 2, is listed in the Appendix.

Table 1. Example 500 tonne per day CO_2 Capture Plant: Design Basis.

Component	**Flue Gas**	**Purified Flue Gas**	**Enriched CO_2 + H_2O**	**Units**
N2+Ar+CO	73.04%	95.02%	0.31%	Mole Fraction
O2	3.50%	4.55%	0.02%	
CO2	8.26%	0.22%	34.87%	
H2O+SO2+NOx	15.20%	0.21%	64.80%	
Sum	100.00%	100.00%	100.00%	
Temperature	425.0	120.0	269.6	°F
	218.3	48.9	132.0	°C
Flow Rate	360,468.2	279,326.1	81,142.1	lb/hr
	81,542.1	62,615.1	18,927.0	scfm
CO2 Capture Rate			500.0	tonnes/day
H2O Capture Rate			380.1	tonnes/day

Table 2 shows the itemized equipment cost, grouped according to the function, i.e., as:

1. Steel for heat exchange surfaces and structural steel in the Moving Bed Adsorber.
2. Adsorbent.
3. Bucket Conveyors.
4. Ancillary Units, including: Quench Tower + Water Cooler + Water Pump, Post-Quench Blower, CO_2 Cooler, Knock-Out Drum, and the Mineral Oil Pump (heat transfer fluid).
5. Steel Buildings.
6. Foundations, etc.

Table 2. Equipment Cost.

LINE ITEM		AMOUNT/COST	UNITS
Steel	Heat Exchangers	121,940	sq ft
	Total Steel	810	tons
	Purchase Cost	$481	per ton
	Fabricated Cost	$2,405	per ton
	Steel Cost	$1,947,530	
Adsorbent	Adsorbent Circulation	22,194	lb ads/min
	Cycle Duration	20	min
	Adsorbent Cost	$1.00	per lb
	Adsorbent Reservoir	443,887	lb
	Adsorbent Init. Cost	$443,887	
	Adsorbent Loss	0.10%	of Reservoir/day
	Adsorbent Cycles	72	per day
	Adsorbent Loss	6.2	lb/cycle
	Adsorbent Repl. Cost	$1.17	per tonne CO2
Bucket Conveyors	Number	3.00	
	Cost	$798,000	
Ancillary Units	Quench Tower	$5,450,000	
	Quench Water Cooler	$1,480,000	
	Quench Water Pump	$187,500	
	Post Quench Blower	$1,880,000	
	CO2 Cooler	$5,220,000	
	Knock-Out Drum	$3,310,000	
	Mineral Oil Pump	$170,000	
	Subtotal	$17,697,500	
Steel Buildings		$135,005	
Foundation, etc.		$40,501	
Subtotal		$21,062,423	
Installation + Contingency		$42,127,577	
Total Cost		$63,190,000	
Amortization	At 4%	$3,654,284	per yr
		$26.70	per tonne of CO2

Table 3 lists the dimensions of the Moving Bed Adsorber, as well as some performance parameters, such as the Adsorbent Working Capacity, Heat Requirement, Single-Pass Heat Recovery (e.g., the function of the Preheater and Recuperator Sections), the Regeneration Temperature, the estimated Flue Gas Pressure Drop, Residence Times for the adsorbent and flue gas in various sections, and the Mass Flow Rate x Heat Capacity for the adsorbent and flue gas .

The appendix lists more tabular information regarding the 21 streams of the process for this example.

Table 3. Moving Bed Adsorber Dimensions and Performance Parameters.

Moving Bed Dimensions				
Overall	Height	65.4	ft	
	Width	7.5	ft	
	Depth	90.0	ft	
	Footprint	675	sqft	
Adsorber	Height	6.6	ft	
Preheater + Regenerator + Recuperator	Height	50.8	ft	
	Duct Depth	12.0	ft	
	Duct Width (Wi)	1.50	in	
	Channel Width (Wo-Wi)	1.50	in	
	Number of Ducts	100		
Performance Parameters				
Adsorbent Working Capacity		4.0%	wt CO_2/wt ads.	
Heat Requirement	Sensible Heating+Losses	993,785	Btu/min	
Single-Pass Heat Recovery	Recuperator	66.2%		
Regeneration Temperature	Regenerator	269.6	°F	
		132	°C	
Flue Gas Pressure Drop	Regenerator	0.034	psid	
		0.93	in H2O	
		Solid	**Gas**	
Residence Times	Adsorber	24	1.25	s
	Regenerator	169	0.85	s
Mass Flow Rate x C_P	Adsorber	81	25	Btu/s
Mass Flow Rate	Adsorber	370	96	lb/s

APPENDIX

Operating Conditions

Streams 1 to 21

		Hot Flue Gas	Cooled Flue Gas	Post-Quench Flue Gas	Boosted Post-Quench Flue Gas	Cool Purified Flue Gas
		1	**2**	**3**	**4**	**5**
Component	MW	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**
N2+Ar+CO	28.020	0.73039	0.73039	0.78658	0.78658	0.95022
O2	32.000	0.03500	0.03500	0.03769	0.03769	0.04553
CO2	44.010	0.08260	0.08260	0.08895	0.08895	0.00215
H2O+SO2+NOx	18.016	0.15201	0.15201	0.08677	0.08677	0.00210
Sum		1.00000	1.00000	1.00000	1.00000	1.00000
Flow Rate	lb/hr	360,468	360,468.2	343,875.4	343,875.4	279,326.1
	kg/hr	163,506	163,505.8	155,979.4	155,979.4	126,700.3
	scfm	81,542	81,542	75,717	75,717	62,615
	lbmol/hr	12,893	12,893	11,972	11,972	9,900
	kgmol/hr	5,848	5,848	5,430	5,430	4,491
Mean MW	g/mol	27.959	27.959	28.724	28.724	28.215
Temperature	°F	425	205	110	120	120
	°C	218	96	43	49	49
Pressure	psig	0.145	0.111	0.039	0.111	0.075
	mbar(g)	9.964	7.639	2.657	7.639	5.148
	in H2O	4.000	3.067	1.067	3.067	2.067
Heat Capacity	Btu/lb°F	0.288	0.273	0.257	0.258	0.250
	kJ/kgK	1.2068	1.1422	1.0759	1.0788	1.0463
Enthalpy	kJ/kg	263.5	109.8	46.6	52.7	51.2
Density	lb/ft3	0.6423	0.8530	1.0175	1.0048	0.9846
Flow Rate	Nm3/s	36.41				

		Warm Purified Flue Gas	Warm Crude CO_2	Cool Crude CO_2	Cool Enriched CO_2	Compressed Enriched CO_2
		6	**7**	**8**	**9**	**10**
Component	**MW**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**
N2+Ar+CO	28.020	0.95022	0.00455	0.00455	0.00791	0.00893
O2	32.000	0.04553	0.00022	0.00022	0.00038	0.00043
CO2	44.010	0.00215	0.50380	0.50380	0.87652	0.98980
H2O+SO2+NOx	18.016	0.00210	0.49144	0.49144	0.11520	0.00084
Sum		1.00000	1.00000	1.00000	1.00000	1.00000
Flow Rate	lb/hr	279,326.1	64,549.2	64,549.2	48,679.4	46,224.3
	kg/hr	126,700.3	29,279.1	29,279.1	22,080.6	20,967.0
	scfm	62,615	13,102	13,102	7,531	6,669
	lbmol/hr	9,900	2,071.53	2,071.53	1,190.65	1,054.38
	kgmol/hr	4,491	939.63	939.63	540.07	478.26
Mean MW	g/mol	28.215	31.160	31.160	40.885	43.840
Temperature	°F	145	269.61	120.00	120.00	120.00
	°C	63	132.00	48.89	48.89	48.89
Pressure	psig	0.002	0.072	0.036	0.000	2000
	mbar(g)	0.166	4.982	2.491	0.000	137,907
	in H2O	0.067	2.000	1.000	0.000	55,362
Heat Capacity	Btu/lb°F	0.251	0.313	0.291	0.237	0.225
	kJ/kgK	1.0516	1.3103	1.2193	0.9928	0.9438
Enthalpy	kJ/kg	66.0	173.0	59.6	48.5	46.1
Density	lb/ft3	0.9393	0.8642	1.0845	1.4195	208.6698
Flow Rate	Nm3/s					

		Byproduct H_2O	Cool Mineral Oil	Warm Mineral Oil	Warm Regenerated Adsorbent	Waste Adsorbent	Cool Adsorbent
		11	**12**	**13**	**14**	**15**	**16**
Component		**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**
N2+Ar+CO		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O+SO2+NOx		1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mineral Oil		0.0000	1.0000	1.0000	0.0000	0.0000	0.0000
Adsorbent		0.0000	0.0000	0.0000	1.0000	1.0000	1.0000
Sum		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Flow Rate	lb/hr	34,917.7	599,247	599,247	1,331,661	18.5	1,331,642
	kg/hr	15,838.4	271,814	271,814	604,032	8.4	604,023
	gpm	70.44	1,292	1,349	3,628	0.05	3,628
	lbmol/hr	1,938.15	-	-	-	-	-
	kgmol/hr	879.13	-	-	-	-	-
Mean MW	g/mol	18.016	100	100	200	200	200
Temperature	°F	124.00	146	243	190	190	120
	°C	51.11	64	117	88	88	49
Pressure	psig	0.036	10	30	0.002	0.002	0.075
	mbar(g)	2.491	690	2,069	0.166	0.166	5.148
	in H2O	1.0000	277	830	0.07	0.07	2.07
Heat Capacity	Btu/lb°F	1.000	0.515	0.479	0.22	0.22	0.22
	kJ/kgK	4.1868	2.1570	2.0067	0.9211	0.9211	0.9211
Enthalpy	kJ/kg	214.0	137.1	235.5	80.7	80.7	45.0
Density	lb/ft3	61.8	57.8	55.4	45.8	45.8	45.8

		Warm Quench Water	Cooled Quench Water	Net Quench Water	Water from Crude CO_2	Water from Compressed CO_2
		17	18	19	20	21
Component		**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**	**Vol. Fraction**
N2+Ar+CO		0.0000	0.0000	0.0000	0.0000	0.0000
O2		0.0000	0.0000	0.0000	0.0000	0.0000
CO2		0.0000	0.0000	0.0000	0.0000	0.0000
H2O+SO2+NOx		1.0000	1.0000	1.0000	1.0000	1.0000
Mineral Oil		0.0000	0.0000	0.0000	0.0000	0.0000
Adsorbent		0.0000	0.0000	0.0000	0.0000	0.0000
Sum		1.0000	1.0000	1.0000	1.0000	1.0000
Flow Rate	lb/hr	553,604	537,011	16,593	15,870	2,455
	kg/hr	251,111	243,585	7,526	7,198	1,114
	gpm	1,128	1,083	33.8	32.0	5.0
	lbmol/hr	30,728	29,807	921	881	136
	kgmol/hr	13,938	13,520	418	400	62
Mean MW	g/mol	18.016	18.016	18.016	18.016	18.016
Temperature	°F	153.3	105.0	153.3	120.0	153.3
	°C	67.4	40.6	67.4	48.9	67.4
Pressure	psig	0.039	0.111	0.075	0.002	0.072
	mbar(g)	2.657	7.639	5.148	0.166	4.982
	in H2O	1.07	3.07	2.07	0.07	2.00
Heat Capacity	Btu/lb°F	1.0000	1.0000	1.0000	1.0000	1.0000
	kJ/kgK	4.1868	4.1868	4.1868	4.1868	4.1868
Enthalpy	kJ/kg	282.1	169.8	282.1	204.7	282.1
Density	lb/ft3	61.2	61.8	61.2	61.8	61.8