FUNDAMENTALS OF A CARBON CAPTURE PROCESS: *UNIT OPERATIONS*

Mark J. McCready
Professor of Chemical and Biomolecular Engineering
University of Notre Dame
Indiana, USA
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GOALS OF THESE LECTURES

- Understand the overall process and the key phenomena and equipment
  - Flow in pipes (momentum transfer)
    - pipes, pumps, tanks, fittings and meters
  - Heat transfer between fluids (energy transport)
    - heat exchangers, boilers and condensers
  - Gas absorption and stripping. (mass transfer)
    - Packed column absorber and stripper

PLAN FOR TODAY

- Overview of CO_2 absorption
  - Motivation and need for the process
  - How it works
- Description of fundamental processes that occur
  - fluid flow, heat transfer, mass transfer
- Part I: Fluid mechanics and process fluid flows.

CARBON DIOXIDE ABSORPTION FROM A GAS MIXTURE

- Why do: To get "pure" CO_2
- Reversible, cyclical process:
  - CO_2 (selectively) dissolves in (lean) MEA solution in the absorber
    - reversible chemical reaction greatly increases solvent capacity and selectivity
  - MEA solution is pumped to the "stripper" where heat (from steam) is used to reduce the CO_2 solubility (and reverse the reaction) so that CO_2 (now) without N_2 will come off.
- Usually need to hit a "spec" on CO_2 emitted.
- Need efficient contacting of gas and liquid
- CO_2 capacity per mass of solvent significantly influences the cost
- Energy to regenerate influences cost

PROCESS OF INTEREST

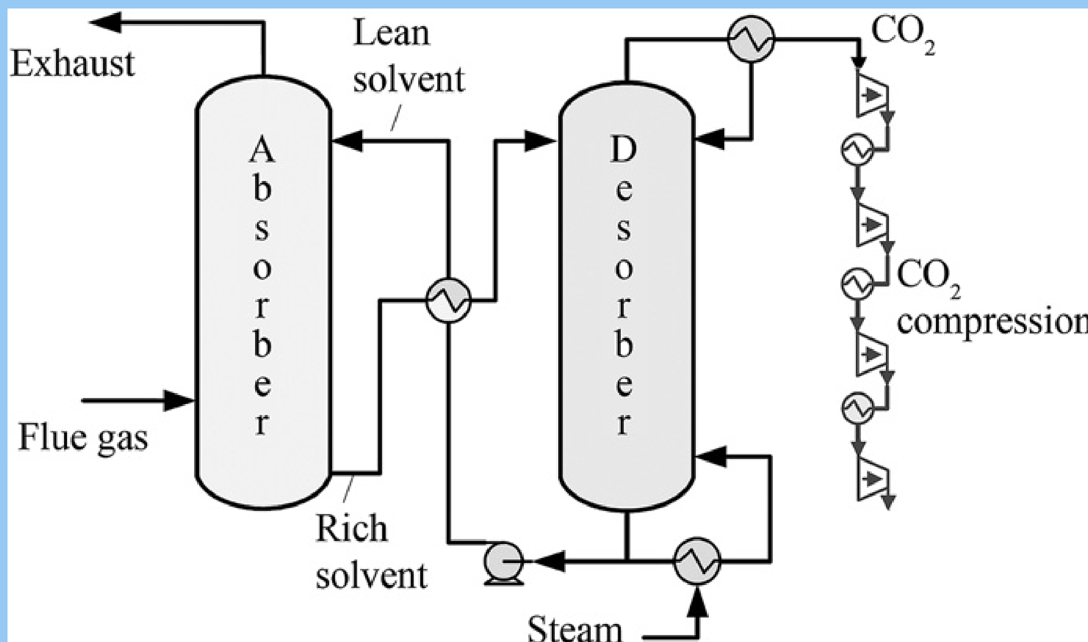
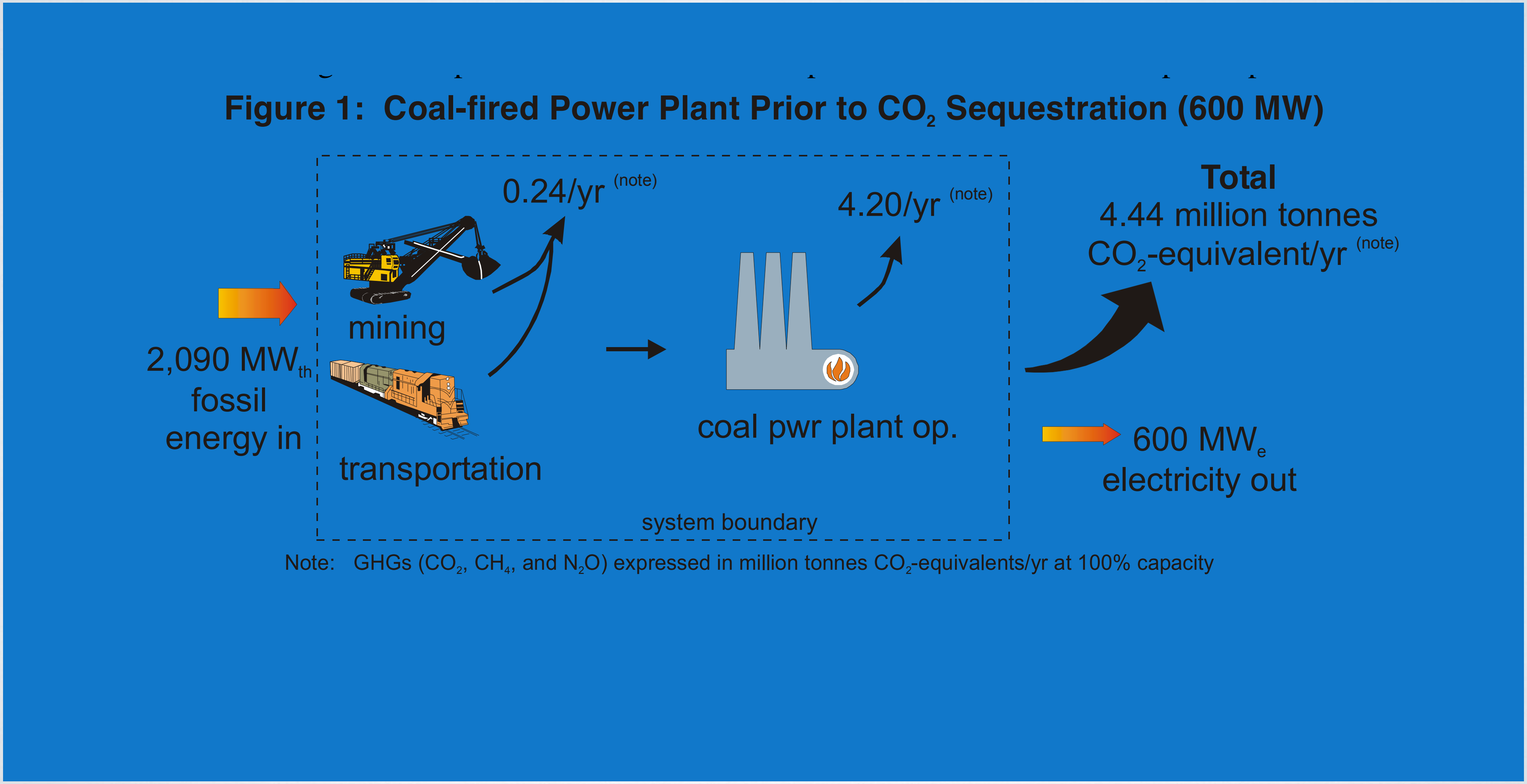


Fig. 1. Schematic diagram of absorption section for CO_2 scrubbing with MEA and DGA solutions [10].

WHY SCRUB CO2?

- Natural gas clean up
  - Very large volumes of gas, low concentration of CO2 (but at elevated pressure)
- Production of hydrogen (also at some elevated pressure)
  - $C + 2H_2O \longrightarrow CO_2 + 2\ H_2$
  - $CH_4 + H_2O \longrightarrow CO + 2\ H_2$
  - $CO + H_2O \longrightarrow CO_2 + H_2$
- Life support (1 ATM)
- Clean up of combustion gases (~1 ATM coming in.)
  - ~3 mol% (CO2) from natural gas, 10-15% from coal

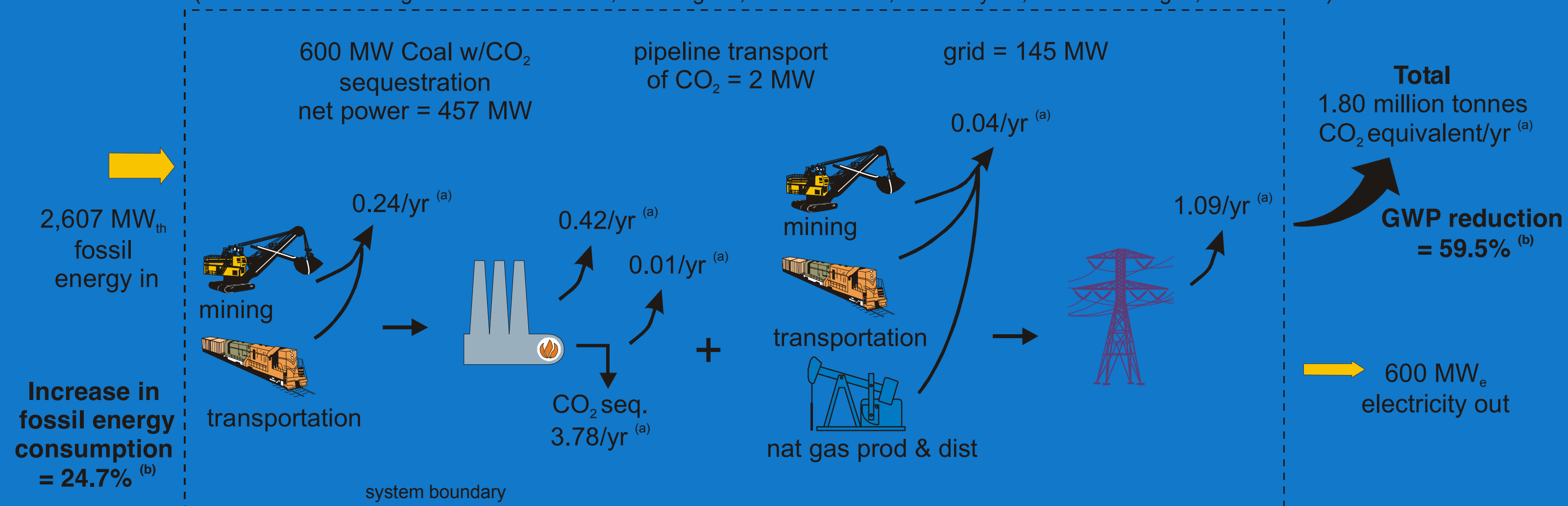
HAVE TO HAVE A GOOD REASON…



25% MORE ENERGY IS NEEDED WITH SEQUESTRATION

Figure 3: Coal-fired Power Plant with CO_2 Sequestration and 145 MW of Grid Capacity Added to Maintain 600 MW

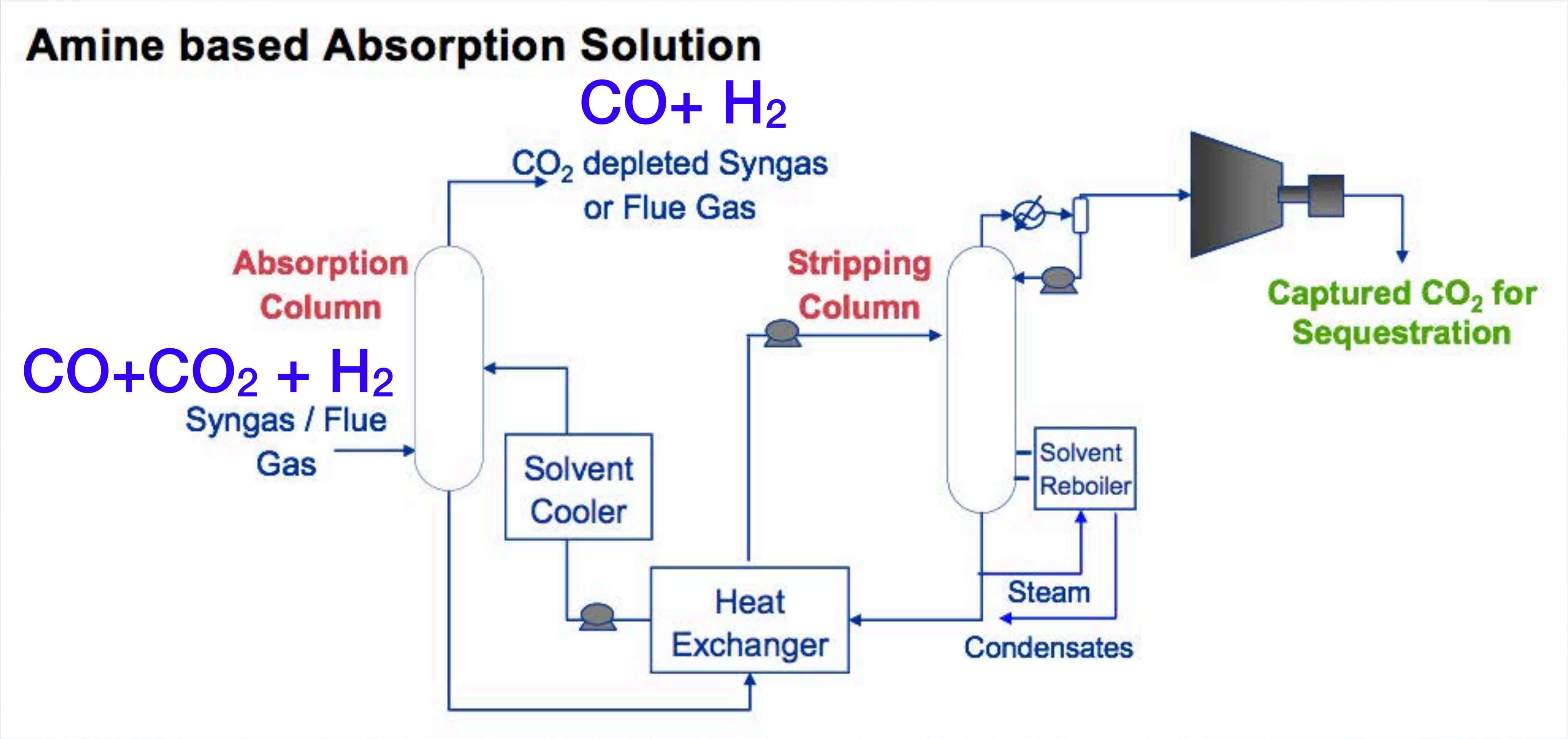
(U.S. mid-continental grid mix is 64.7% coal, 5.1% lignite, 18.4% nuclear, 10.3% hydro, 1.4% natural gas, and 0.1% oil)



Notes: (a) GHGs (CO_2, CH_4, and N_2O) expressed in million tonnes CO_2-equivalents/yr at 100% capacity; (b) Change in GWP and change in fossil energy consumption compared to reference

OTHER APPLICATIONS FOR CO2 SCRUBBING

HYDROGEN PRODUCTION



METHODS FOR CO_2 SEPARATION

- Membranes
- Absorption into basic solutions (carbonate, hydroxides)
- Absorption into amines
- Solid bed adsorption
- Cryogenic distillation

The Scientific World Journal

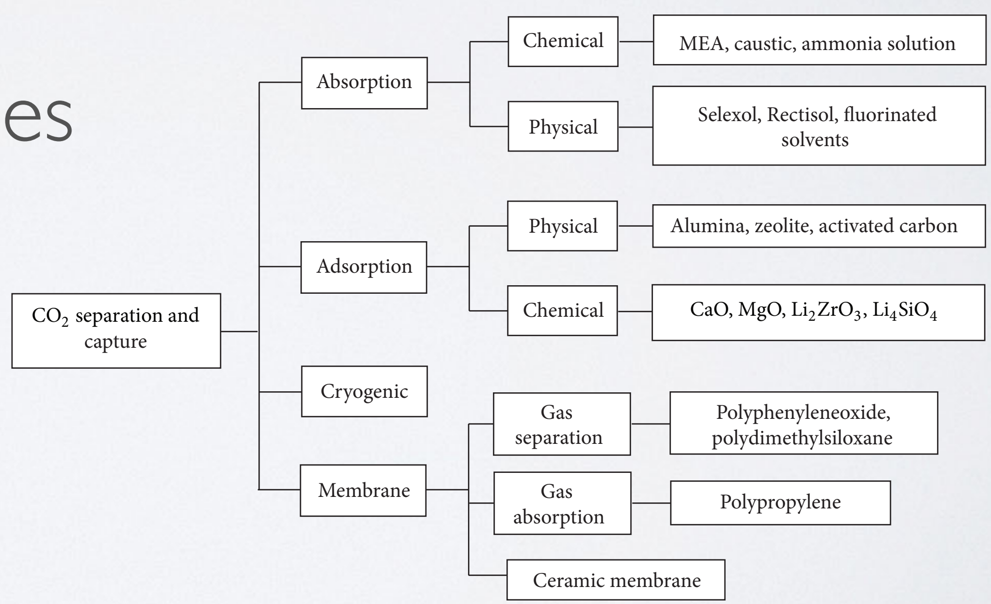
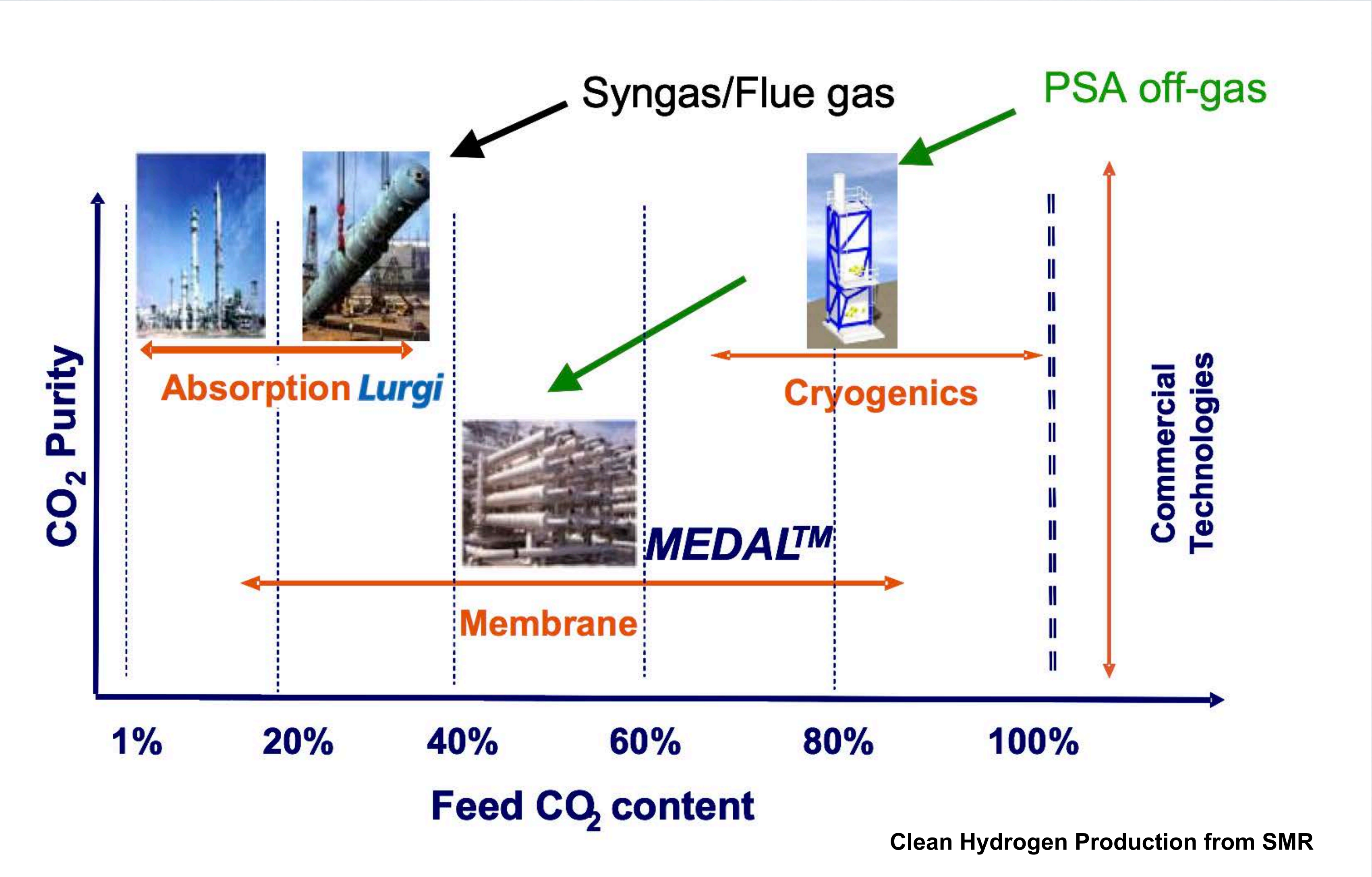


FIGURE 4: Different technologies for CO_2 separation [29].

COMPARING SEPARATION METHODS



PROCESS OF INTEREST

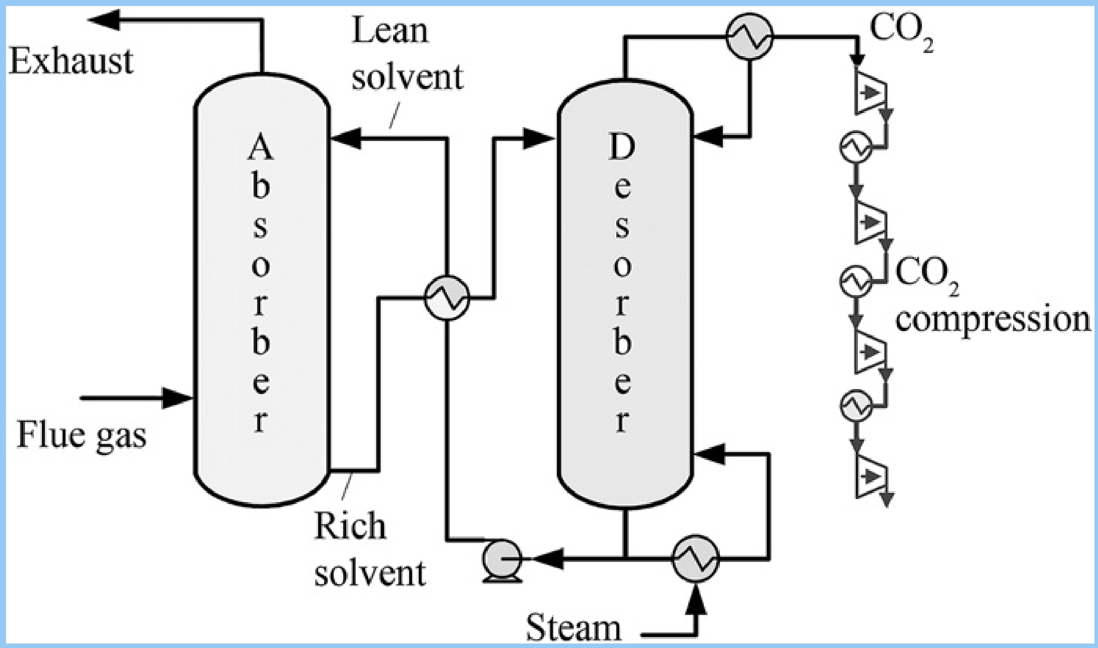


Fig. 1. Schematic diagram of absorption section for CO_2 scrubbing with MEA and DGA solutions [10].

SIGNIFICANT COMPRESSION IS NEEDED

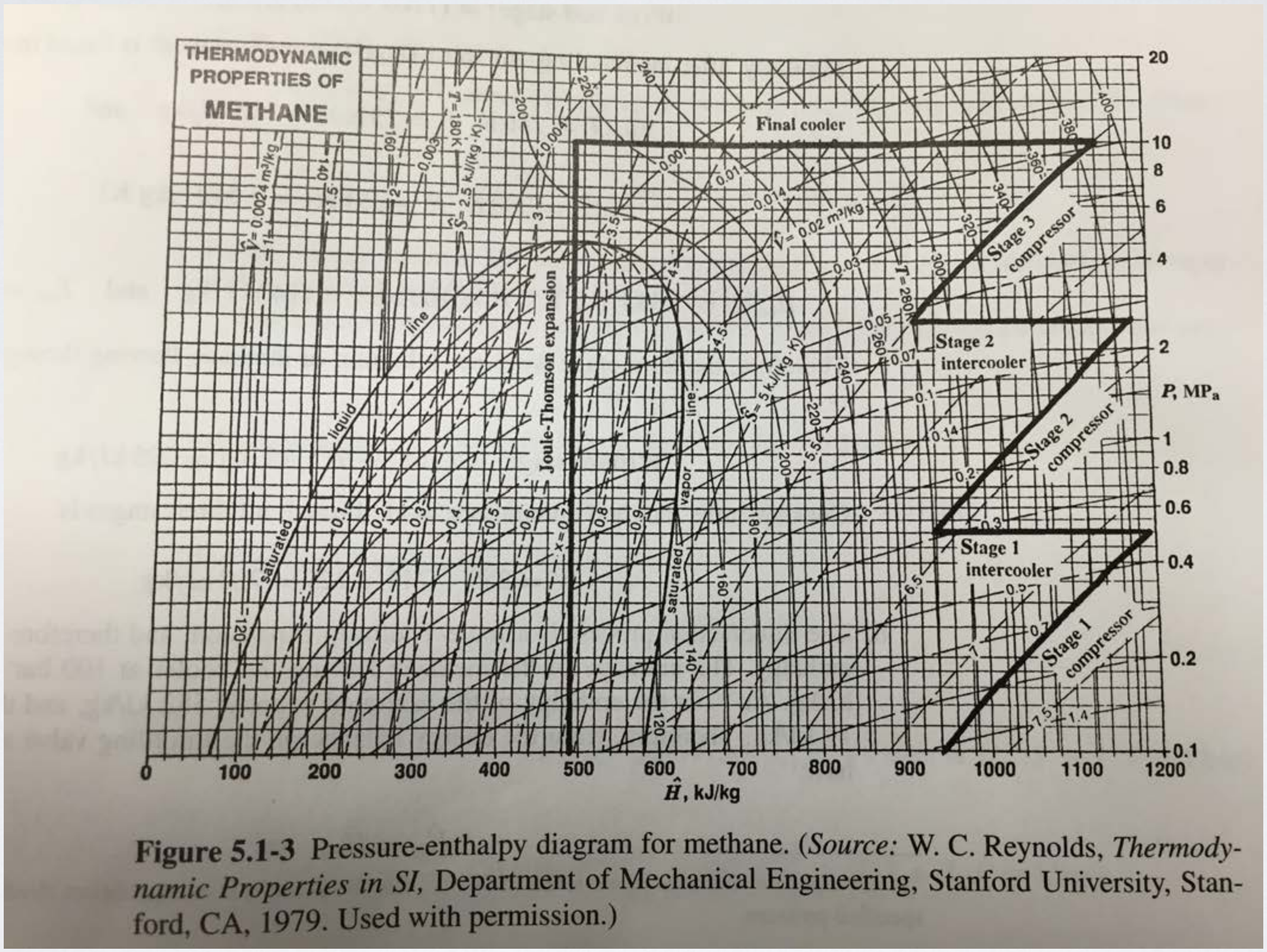


Figure 5.1-3 Pressure-enthalpy diagram for methane. (*Source:* W. C. Reynolds, *Thermodynamic Properties in SI,* Department of Mechanical Engineering, Stanford University, Stanford, CA, 1979. Used with permission.)

PILOT PLANT FACILITY

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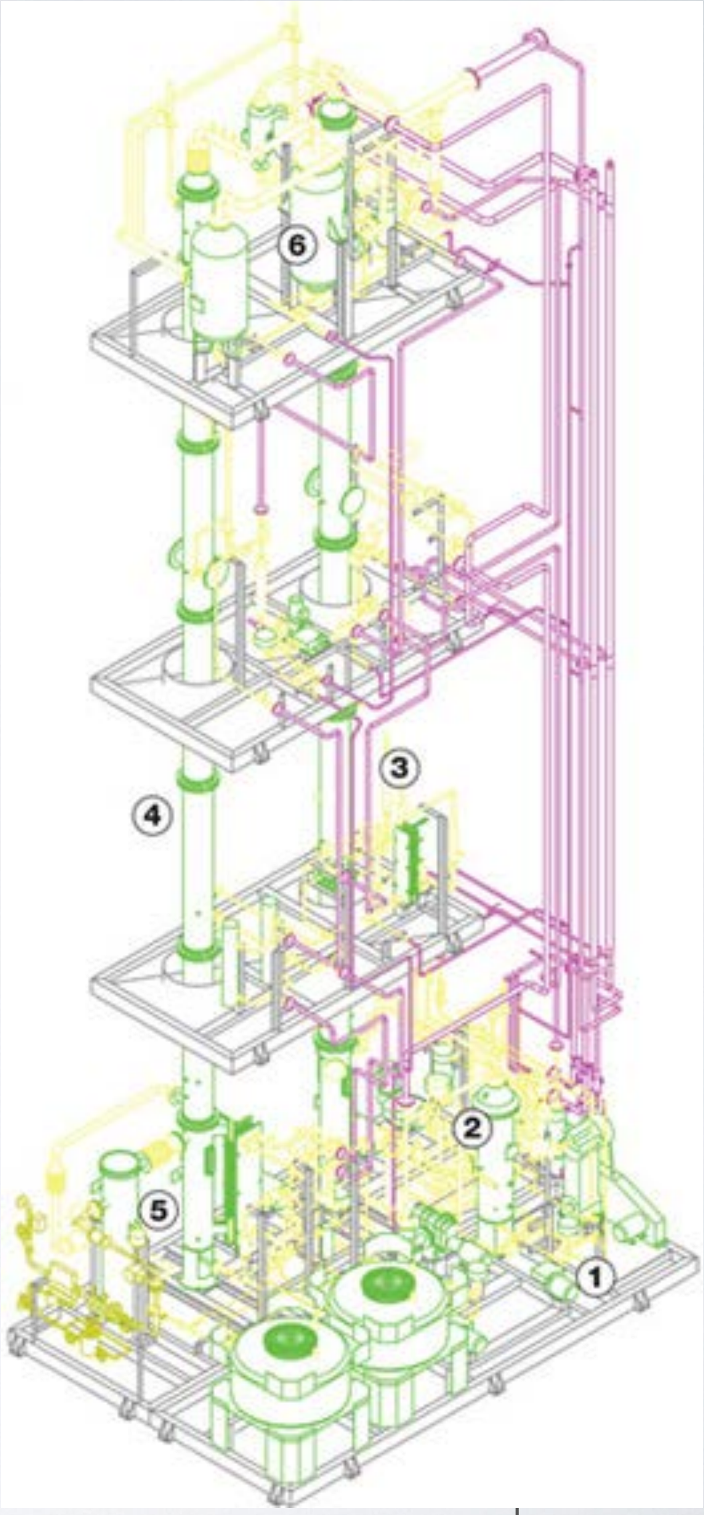
SCHEMATIC OF IMPERIAL PILOT PLANT



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PILOT PLANT

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THE TWO COLUMNS

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STUDENTS WORKING IN PLANT

University of Notre Dame, USA

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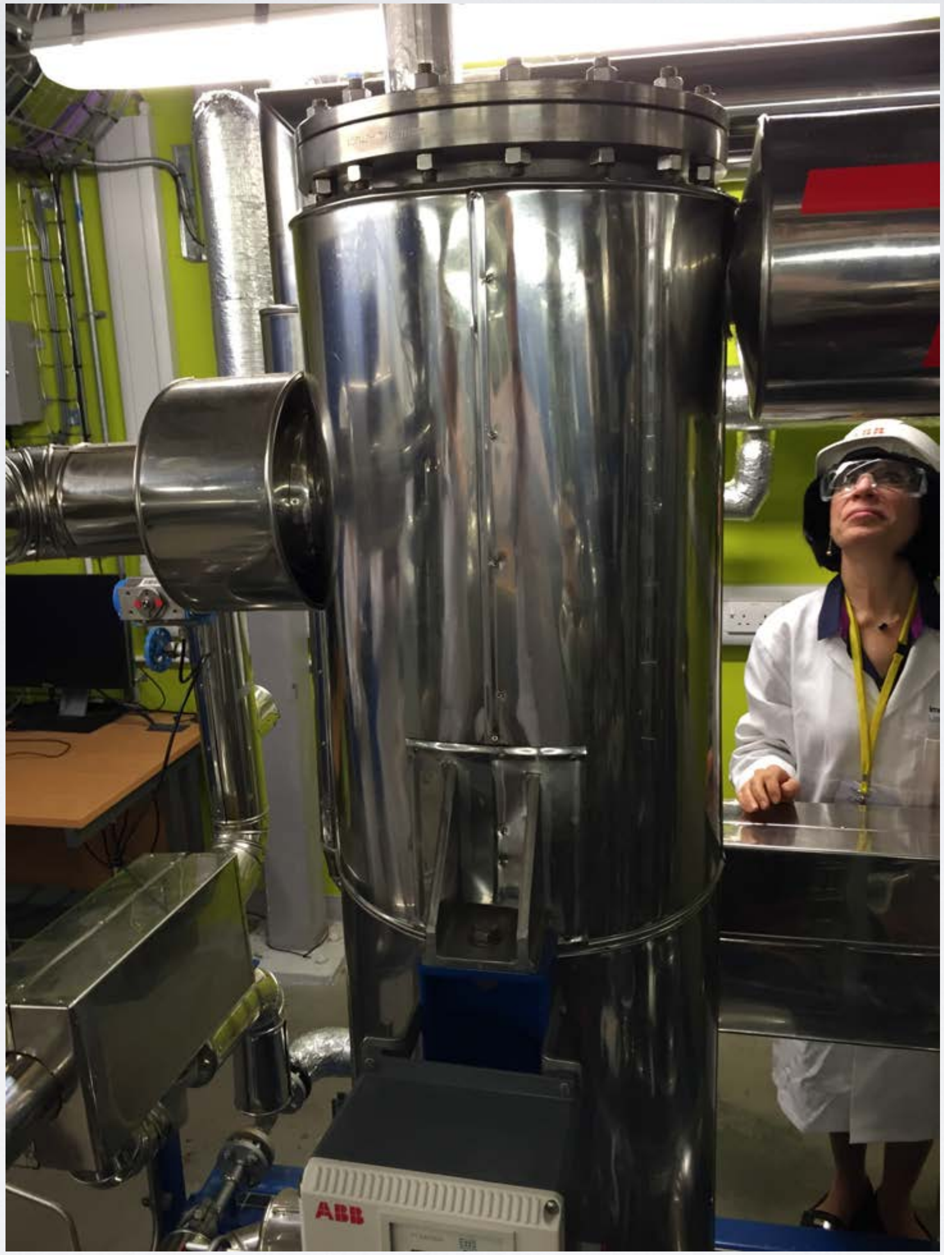
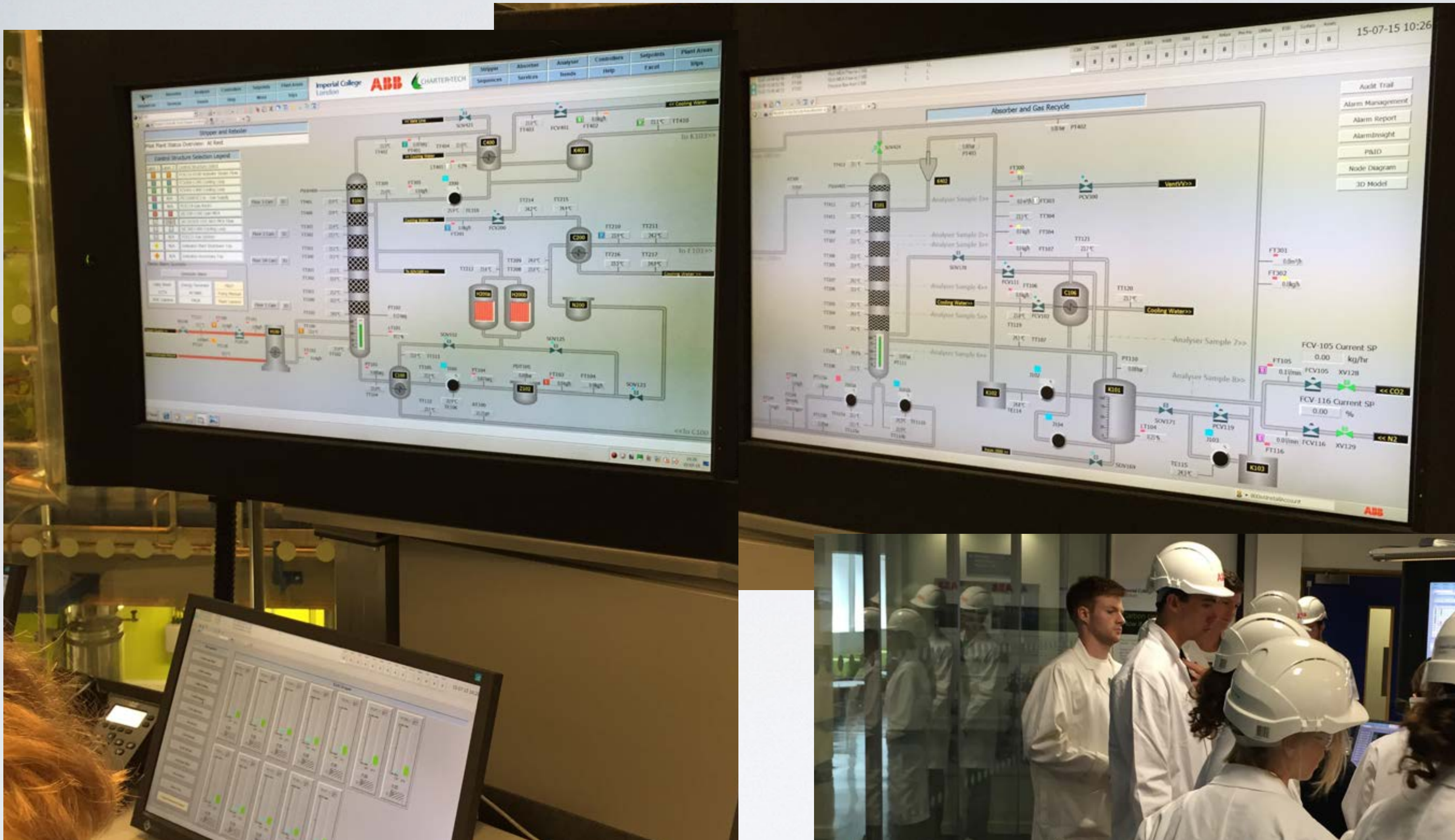
PROFESSOR SADDAWI INSPECTS THE REBOILER!



CONTROL ROOM



LOTS OF SENSORS FOR "CONTROL"

PROCESS DIAGRAM

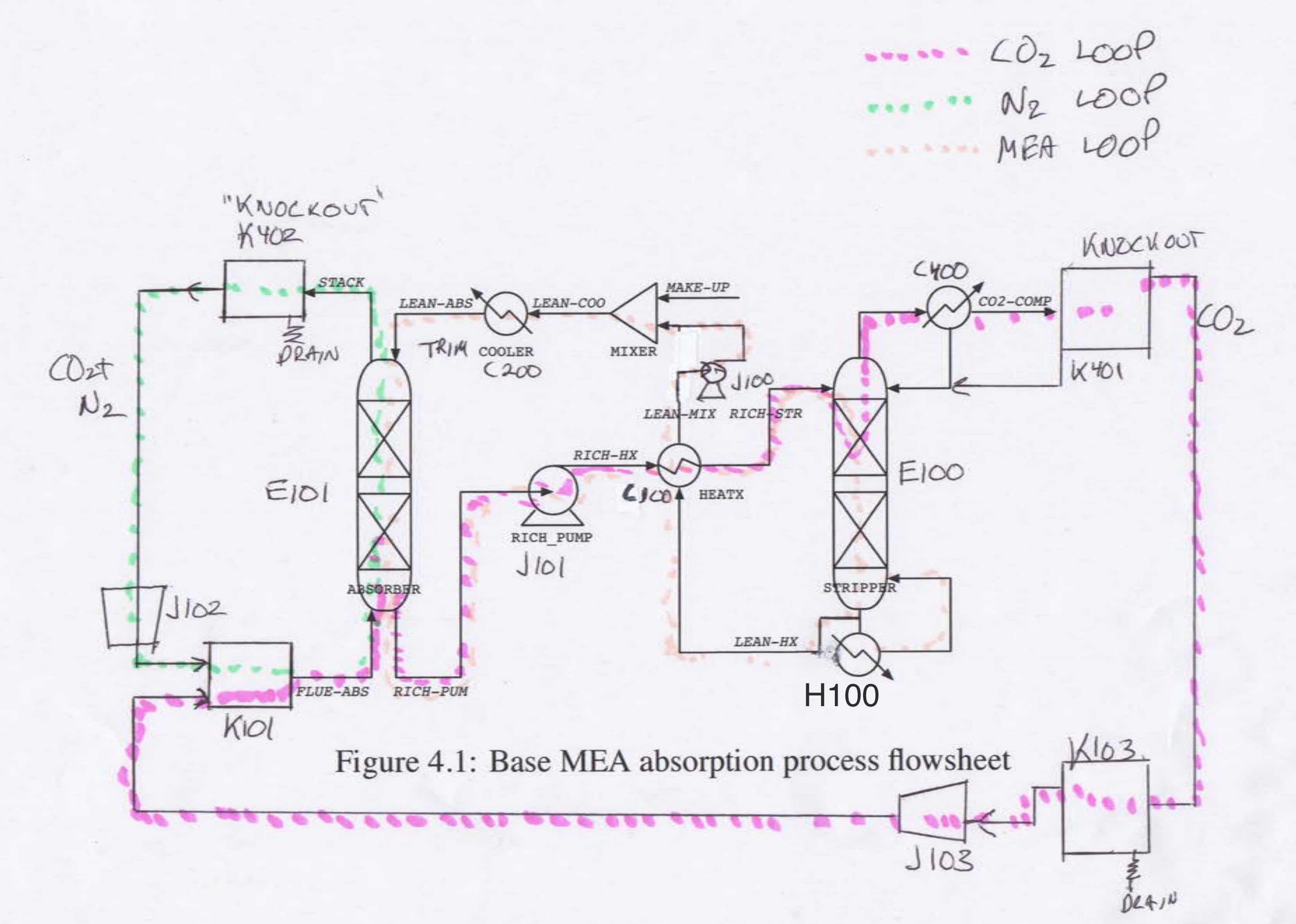
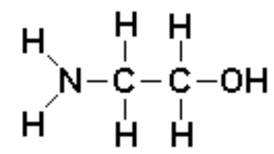


Figure 4.1: Base MEA absorption process flowsheet

SOLVENT

- Monoethanolamine (15% in water)



monoethanol-amine (MEA)

- Reactions with CO_2 and water

$$2\,H_2O \rightleftharpoons OH^- + H_3O^+ \tag{4.1}$$
$$CO_2 + 2\,H_2O \rightleftharpoons HCO_3^- + H_3O^+ \tag{4.2}$$
$$HCO_3^- + H_2O \rightleftharpoons CO_3^{2-} + H_3O^+ \tag{4.3}$$
$$RNH_3^+ + H_2O \rightleftharpoons RNH_2 + H_3O^+ \tag{4.4}$$
$$RNHCOO^- + H_2O \rightleftharpoons RNH_2 + HCO_3^- \tag{4.5}$$

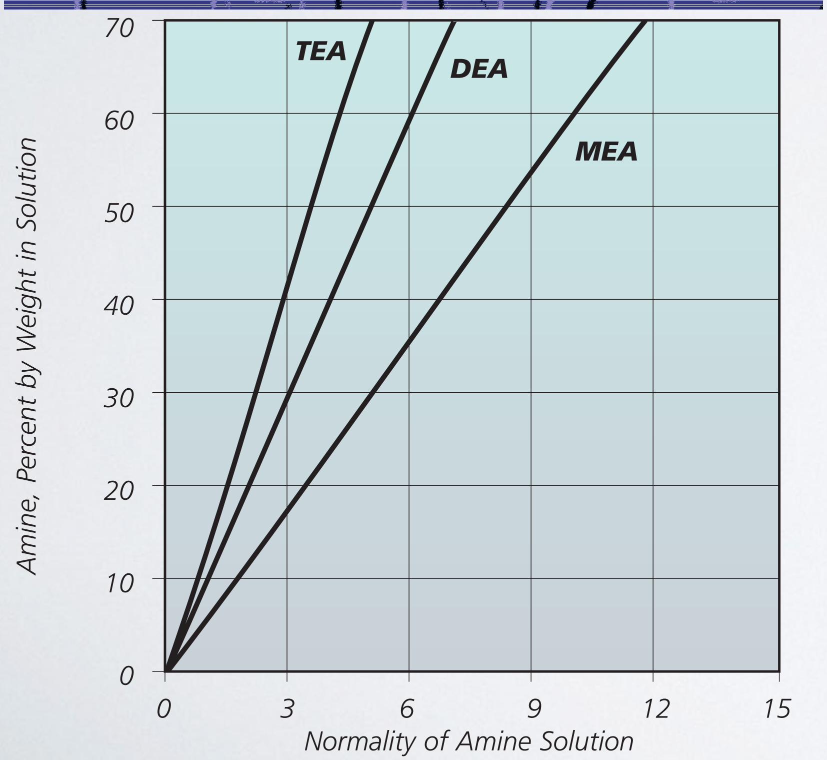


Table 1 • Typical Properties of DOW Ethanolamines

	Monoethanolamine	Diethanolamine	Triethanolamine
Formula	$H_2NCH_2CH_2OH$	$HN(CH_2CH_2OH)_2$	$N(CH_2CH_2OH)_3$
Molecular Weight	61.08	105.14	149.19
Apparent Sp. Gr. at 20/20°C	1.017	1.092[a]	1.126[f]
ΔSp. Gr./Δt at 10 to 80°C	0.00080	0.00065[b]	0.00059
Boiling Point at 760 mm Hg, °C	170.4	268[c]	335[c]
at 50mm Hg, °C	101	182	245[c]
at 10mm Hg, °C	71	150	205
Vapor Pressure at 20°C, mm Hg	<1	<0.01	<0.001
Freezing Point, °C(°F)	10.5 (50.9)	28.0 (82.4)	21.6 (70.9)[e]
Absolute Viscosity at 20°C, cP	24.1	—	921[f]
at 30°C, cP	16.2	380	404
Solubility at 20°C, % by wt			
In Water	Complete	Complete[f]	Complete[f]
Water In	Complete	—	Complete[f]
Solubility in Organic Liquids at 25°C, % by wt			
Acetone	Complete	Complete[f]	Complete
Benzene	0.6	0.03	2
Carbon Tetrachloride	0.1	0.01	Complete
Ethyl Ether	0.7	0.5	2
Heptane	0.1	0.03	<0.03
Methanol	Complete	Complete[f]	Complete
Surface Tension, dynes/cm	48.3[d]	48.5[g]	48.9[d]
Refractive Index, n_D^{20}	1.4539	1.4747[g]	1.4852[f]
$\Delta N_D/\Delta t$ at 20 to 40°C per °C	0.00034	0.00027[b]	0.00020
Flash Point, °C (°F)	96 (205)[h]	191 (375)[h]	208 (407)[h]

(a) At 30/20°C
(b) At 35 to 65°C
(c) Extrapolated (decomposes)
(d) At 25°C
(e) Supercools easily
(f) Supercooled liquid
(g) At 30°C
(h) Determined by ASTM Method D 93, using the Pensky-Martens Closed Cup

DATA FOR CO2 INTO MEA

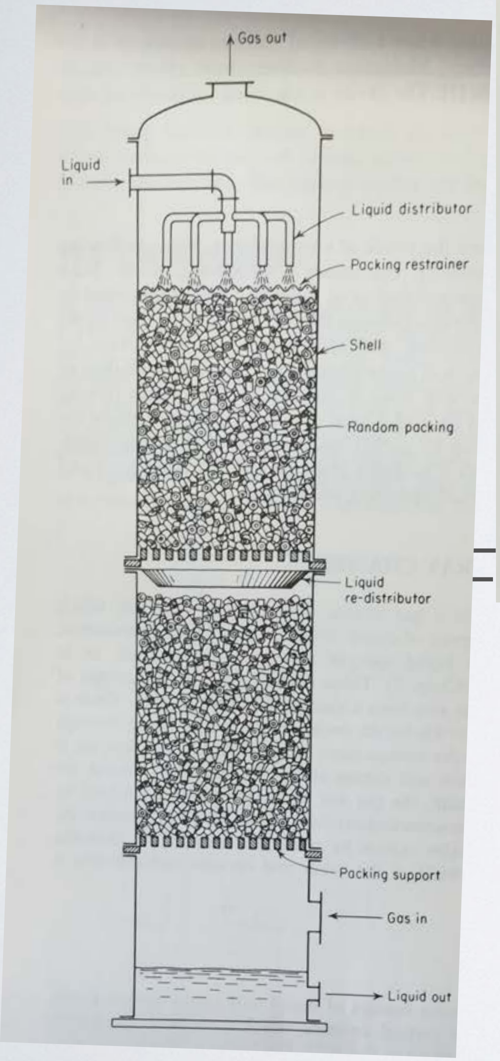
Table 14-37A. Smoothed Values for Solubility of Carbon Dioxide in 15.3 Weight Per Cent Monoethanolamine

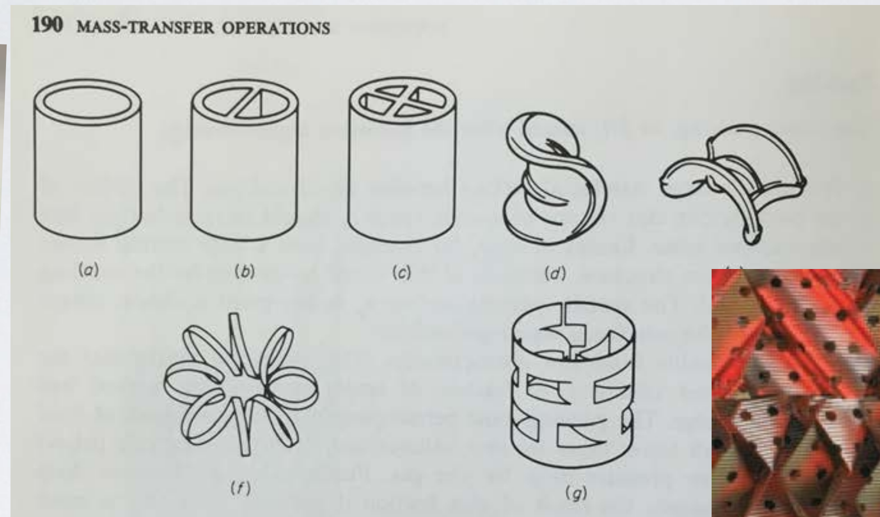
Partial pressure CO_2, mm. Hg	Moles carbon dioxide per mole amine					
	40°C.	60°C.	80°C.	100°C.	120°C.	140°C.
1	0.383	.....	.....	0.096		
5	.438	.....	.....	.152		
10	.471	0.412	.....	.194		
30	.518	.459	0.379	.265		
50	.542	.482	.405	.299		
70	.558	.498	.422	.322	0.200	
100	.576	.516	.442	.347	.227	0.109
200	.614	.552	.481	.393	.281	.162
300	.639	.574	.505	.423	.314	.194
400	.657	.591	.523	.442	.336	.219
500	.672	.605	.538	.458	.355	.237
600	.686	.615	.550	.472	.370	.254
760	.705	.631	.566	.489	.390	.275
1000	.727	.650	.584	.509	.413	.300
2000	.....	.702	.637	.562	.476	.366
3000	.....	.....	.669	.596	.513	.408
5000	.....	.....	.712	.641	.562	.464
7000	.....	.....	.742	.672	.597	.500

Table 14-36A. Equilibrium Data for Monoethanolamine Solutions

Temp., °C.	Normality of amine	Partial pressure of CO_2 mm. Hg	Liquid concentration, moles CO_2 per mole amine
0.0	0.5	745.8	1.110
.0	.5	256.3	0.990
.0	.5	45.3	.817
.0	.5	10.6	.675
25.0	.5	735.7	1.004
25.0	.5	251.8	0.886
25.0	.5	99.6	.795
25.0	.5	44.2	.720
25.0	.5	10.8	.607
50.0	.5	661.3	.880
50.0	.5	228.3	.757
50.0	.5	40.1	.596
75.0	.5	475.8	.685
75.0	.5	130.3	.584
75.0	.5	50.0	.476
0.0	2.0	754.4	.900
.0	2.0	206.1	.776
.0	2.0	79.4	.718
.0	2.0	11.4	.601
25.0	2.0	736.4	.795
25.0	2.0	252.2	.697
25.0	2.0	98.6	.623
25.0	2.0	44.2	.589
25.0	2.0	10.6	.527
50.0	2.0	668.2	.698
50.0	2.0	183.1	.607
50.0	2.0	70.9	.556
50.0	2.0	10.1	.489
75.0	2.0	477.0	.560
75.0	2.0	130.6	.474
75.0	2.0	51.1	.430

PACKED TOWER FOR GAS ABSORPTION




190 MASS-TRANSFER OPERATIONS

(a) (b) (c) (d) (f) (g)

Figure 6.28 Some random tower packings: (*a*) Raschig rings, (*b*) Lessing ring, (*c*) … Berl saddle *(courtesy of Maurice A. Knight)*, (*e*) Intalox saddle *(Chemical Processing … Norton Co.)*, (*f*) Tellerette *(Ceilcote Company, Inc.)*, and (*g*) pall ring *(Chemical P… Division, Norton Co.)*.

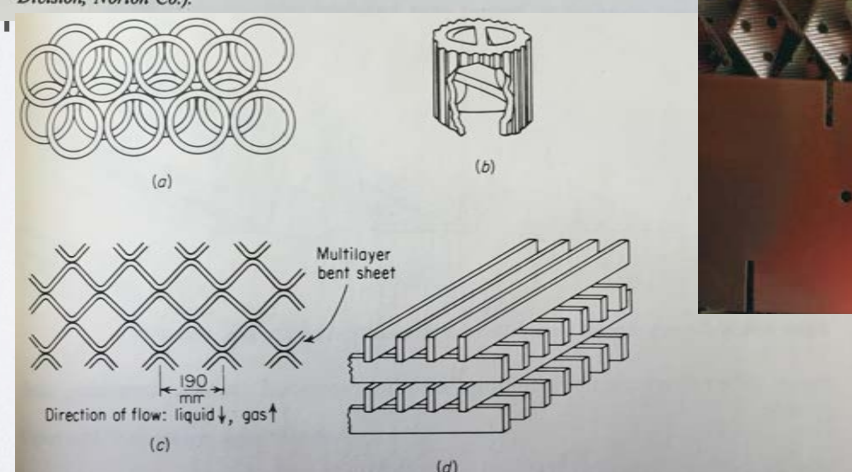
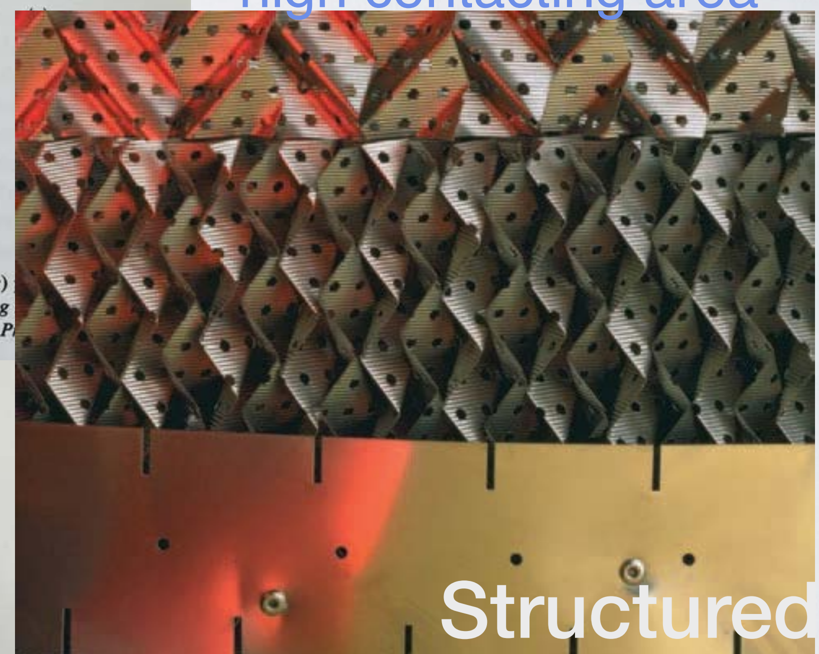


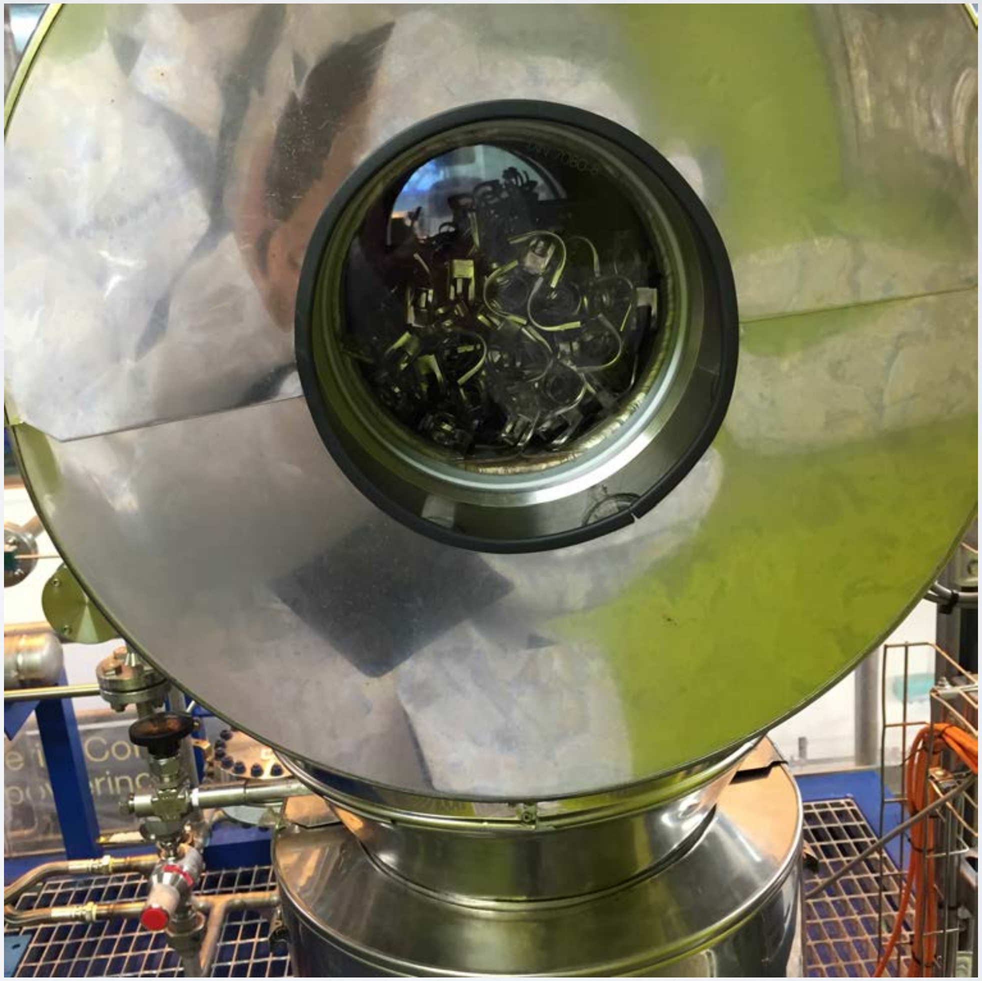
Figure 6.29 Regular, or stacked, packings: (*a*) Raschig rings, stacked staggered (top view), (*b*) double spiral ring *(Chemical Processing Products Division, Norton Co.)*, (*c*) section through expanded-metal-lath packing, (*d*) wood grids.

350 m^2/m^3

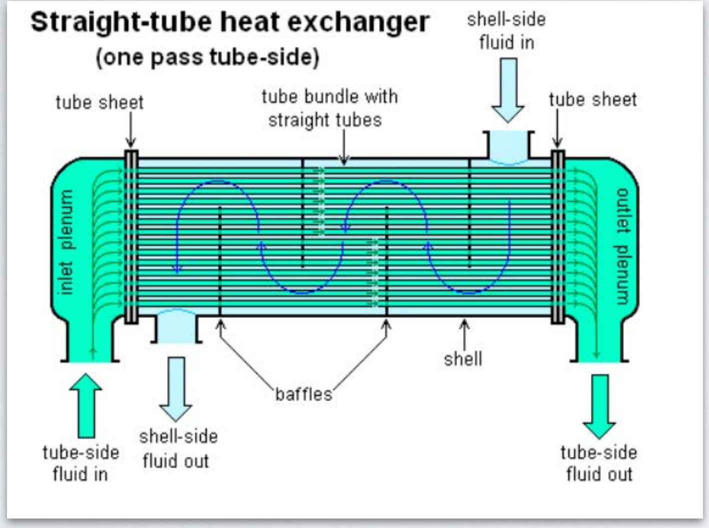
high contacting area

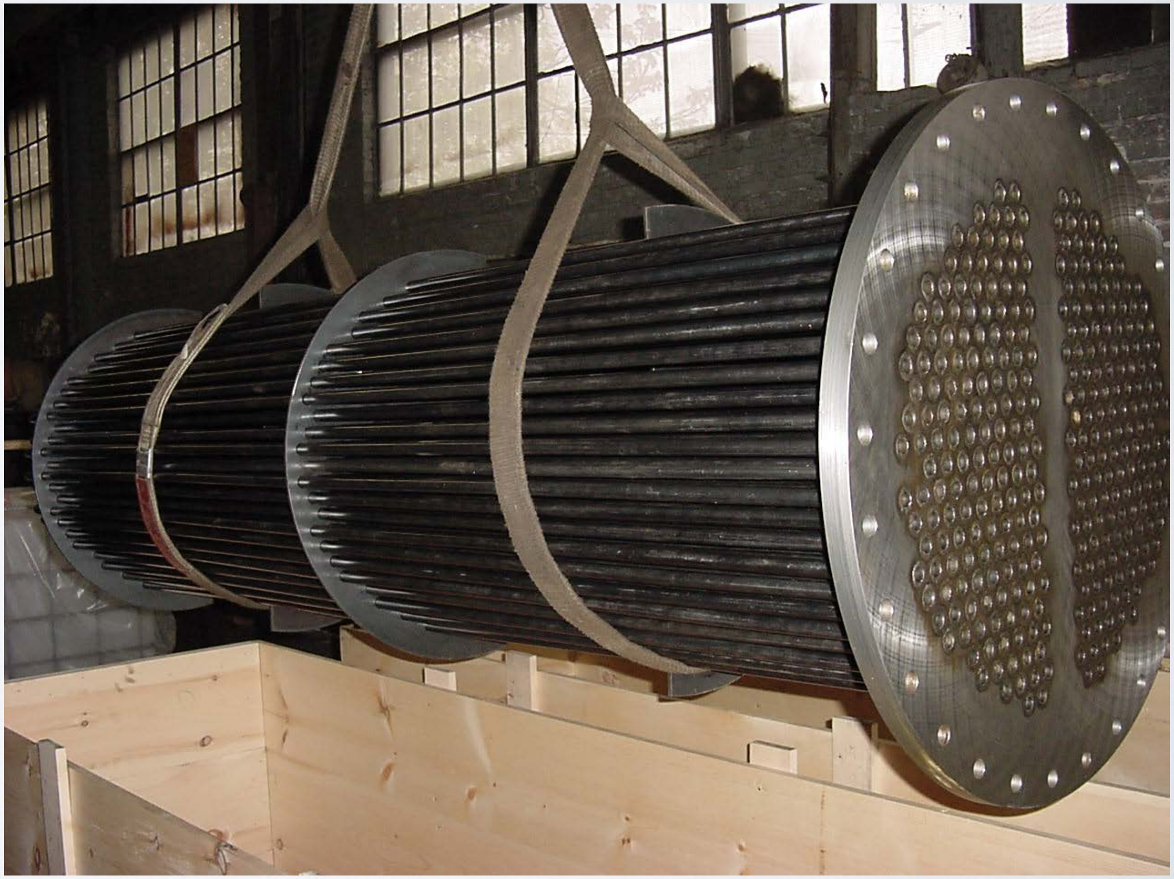


RANDOM PACKING IN STRIPPING COLUMN



HEAT EXCHANGERS





IMPERIAL HEAT EXCHANGERS

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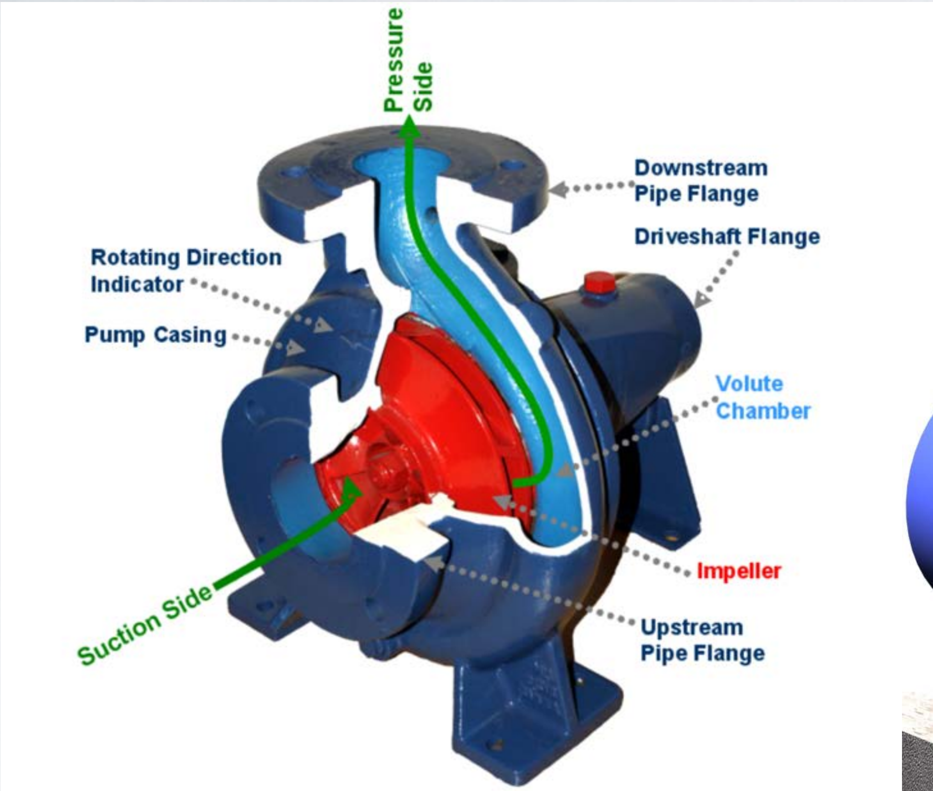
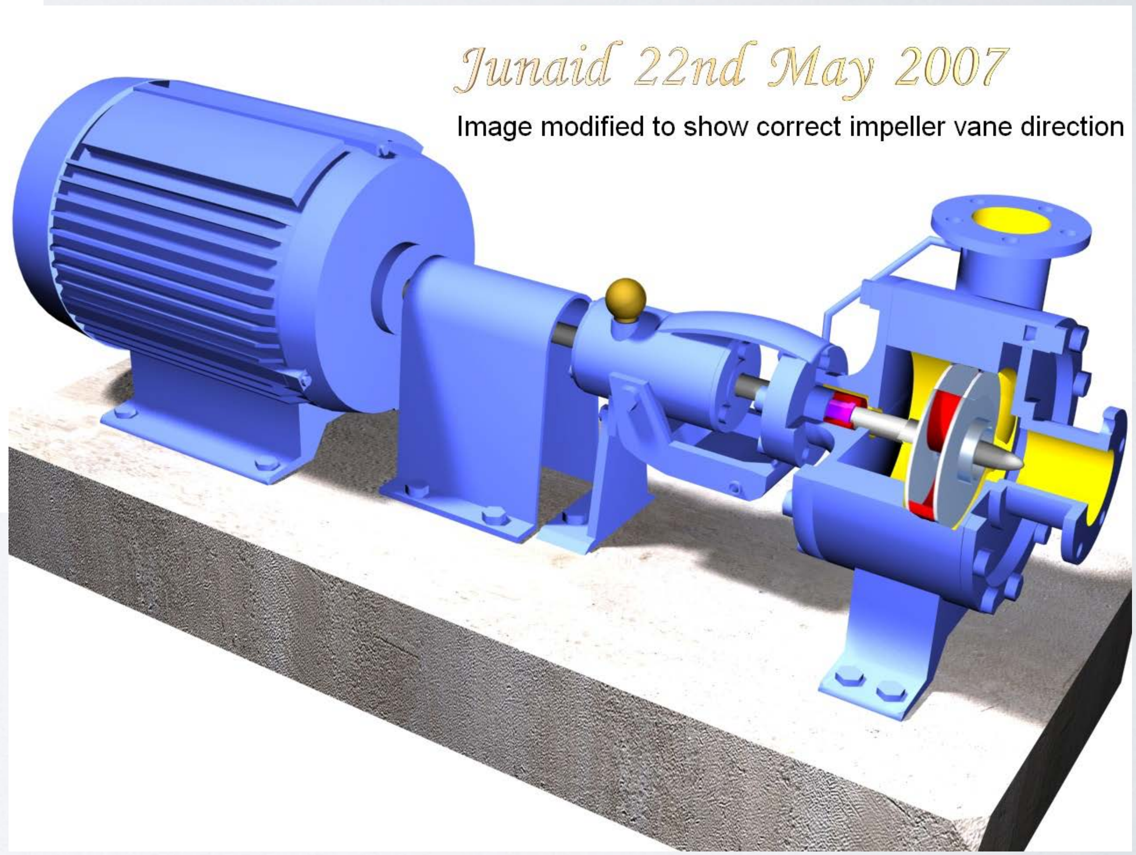
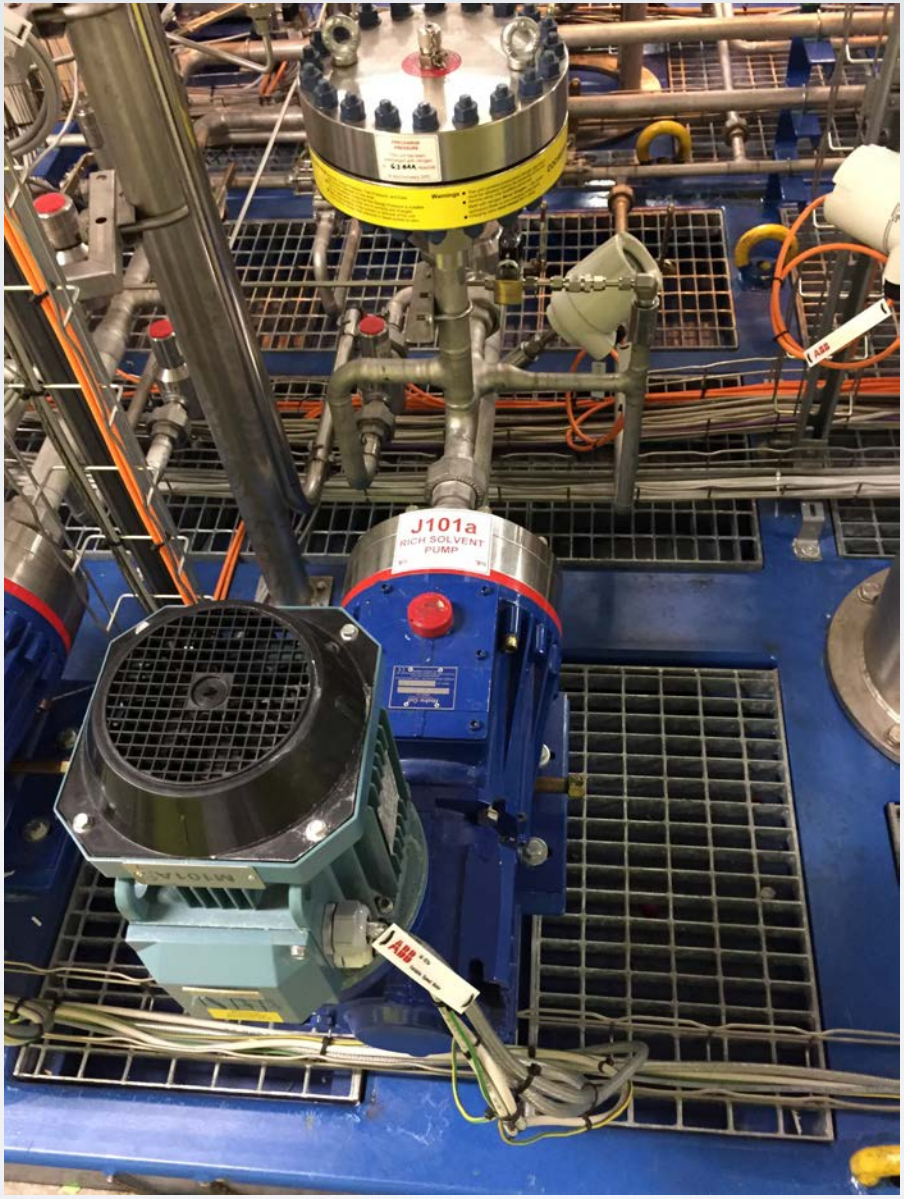
PUMPS


Pressure Side
Downstream Pipe Flange
Driveshaft Flange
Rotating Direction Indicator
Pump Casing
Volute Chamber
Impeller
Suction Side
Upstream Pipe Flange


Junaid 22nd May 2007
Image modified to show correct impeller vane direction

PUMP FOR MEA



GAS COMPRESSOR/BLOWER

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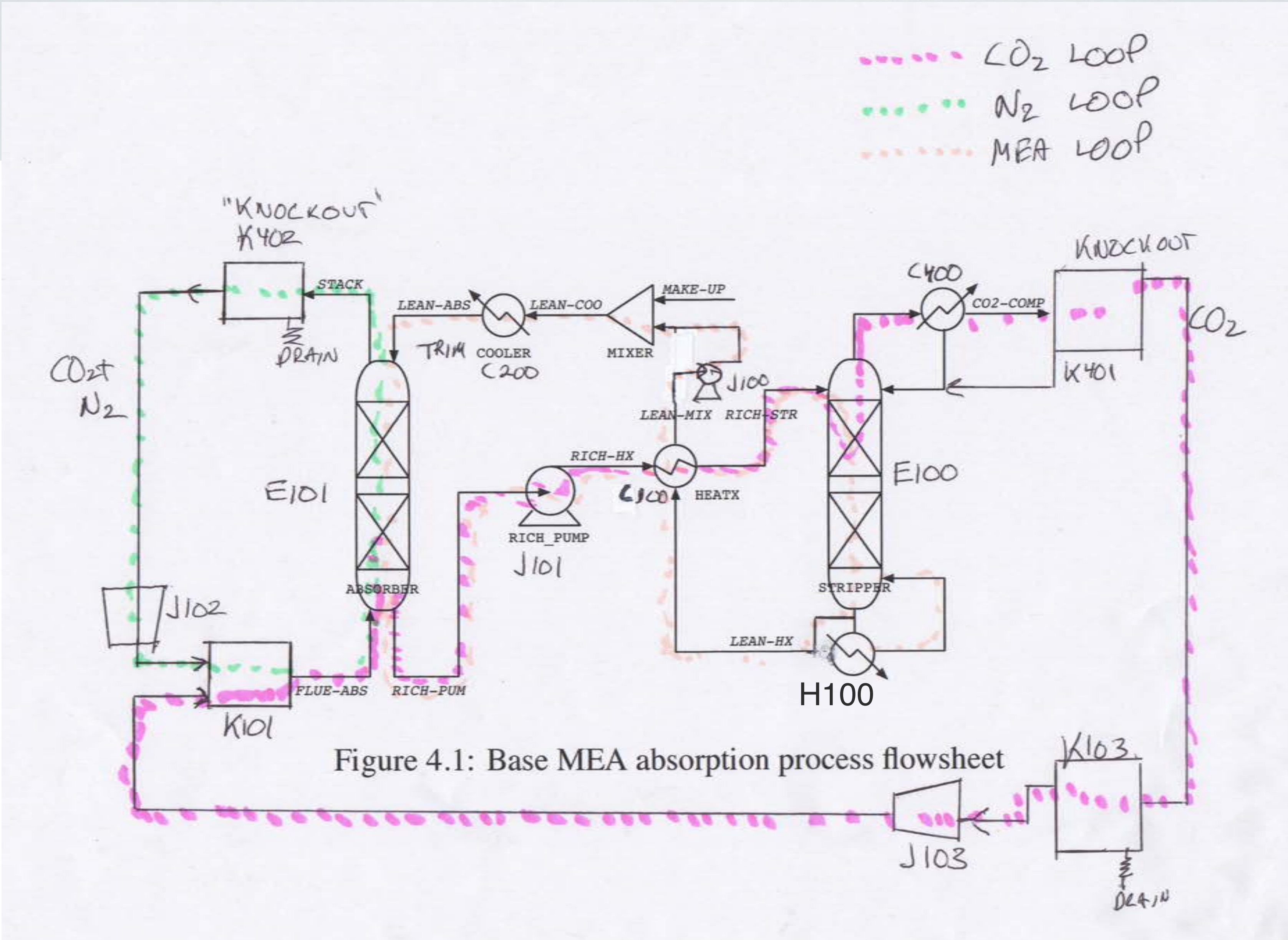
PROCESS DIAGRAM



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