P&I DIAGRAMS
PROCESS CONTROL

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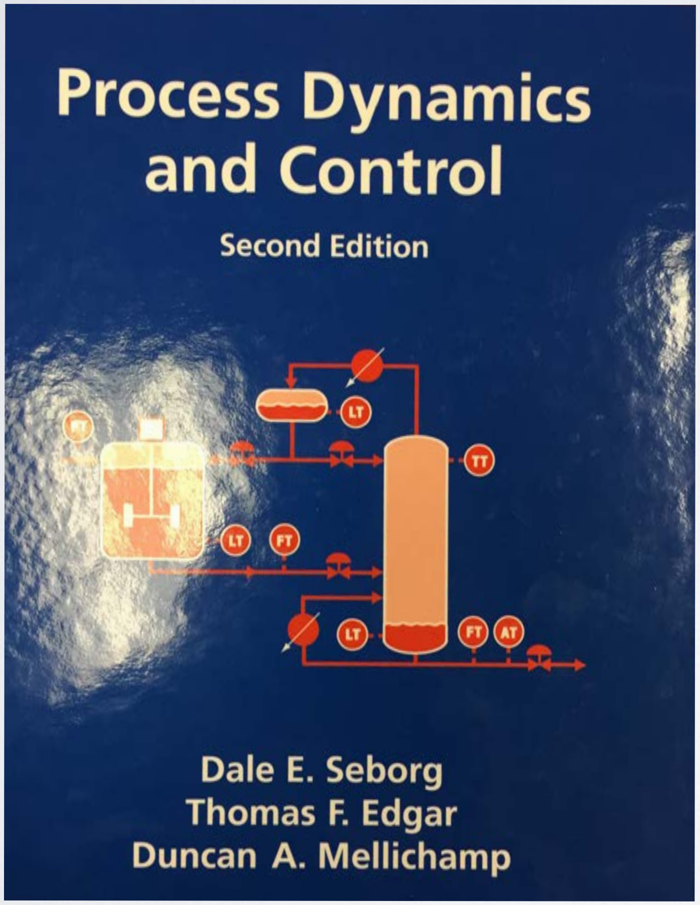
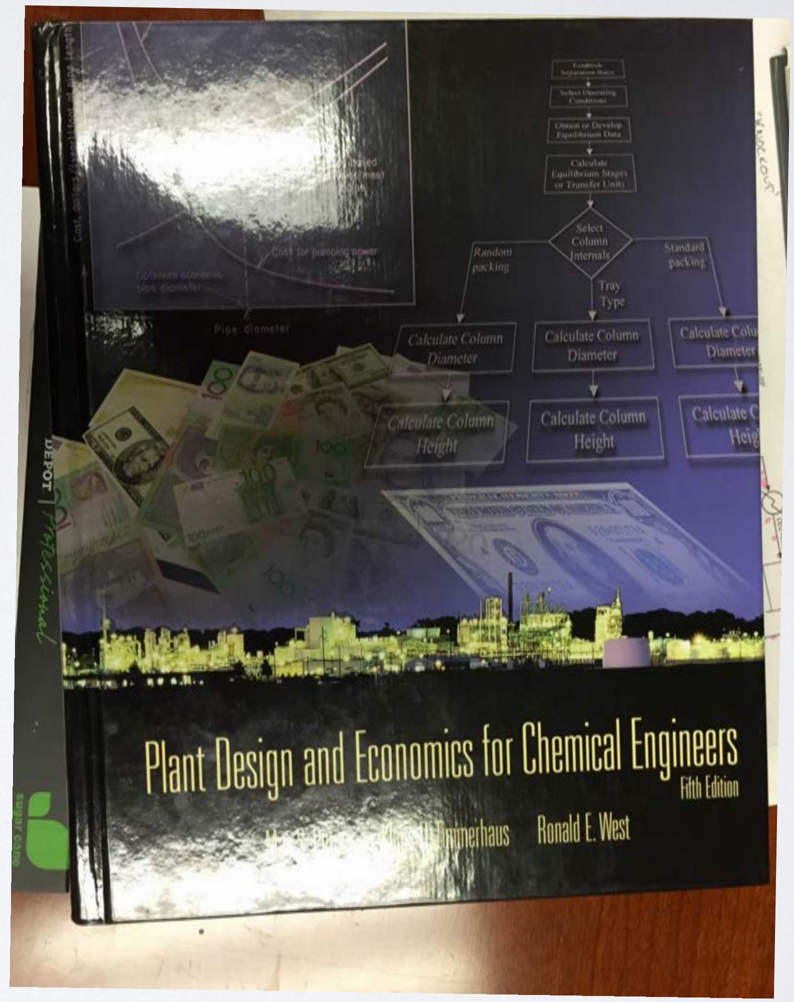
PARTIAL REFERENCES FOR TODAY





GAS ABSORPTION/STRIPING

- Mass transfer is the main "business" of the process!
- The absorber is a column packed with a structured packing
  - Inlet gas mixture of N_2 and CO_2
  - Absorption liquid is monoethanolamine in water
    - reacts reversibly with CO_2, to selectively remove CO_2 from N_2
- The stripping column is packed with a random, metal packing
  - Steam flow to reboiler, boils the mixture, reversing the reaction and the steam that is generated helps to carry the CO_2 out of the column

IMPERIAL FLOWSHEET

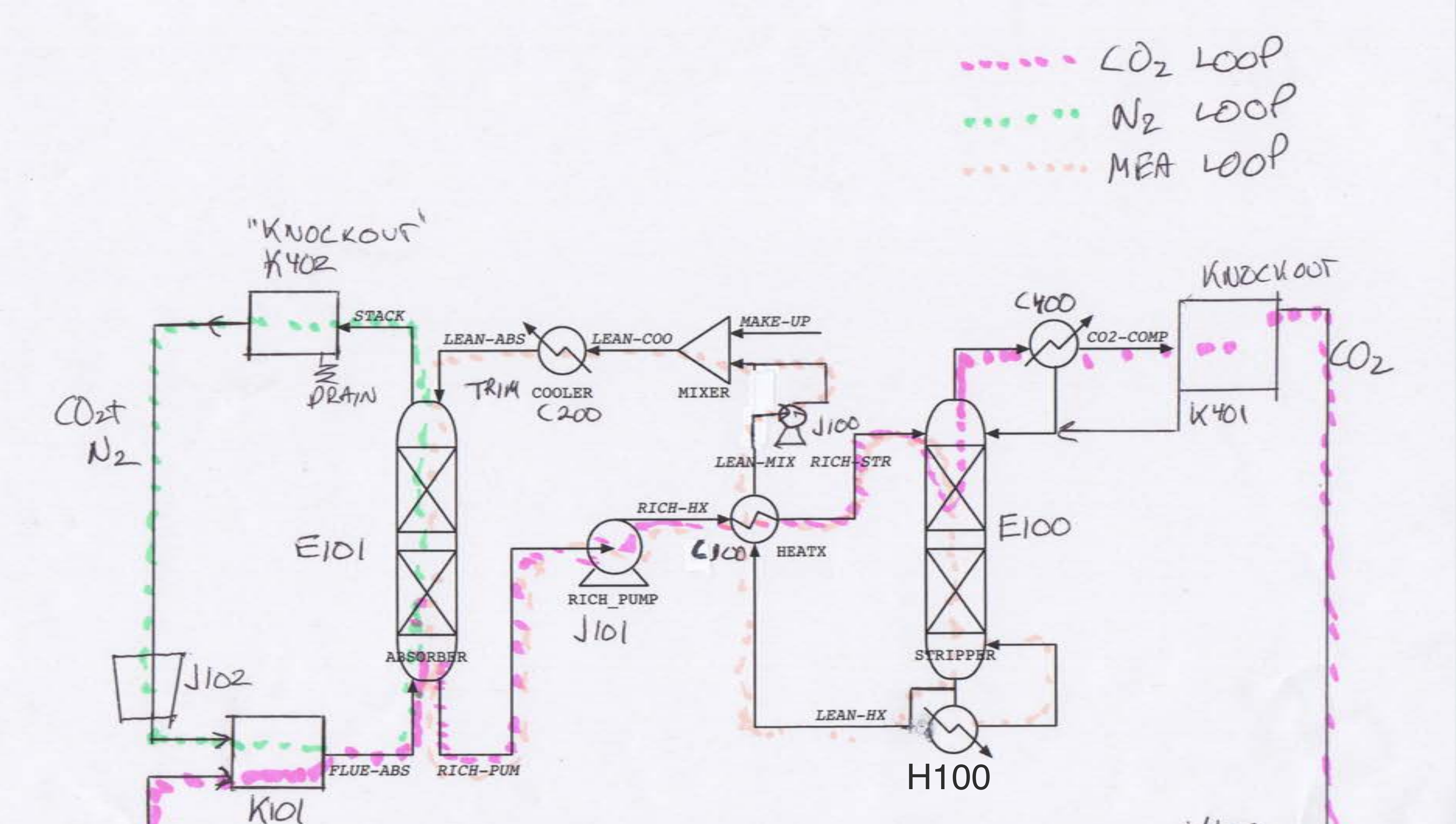


Figure 4.1: Base MEA absorption process flowsheet

PIPING AND INSTRUMENTATION DIAGRAMS

- Intended to show the details of <u>all</u> pipes, valves, sensors/transducers of the process.
- If it were "your" process, you would want to know everything.
- There may be bypasses, multiple pumps, extra valves, heat exchangers in series, backup thermocouples, …
    - that are not shown on the process flow diagram but might be important in an emergency or just for maintenance.
- The Imperial Instructors take this knowledge of the hardware very seriously so you will get a lot of time to trace every connection in the plant.

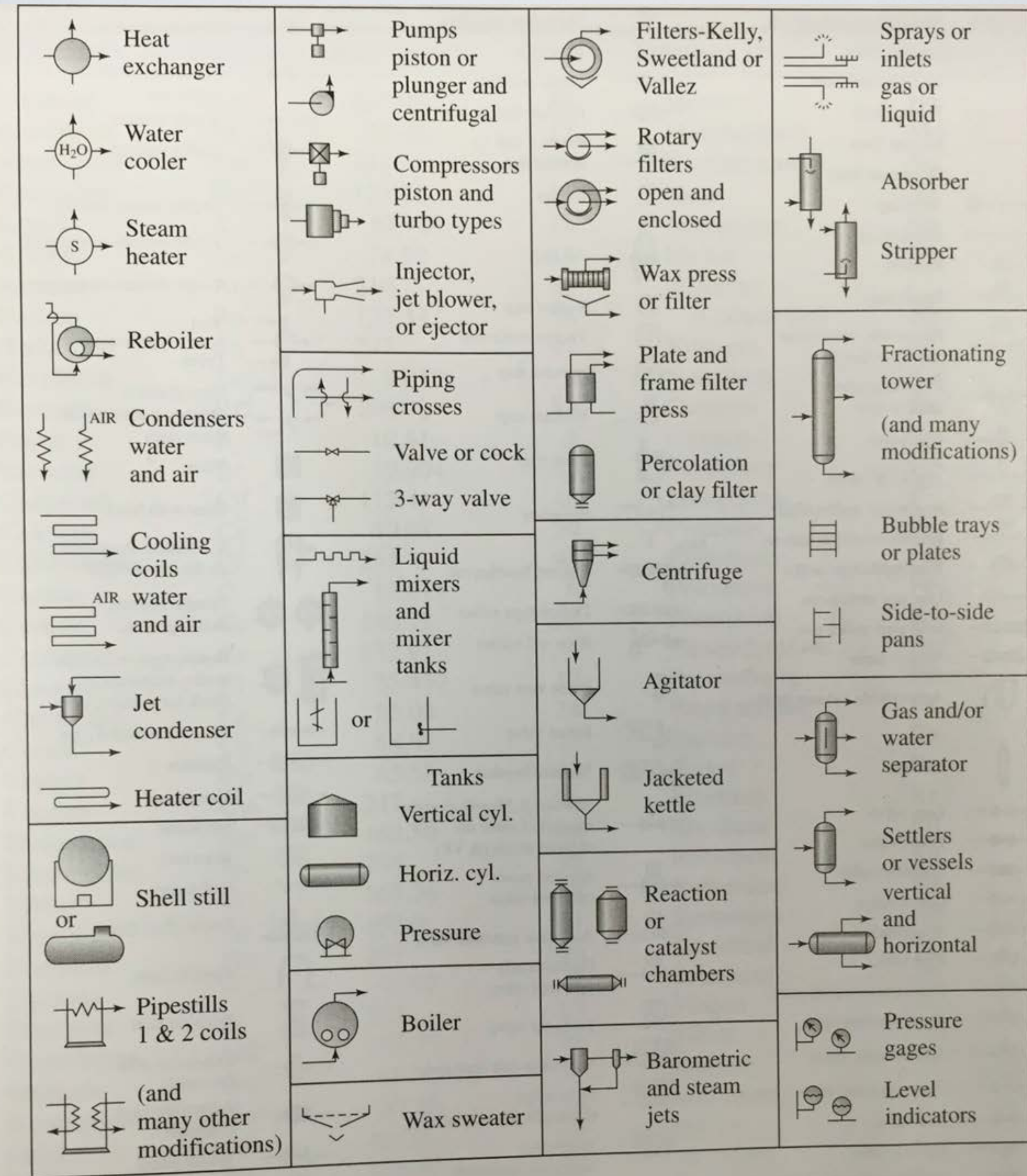


Figure D-5
Equipment symbols

Figure D-6
Flowsheet symbols, particularly for detailed equipment flowsheets. *(Courtesy of the*

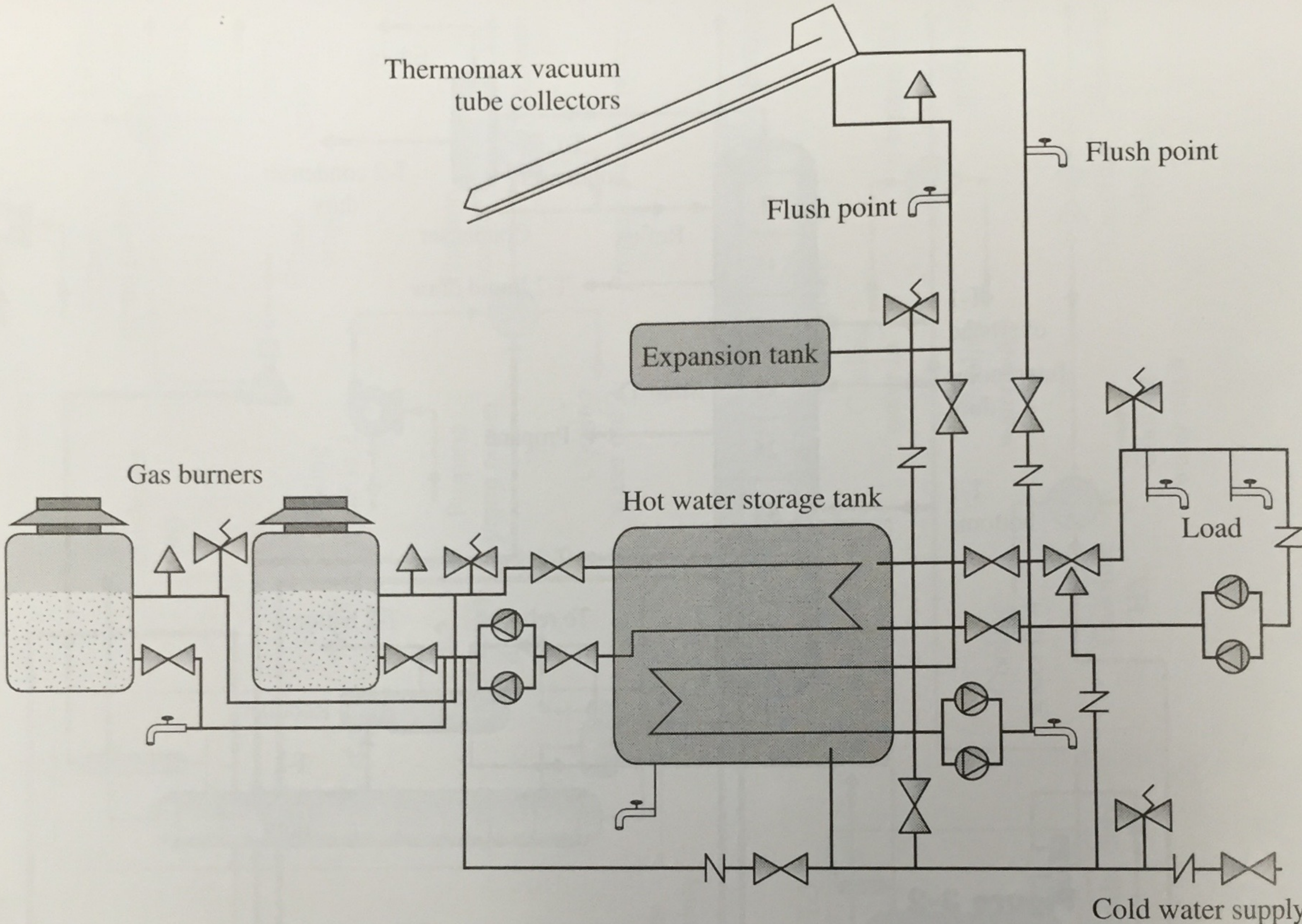
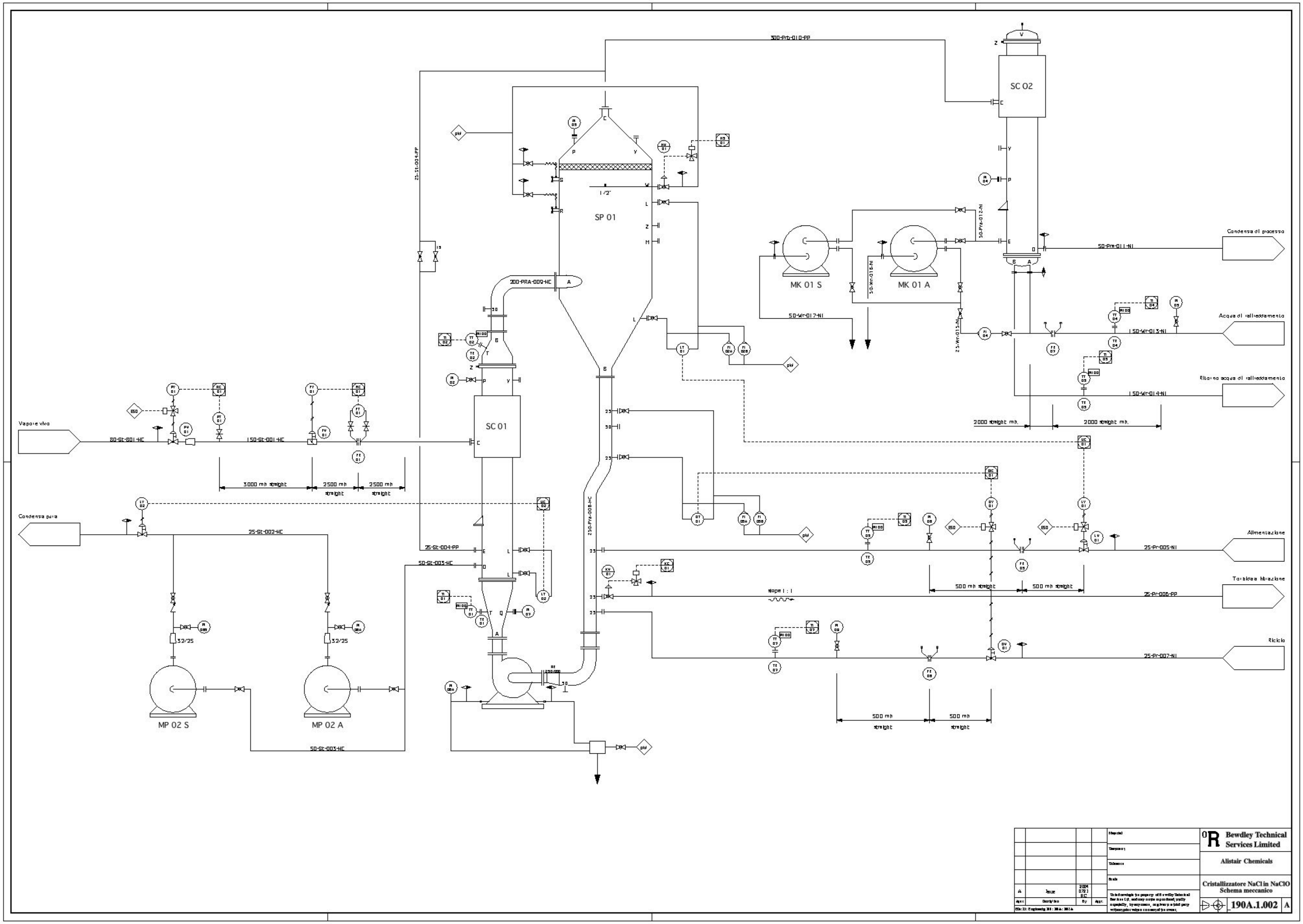


Figure 3-3
Piping and instrumentation diagram for a commercial integrated solar water heating system


SC 02
SP 01
SC 01
MK 01 S
MK 01 A
MP 02 S
MP 02 A
Vapore vivo
Condensa pura
Condensa di processo
Acqua di raffreddamento
Ritorno acqua di raffreddamento
Alimentazione
Torbida filtrazione
Riciclo
Bewdley Technical Services Limited
Alistair Chemicals
Cristallizzatore NaCl in NaClO
Schema meccanico
190A.1.002

IMPERIAL FLOWSHEET

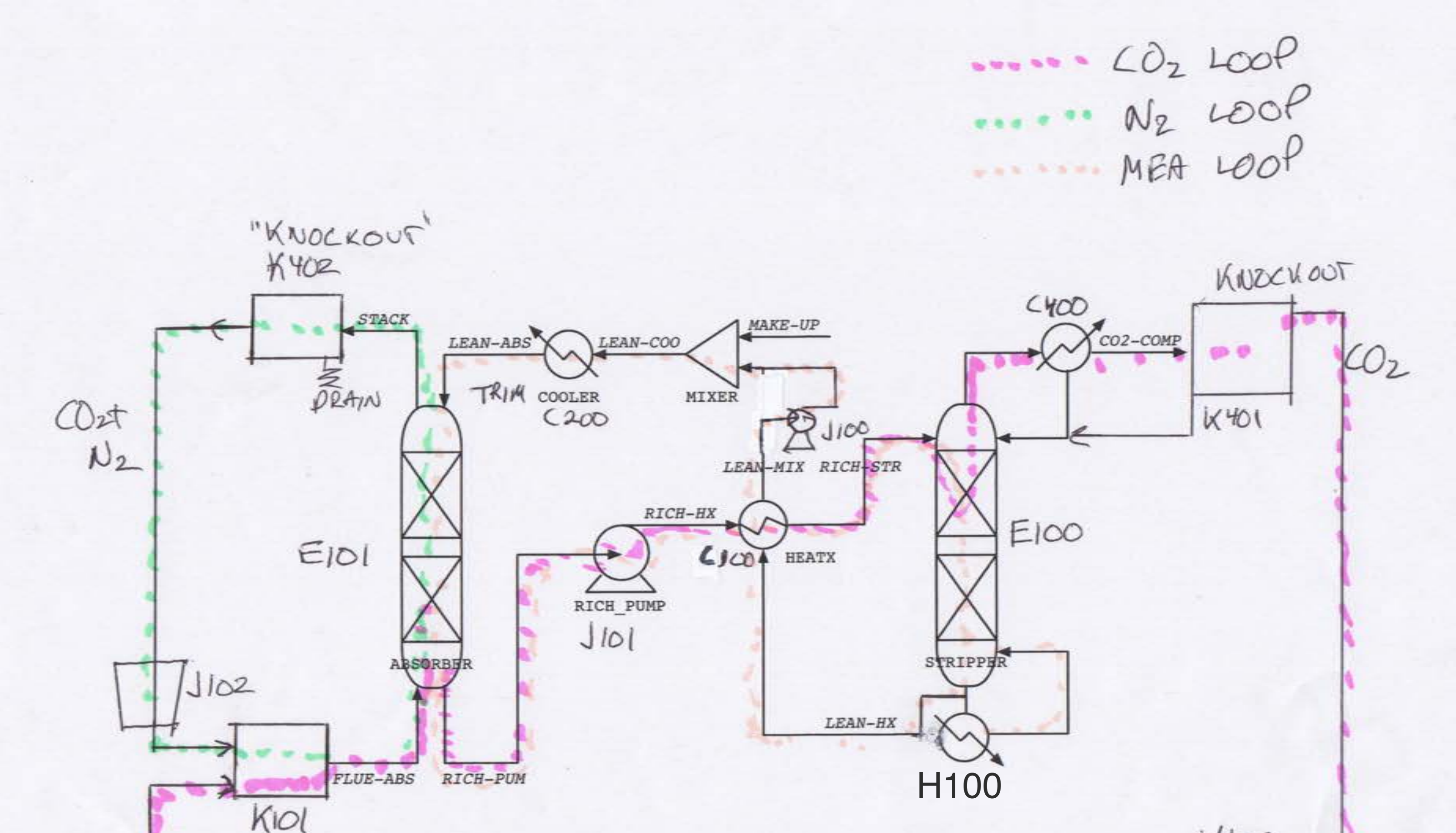
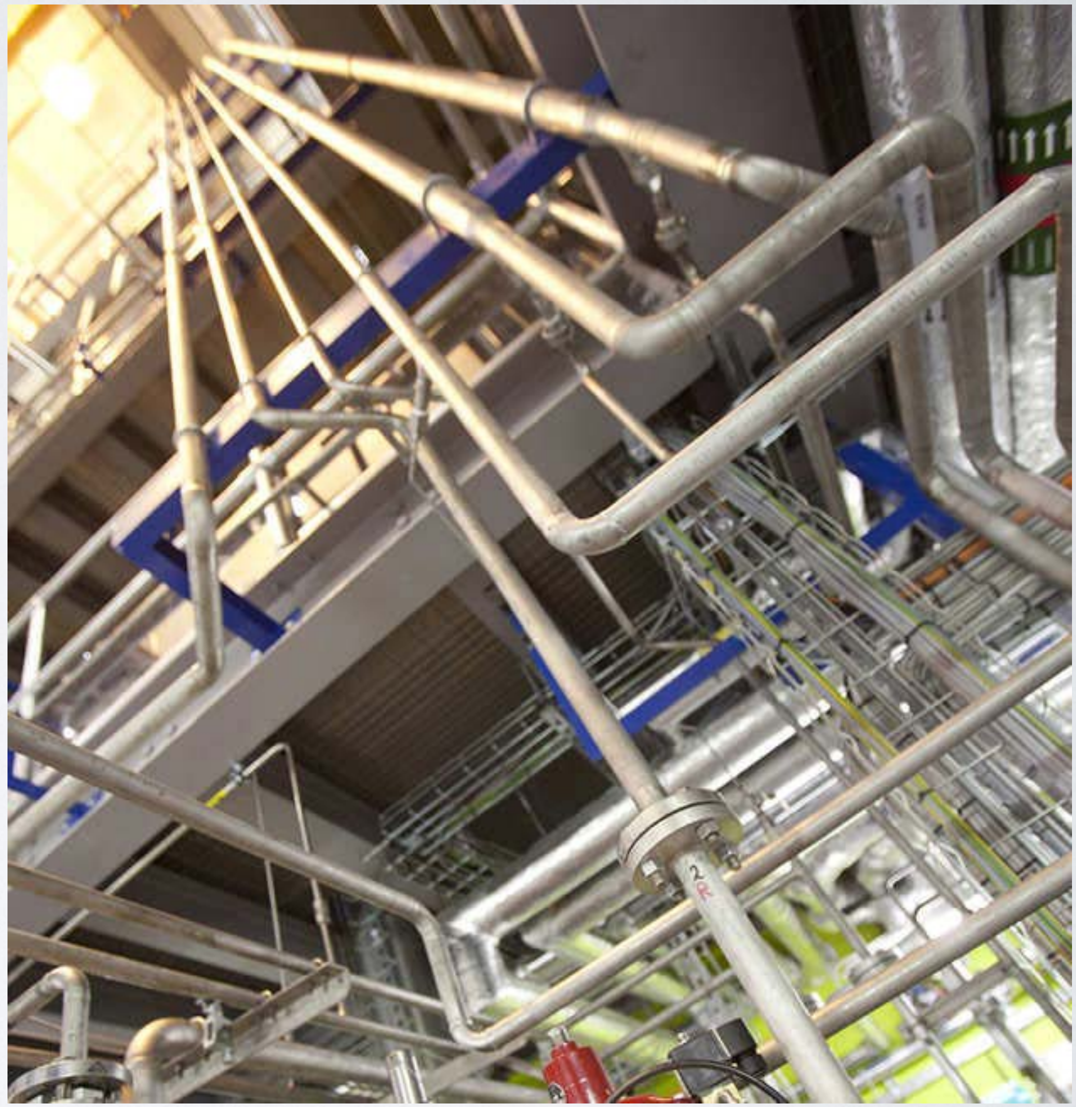


Figure 4.1: Base MEA absorption process flowsheet

PIPES!



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INFRA-RED SPECTROSCOPY

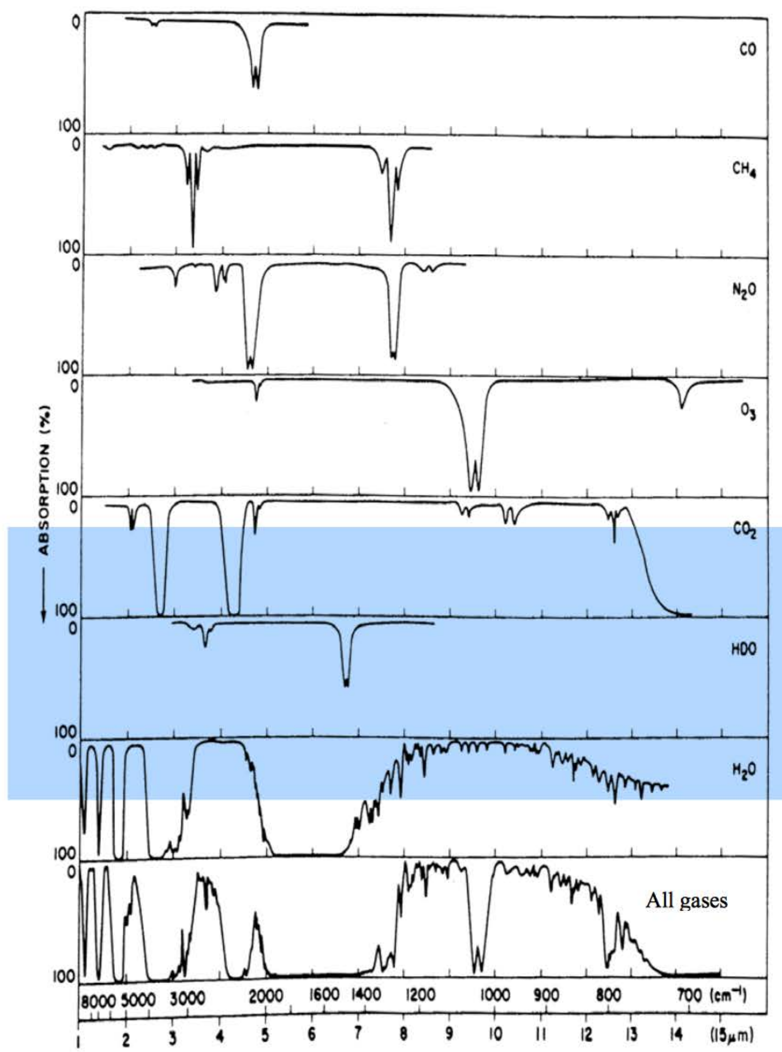


Figure 6.2 ***Low-resolution*** infrared absorption spectra of the major atmospheric gases.
(compare to Figure 6.3 that shows transmission with higher spectral resolution)

CONTROL: DRIVING A CAR

- If we just stick the basic situation…
  - You are driving a car on a "test track" with no other cars.
  - The goal is to drive a preferred "line" at constant speed.
  - How could this be accomplished?

DRIVING CAR

- *Feedback* control
  - You could be watching or listening to see/hear if you are "on" the track (or preferred "line")
    - Yes: do nothing, No: turn wheel 1/12 turn in correct direction (on/off)
    - Pretty crude and might not get you back *on* in time
  - You could have in mind a range of paths that are more or less desirable. As you get further away from a more desirable position, you correct harder
  - The second might work, but you could be *surprised* if the path changes

DRIVING CAR

- *Feedforward* Control
  - You look at the road ahead and turn the wheel according to a specified set of rules or equations that are presumed to be adequate to keep the car on track. In the simplest idealization you are not looking at where you are on the road, only what is coming up.
    - The ability to anticipate is certainly a benefit and if all goes will could get the car almost exactly on track
    - If something goes wrong, e.g., the road has bumps or some slope, then the specified turning won't work perfectly.

DRIVING A CAR

- We could also mention: Sensitivity/stability
  - Let's not..
    - or just say you will have to drive different vehicles differently!
- So what you really use is a combination of feedback and feedforward control
  - With feedback you use a complex algorithm that includes thinking of how fast the car is returning to the path.

PROCESS CONTROL

- These same principles apply to chemical processes.
  - Feedback to make sure you are on track
  - Feedforward to anticipate "upsets" — that could be caused by fluctuations in the feed concentration or temperature
- For either driving or a chemical process, you need specifications (e.g., concentration) from which you create "setpoints".

SIMPLE PROCESS EXAMPLE

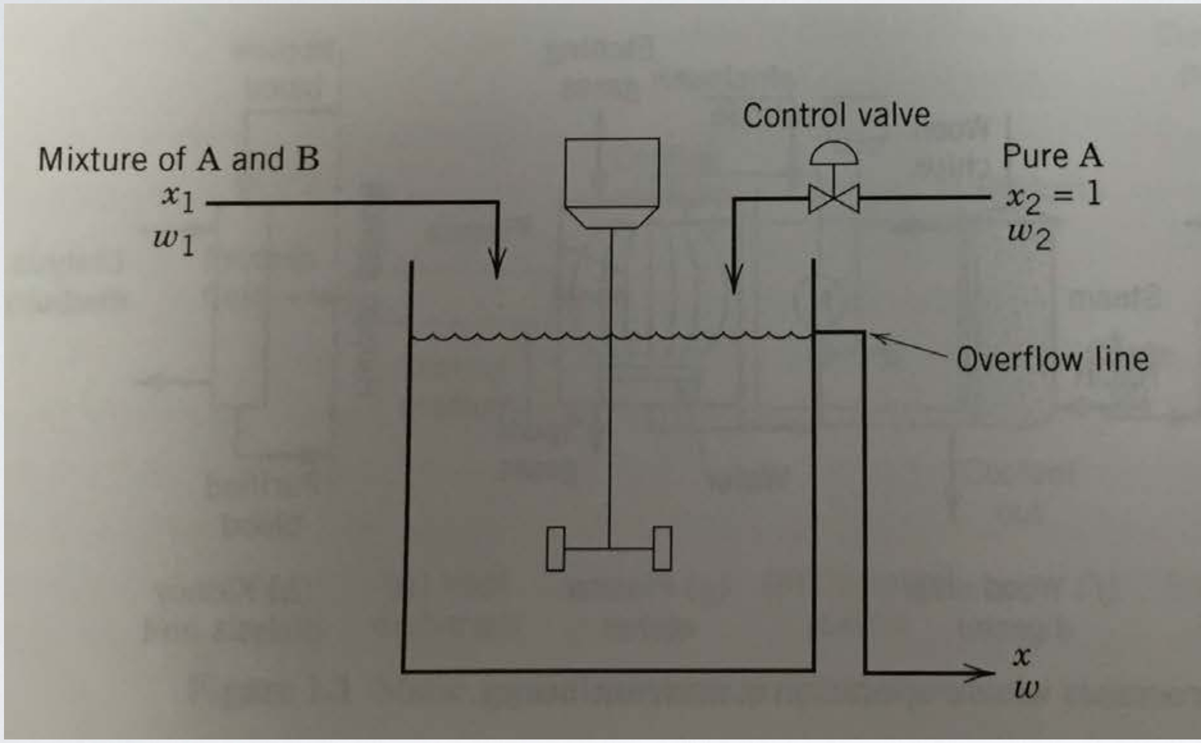
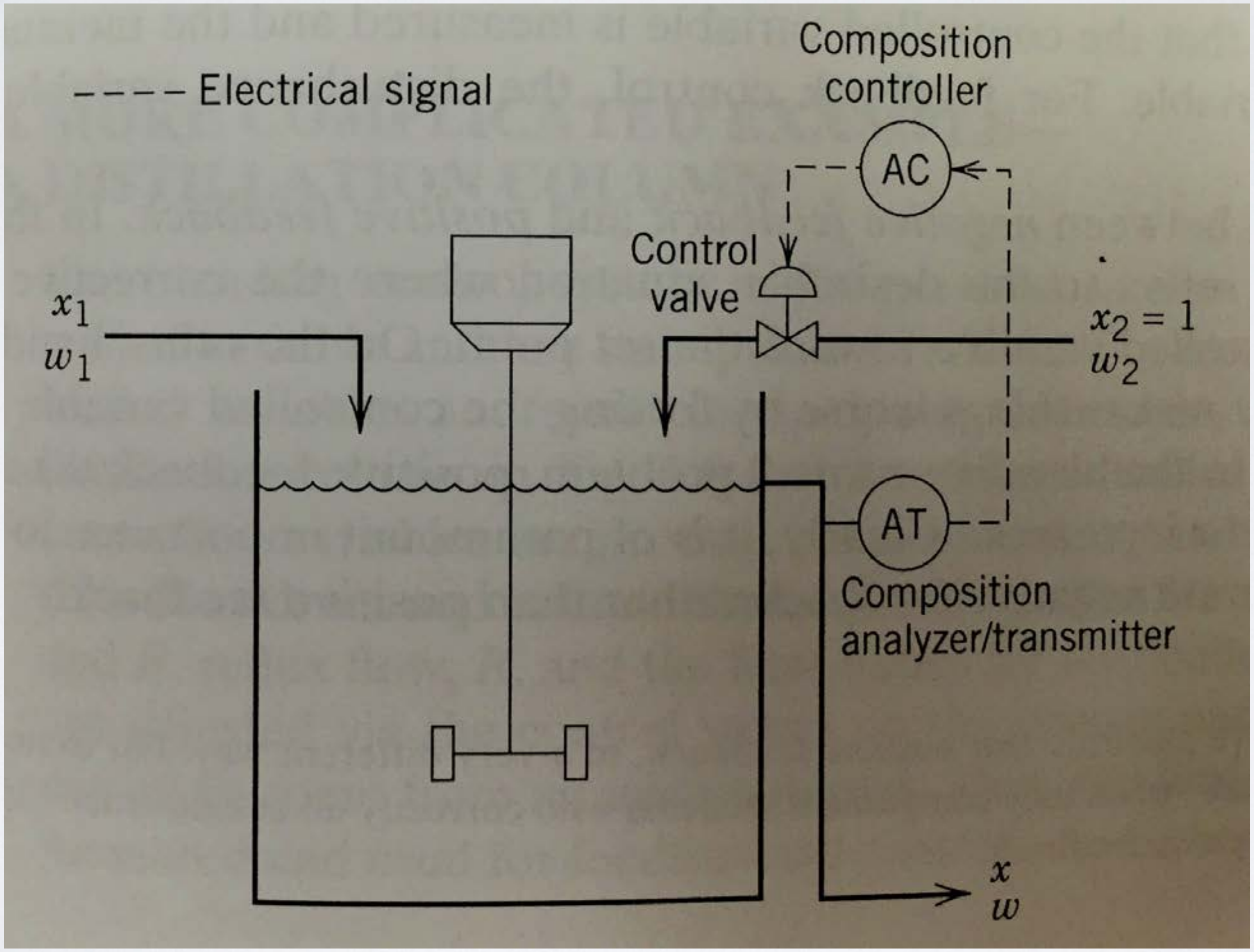


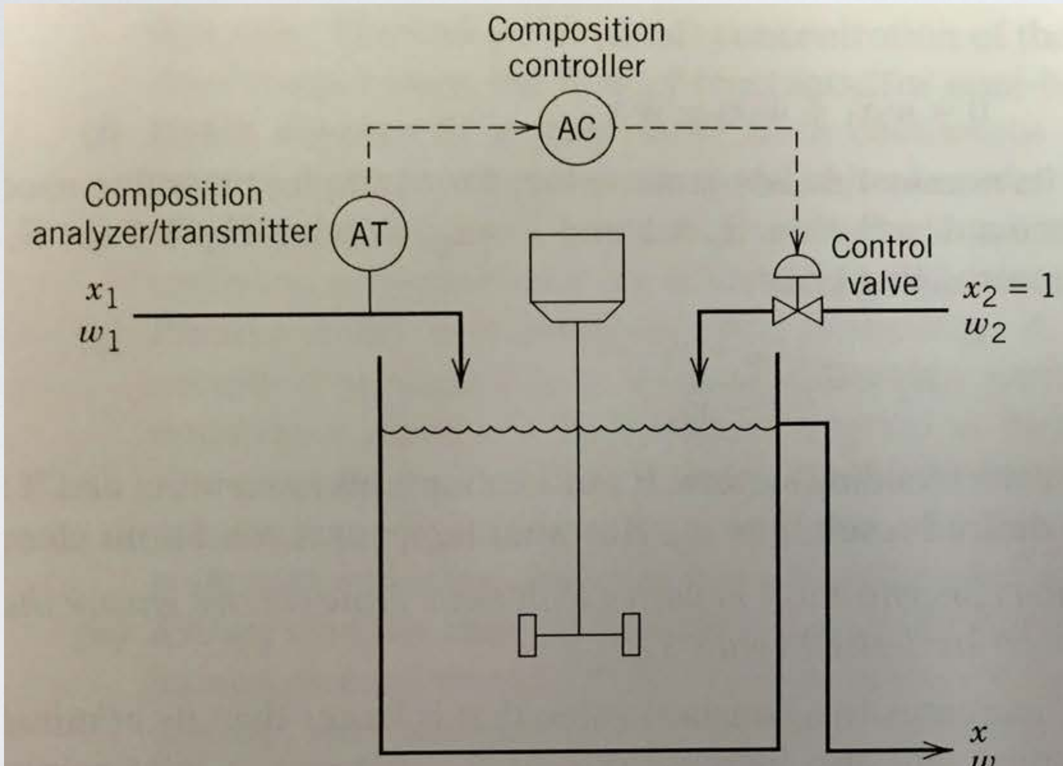
Figure 1.3 Stirred-tank blending system.

We are changing the relative concentration of A and B in a blending process

FEEDBACK: MEASURE OUTPUT, ADJUST "A" INPUT TO KEEP ON "SPEC"



FEEDFORWARD



Measure input, adjust flow to match what is *apparently* needed to keep output on "spec"

Figure 1.5 Blending system and Control Method 2.

Method 2. *Measure x_1, adjust w_2.* As an alternative to Method 1, we could measure disturbance variable x_1 and adjust w_2 accordingly. Thus, if $x_1 > \bar{x}_1$, we would decrease w_2 so that $w_2 < \bar{w}_2$. If $x_1 < \bar{x}_1$, we would increase w_2. A control law based on Method 2 can be derived from Eq. 1-3 by replacing $\bar{x}_1$ with $x_1(t)$ and $\bar{w}_2$ with $w_2(t)$:

OUR PROCESS

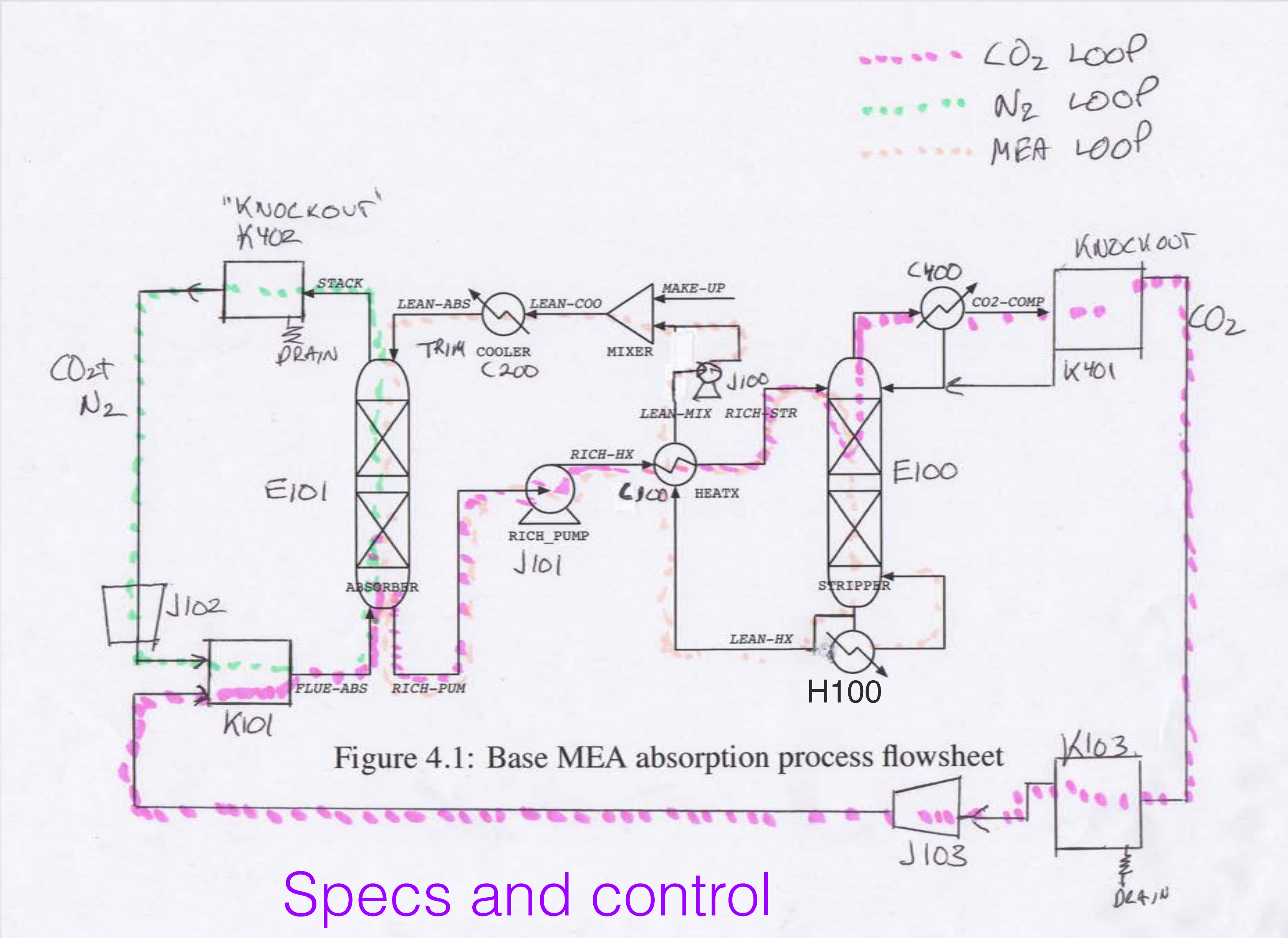


Figure 4.1: Base MEA absorption process flowsheet

Specs and control

EXPECTED "SPECS"

- CO_2 concentration in Absorber exit is below ~1% or 5%
- Either because the other gas needs a specified purity or because you are required to remove a certain fraction of the CO_2
  - adjust temperature of input MEA stream (easy)
  - adjust flow rate of input MEA stream (easy, but propagates back through the process and changes concentration only in certain ranges)
  - remove more CO_2 from MEA in stripper

For dilute systems:

$$z = H_{OG} N_{OG} = H_{OG} \int_{y_2}^{y_1} \frac{dy}{y - y^*}$$

$$H_{OG} = \frac{V}{K'_y a S} = \frac{V}{K_y a (1 - y)_{*M} S}$$

- *V* is the gas flow rate in moles/time
- K'_y is the appropriate mass transfer coefficient
- *a* is the area of gas-liquid contact per volume of packed bed
- *S* is the cross sectional area of the column
- *y* is the mole fraction of the component in the gas
- *y** is the equilibrium value of the transferring gas component in the liquid.

EXPECTED SPEC

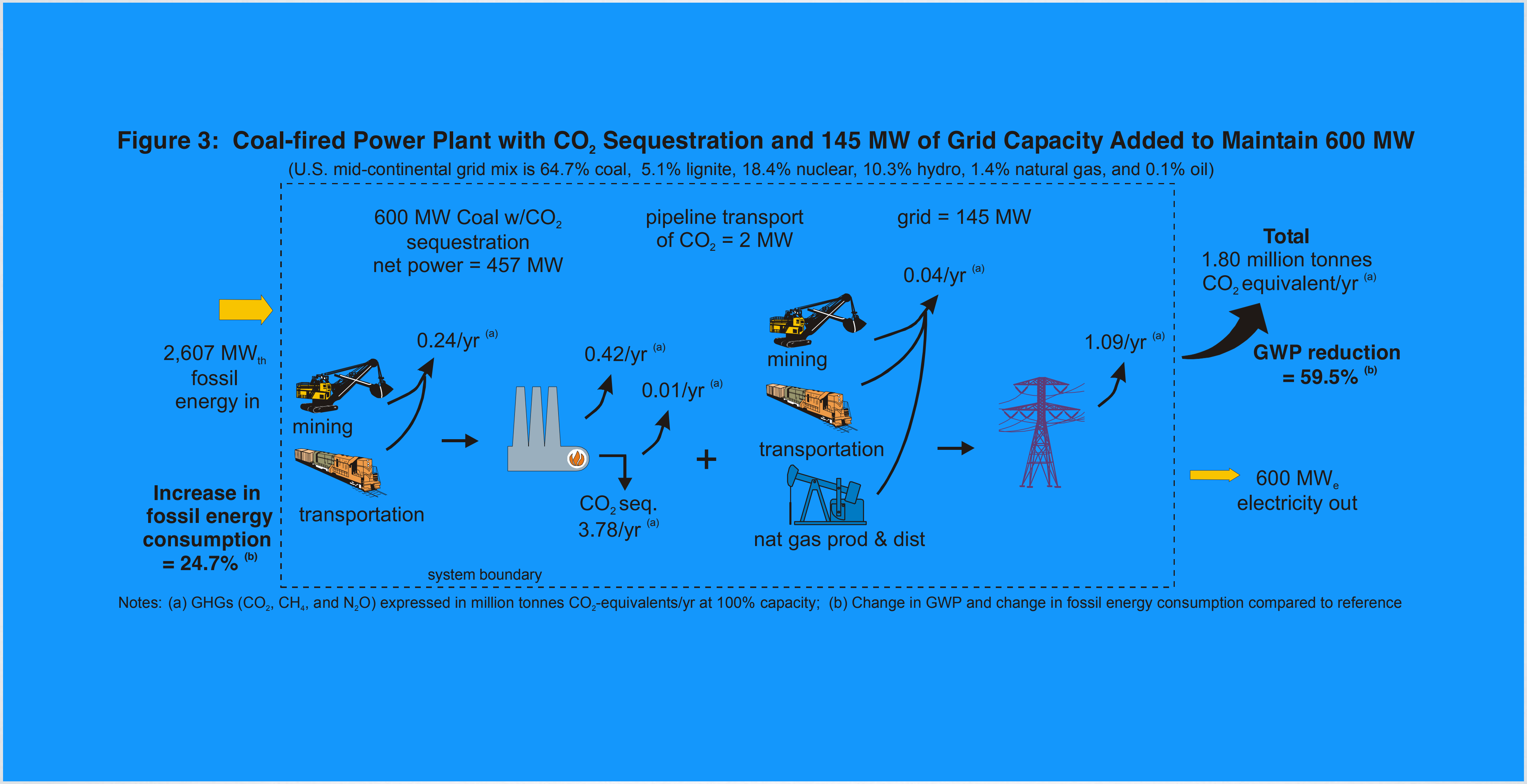
- Nitrogen in exit CO_2 stream
  - Change temperature in absorber
- Water vapor in exit CO2 stream
  - More/colder water in condenser

PROPAGATED EFFECT

- If you change the MEA flowrate or want to change the concentration of CO_2 in the MEA feed, the reboiler steam rate will have to be adjusted

REVIEW

COAL/W SEQUESTRATION (+NG)



PROCESS DIAGRAM

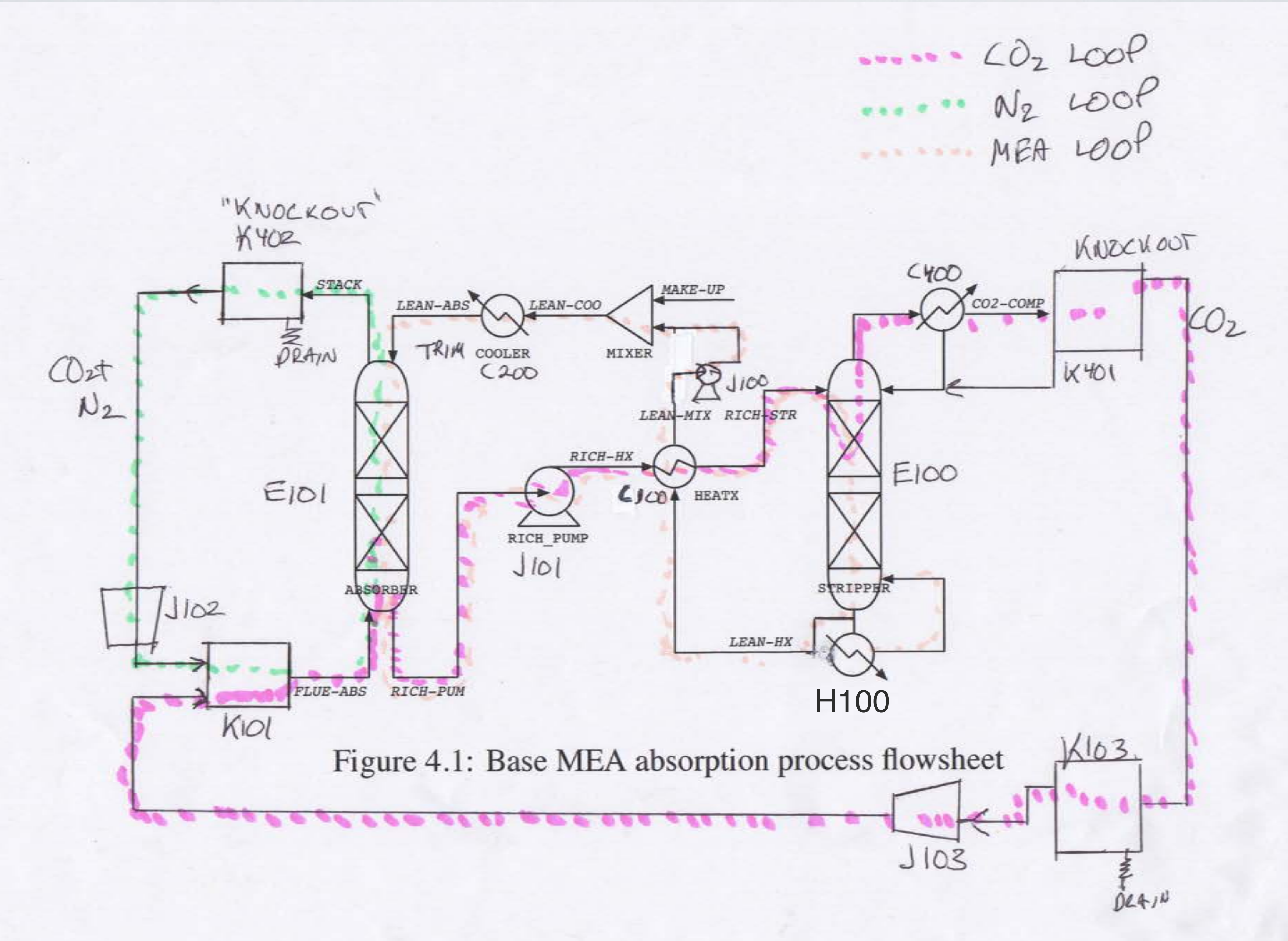


Figure 4.1: Base MEA absorption process flowsheet

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

ANALYSIS: TWO BASIC PRINCIPLES

- Conservation of mass
  - Keep track of chemical species in the two different flows
- Rate of interphase transfer equation
  - Analogous to Newton's Law of cooling
  - Driving force is a concentration difference:
    - Gas-liquid phase equilibria may include reaction

MECHANISMS OF MASS TRANSFER

- *Diffusion* (analogous to *Conduction* in heat transfer)
  - Transport by random molecular motion gases and liquids.
  - Fick's Law: $j = D\frac{\partial C}{\partial x}$ (same as Fourier's Law)
- *Convection* (essentially the same as *Convection* in heat transfer)
  - Transport by net motion of fluid. (molecular motion that is correlated, not random)
  - Describe using analog to Newton's law of cooling

$$N_A = k\,A\left(C_{gas} - C^*\right)$$

SUMMARY OF HEAT TRANSFER FUNDAMENTALS

- Three modes of heat transfer can occur:
  - Radiation (electromagnetic radiation) $q \sim \boldsymbol{\varepsilon\, \sigma}\, (T^4 - T_0^4)$
  - Conduction (random motion of molecules, atoms and electrons) $q \sim k_A \frac{\Delta T_A}{\ell}$
  - Convection (heat transfer that is aided by bulk fluid motion)

HEAT EXCHANGER SUMMARY

- Heat exchangers are first analyzed using an energy balance

$$\dot{m}_c d\hat{H}_c = \dot{m}_c C_p dT_c = dq_c$$

- The rate of transfer across the walls is modeled using Newton's Law of cooling

$$q = hA(T_w - T_\infty)$$

- We get individual *h*'s from correlations

$$Nu = 0.023 Re^{.8} Pr^{.4}$$

- We get a *U*'s from a sum of resistances

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{A_i}{k\Delta r} + \frac{A_i}{h_o A_i}$$

- Because the temperature difference between the two sides of the heat exchanger is changing along the pipe, we formulate the problem as a differential slice of pipe and integrate. This gives the temperature driving forces as a "Log-Mean delta T"

$$\frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

FLUID FLOW SUMMARY

- Pipe sizing and piping system design is done based on the pressure drop — flow rate behavior that occurs
- This is well known and for simple fluids is captured in the single plot of friction factor and Reynolds number
- To design an entire pipe system and to determine the power necessary for pumping, the Engineering Bernoulli Equation is used.

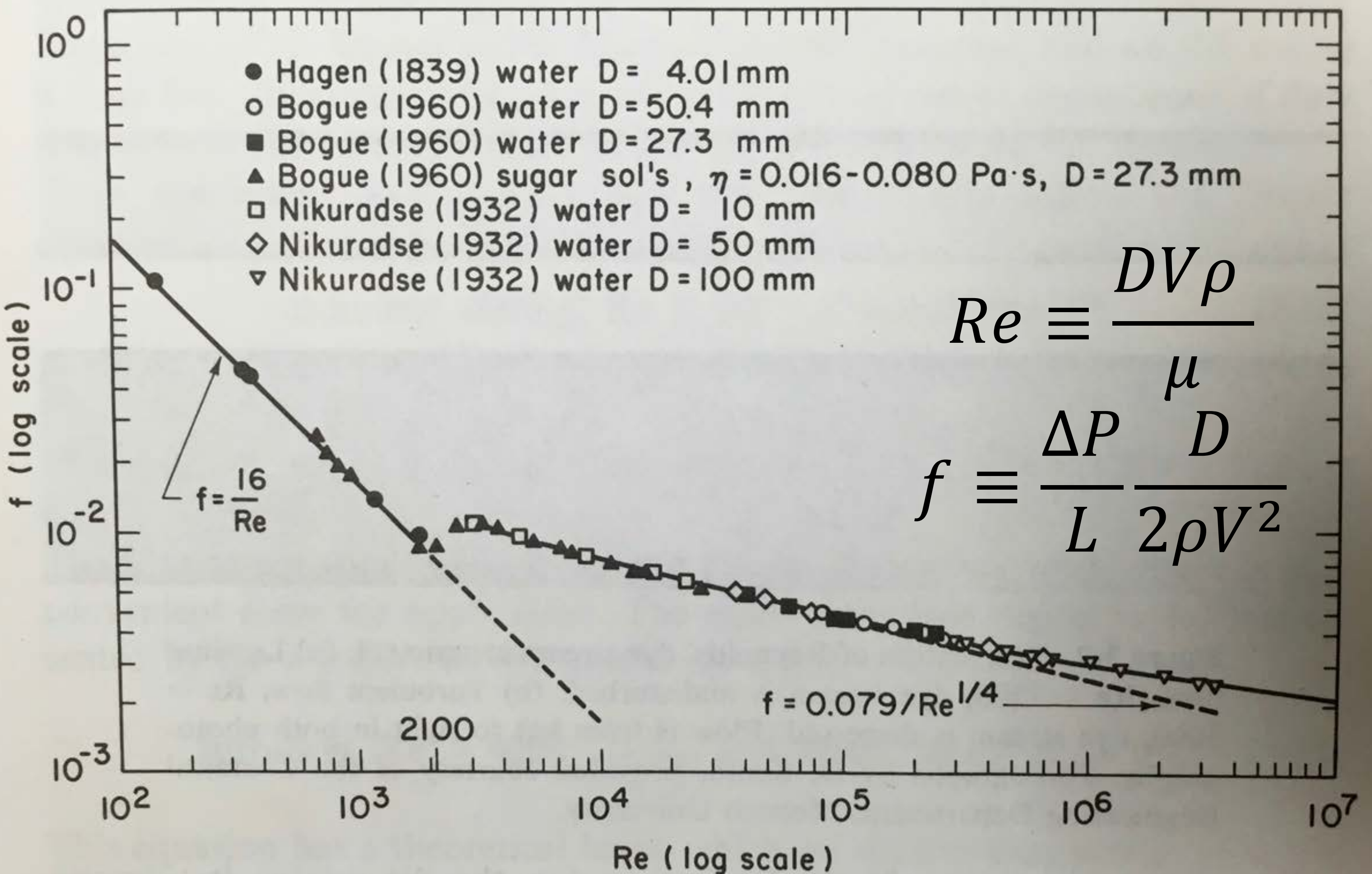
BERNOULLI EQUATION

- To include gravity, friction from all of the straight sections of pipe and the pressure change associated with all of the fittings, the typical equation that is most convenient is the "Engineering Bernoulli Equation"

- This can be derived from the first and second laws of thermodynamics and the equation can be applied between any 2 "continuous flow paths" in a process system.

$$\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) + g(h_2 - h_1) + \frac{P_2 - P_1}{\rho} = \delta W_s - l_v$$

THIS FORMULATION WORKS!
DATA FOR LAMINAR AND TURBULENT PIPE FLOW



$$Re \equiv \frac{DV\rho}{\mu}$$

$$f \equiv \frac{\Delta P}{L}\frac{D}{2\rho V^2}$$

From: M. M. Denn, Process Fluid Mechanics

Figure 3-1. Friction factor as a function of Reynolds number for incompressible Newtonian fluids.