FLOW IN PIPES

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July 24, 2017

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OVERVIEW

- This lecture will provide the simplest framework to explain
  - The three forces at that are important to fluid flow in pipes
  - The three equations that needed
  - The three basic flow situations that comprise process pipe flows

IMPERIAL FLOWSHEET

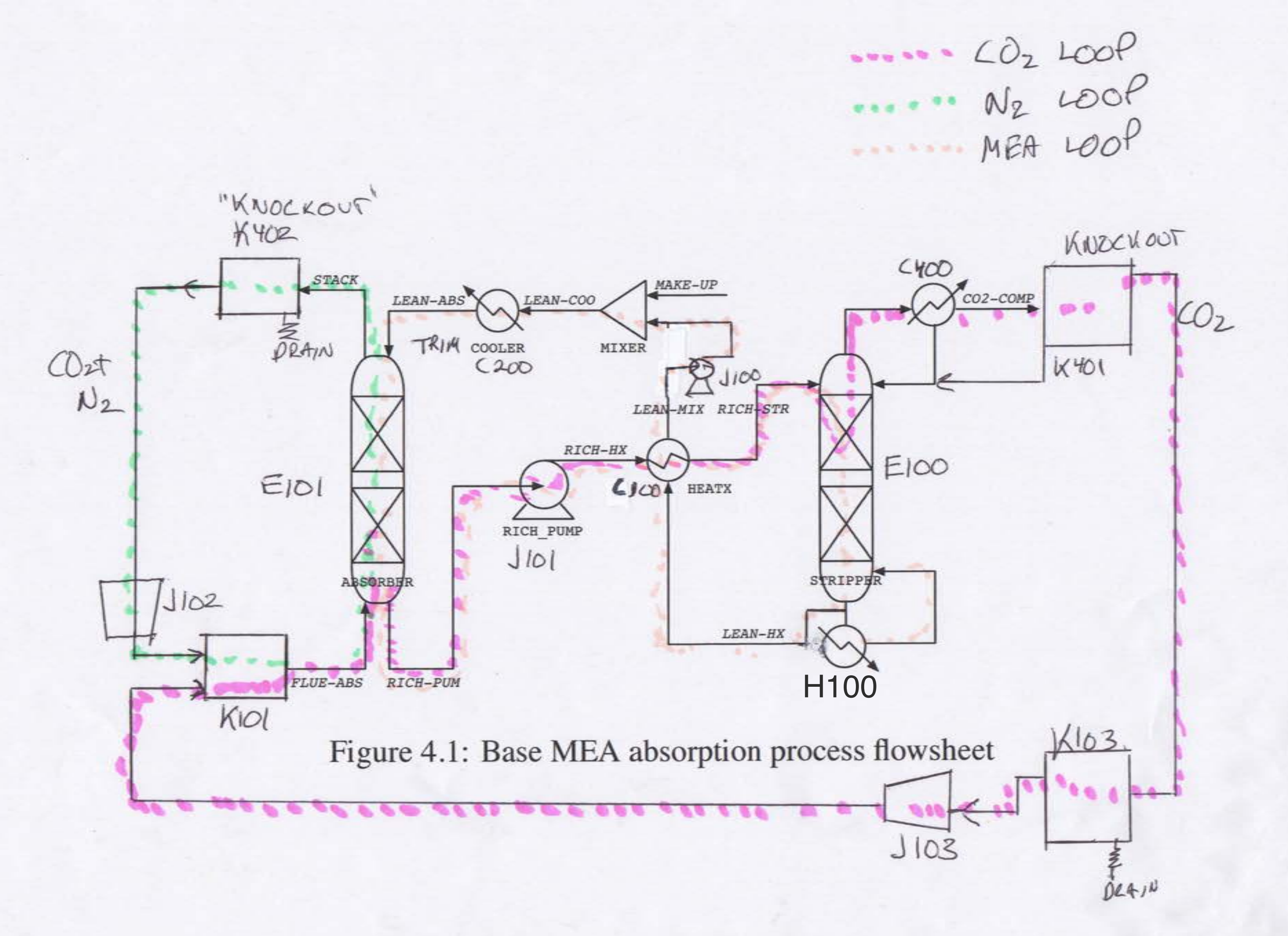
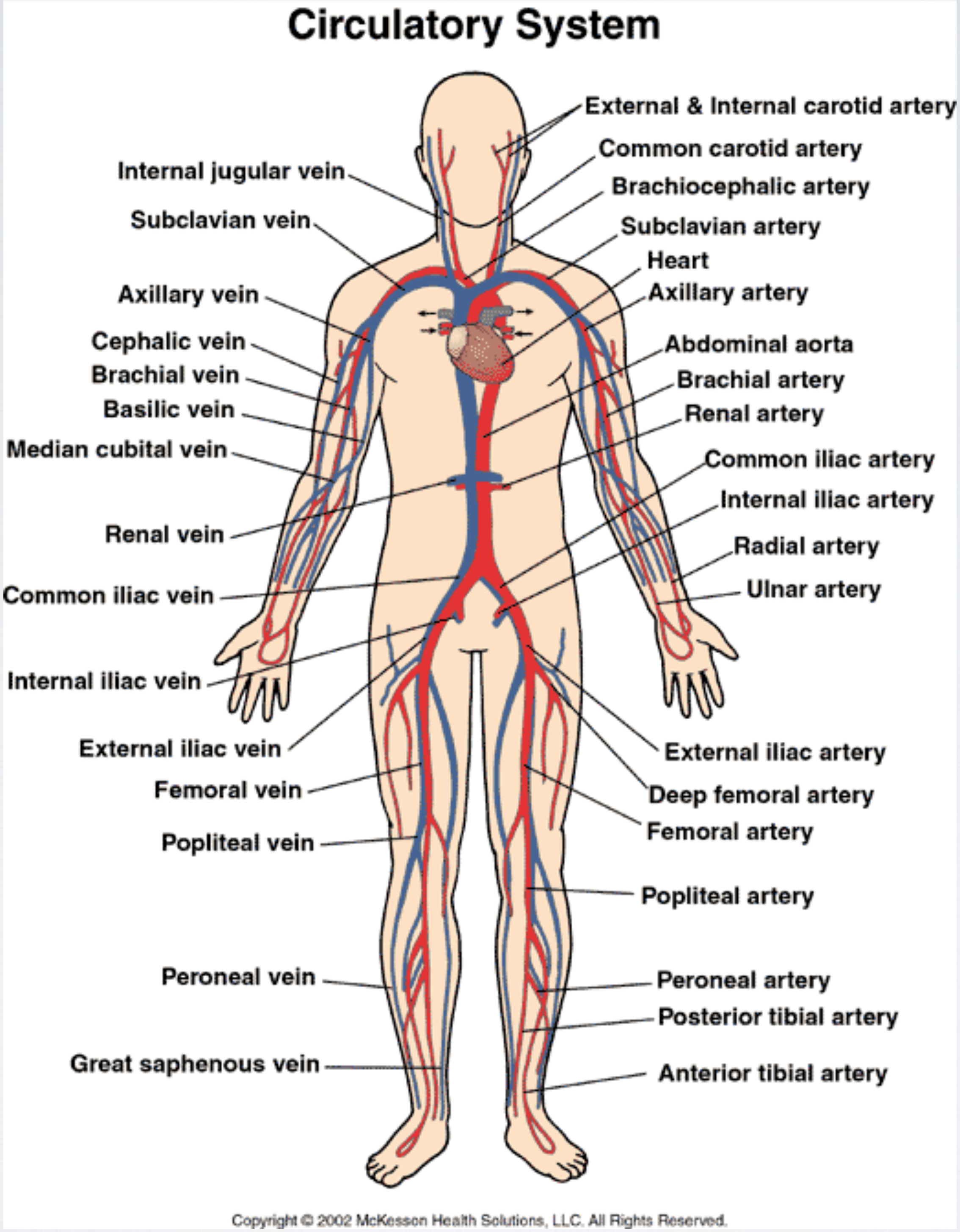


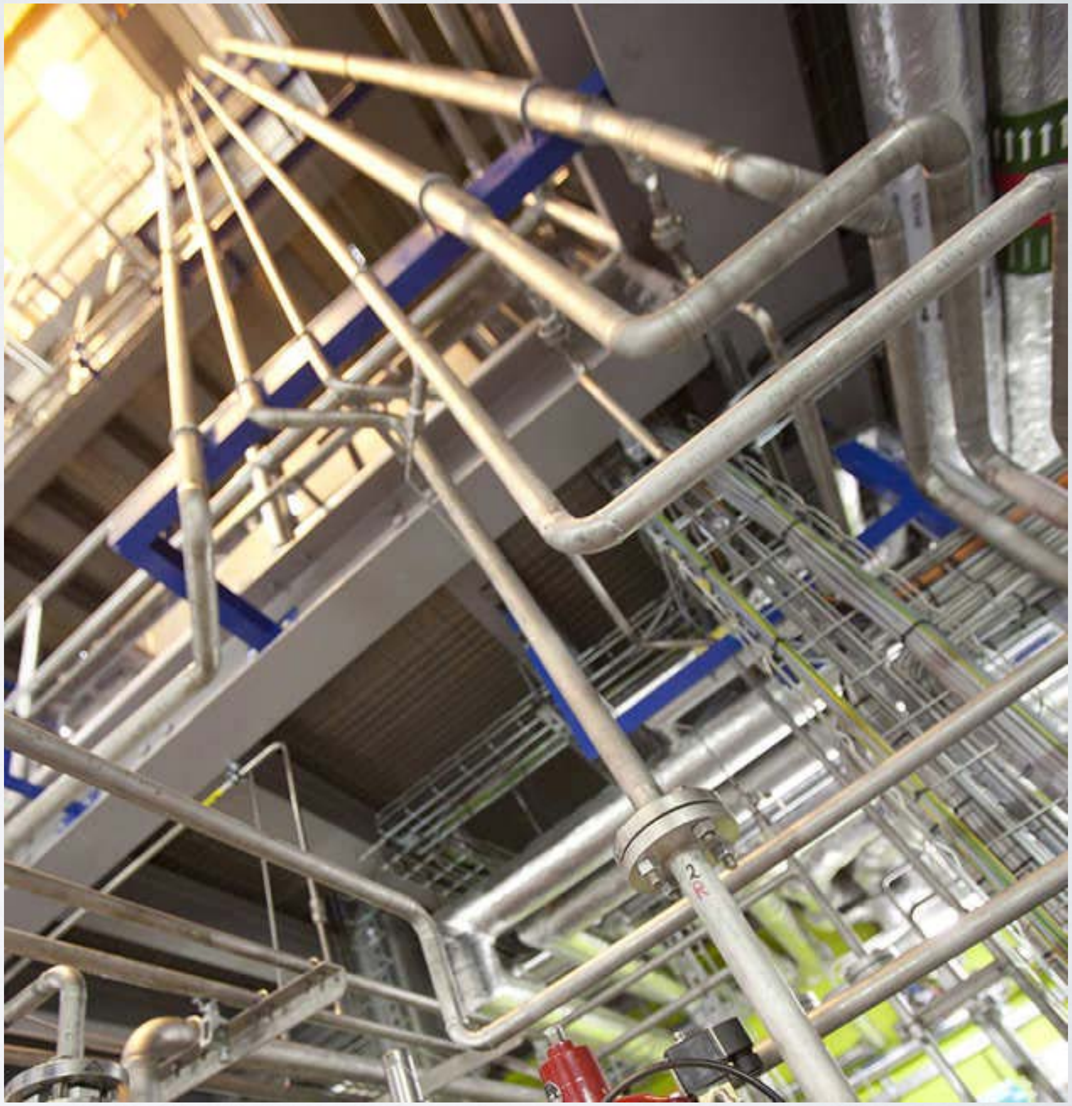
Figure 4.1: Base MEA absorption process flowsheet

BASIC FORCES THAT AFFECT A FLOWING FLUID

- Gravity: We observe that liquids flow down-hill and hence know that we will have to overcome the action of gravity to pump the liquid to top of the column
  - $\boldsymbol{F}_g = m\,\boldsymbol{g}$
- "Friction" caused by the "viscosity" of the liquid or gas: From the observations that pipes and tubes of different diameters are used in the same systems, presumably for different flow rates of the same liquid, (or when we try to drink using straws of different diameters, we expect that there is a resistance to fluid flow that must be overcome)
  - $F_{\boldsymbol{v}} = f(\mu) \Longrightarrow 1/2\, k\, v^2$
- With reference to the "straw", but when we are expelling air, (or simply playing the tuba), to make the fluid move, we need to make the pressure higher on one side of the tube. In a process, we use a pump to create the pressure increase
  - $\boldsymbol{F}_p = p\,\boldsymbol{A} \Longrightarrow \Delta p\,\boldsymbol{A}$


Circulatory System
External & Internal carotid artery
Internal jugular vein
Common carotid artery
Brachiocephalic artery
Subclavian vein
Subclavian artery
Heart
Axillary vein
Axillary artery
Cephalic vein
Abdominal aorta
Brachial vein
Brachial artery
Basilic vein
Renal artery
Median cubital vein
Common iliac artery
Internal iliac artery
Renal vein
Radial artery
Common iliac vein
Ulnar artery
Internal iliac vein
External iliac vein
External iliac artery
Deep femoral artery
Femoral vein
Femoral artery
Popliteal vein
Popliteal artery
Peroneal vein
Peroneal artery
Posterior tibial artery
Great saphenous vein
Anterior tibial artery

PIPES!



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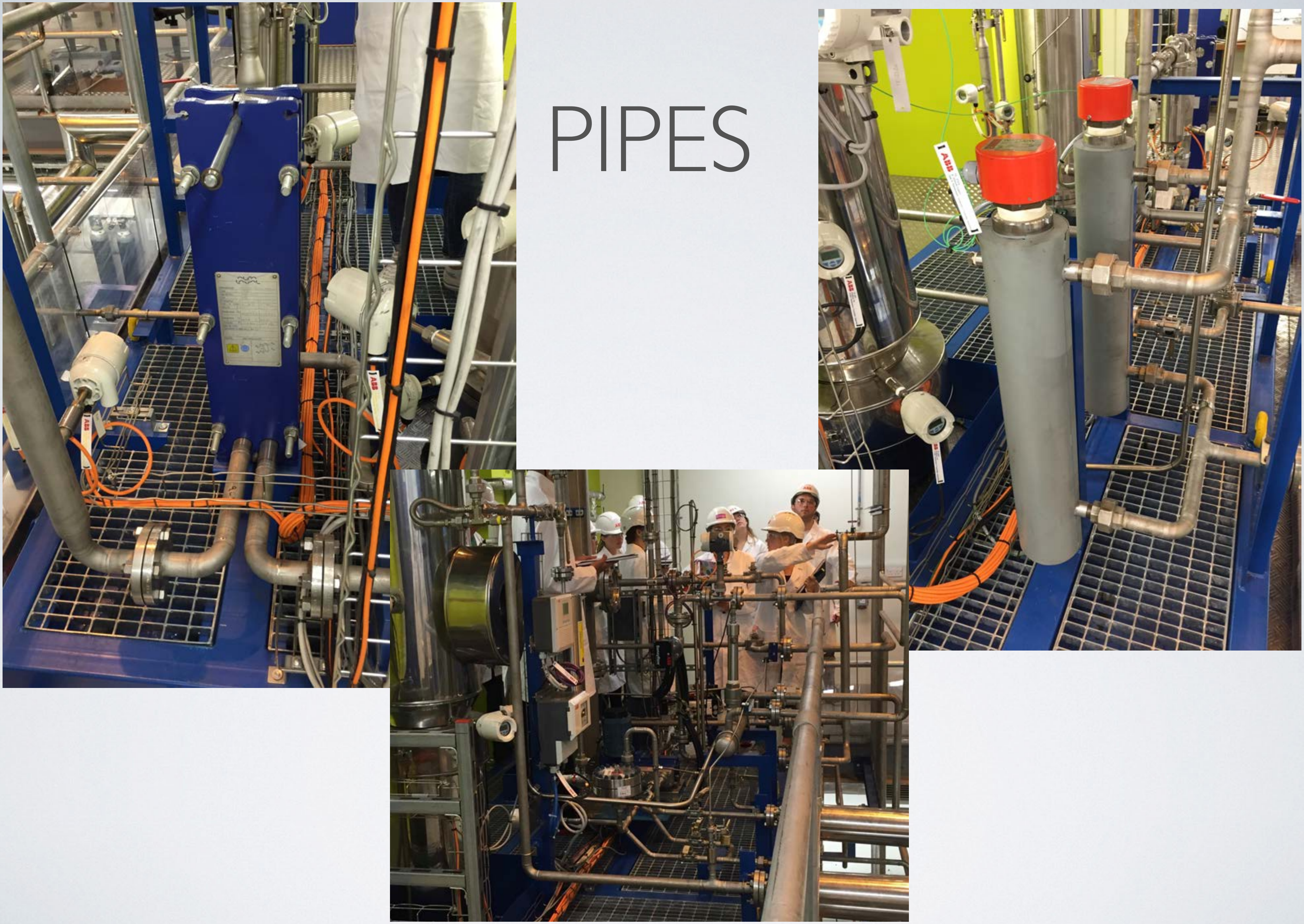
PIPES



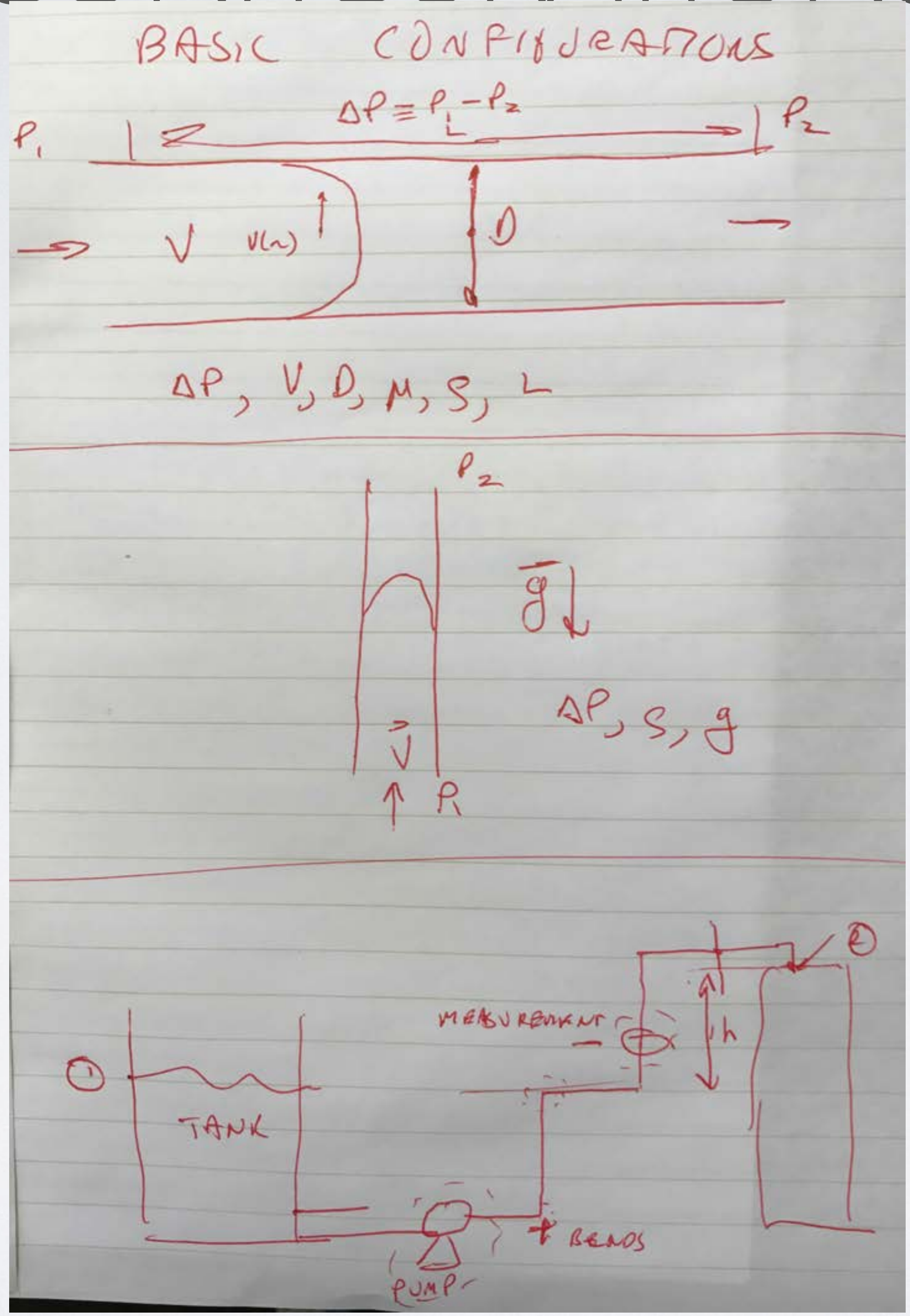
PIPE SIZES

- We have to presume that engineers have picked the sizes of pipes for different applications in some sensible (optimal) fashion.
- Likewise, we expect that over millions of years, evolution has determined what size blood conduits should be.
- Thus one of the questions we would like to answer is how do we determine how large a pipe should be for a given flow rate
  - The essence of this calculation is to determine the relationship between flow rate and “pressure drop” for liquids and gases in pipes.

ENGINEERING TRADEOFF

- Capital costs
- Operating Costs
- “Optimal pipe diameter” is a classic problem
  - For engineers and
  - It is evident in your circulatory system!
    - “Murray’s Law”

CONFIGURATIONS



BASIC CONFIGURATIONS

$\Delta P \equiv P_1 - P_2$

$\Delta P, V, D, \mu, \rho, L$

$\Delta P, \rho, g$

DIMENSIONAL REASONING AND DIMENSIONAL ANALYSIS

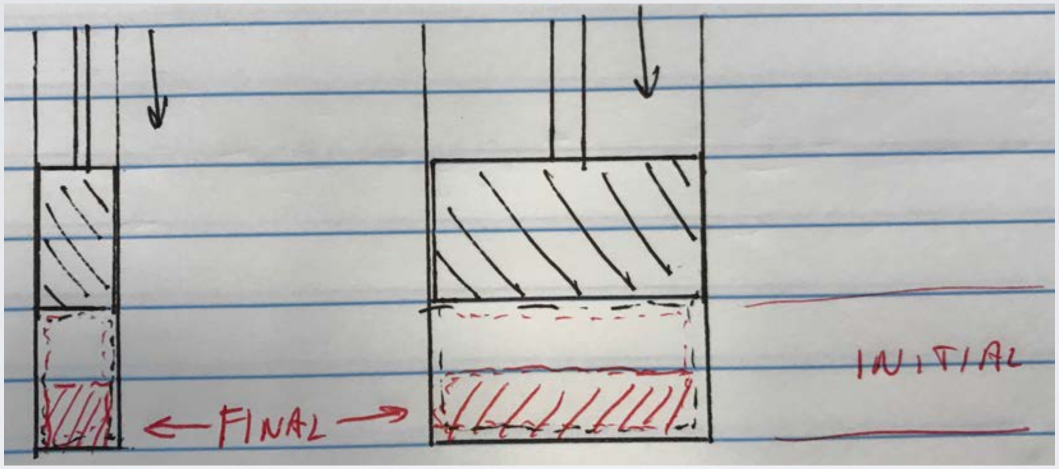
- Before we address the specific questions related to fluid flow, it is worthwhile to introduce a **general concept**, that provides useful insights and quantitative results, across all transport process and many other topics in chemical engineering and other technical disciplines

- That we can gain understanding of fundamental behavior by first identifying quantities such as a *time scale* or a *length scale* associated with a process or device.
  - Then by comparing these scales to an *alternative* scale of the same fundamental dimension.

DIMENSIONAL REASONING

- Simplest example: compare the same variable for a process at two different times
    - Suppose that in one device, 1 mole of gas at STP is trapped in a piston and the initial volume is increased from 22.4 l to 44.8 l.
    - In a second device, 10 moles of gas at STP are trapped in a piston and the initial volume is increased to from 224 l to 448 l.
    - We realize the final temperature and pressure in both pistons is the same and only the **ratio** of volume 2 to volume 1 is needed to characterize the process.
        - This <u>comparison of like quantities</u> tells us exactly how compare the two processes
        - However, we would find it nonsensical to compare the initial volume to the final temperature.

ISOTHERMAL COMPRESSION



- If we want the temperature to be constant within the piston as we compress from V_1 to V_2, how slowly do we need to conduct the process?
  - <u>Intuition</u> tells us that the one on the right will have to be slower.
- This is a statement saying we need to compare the time, τ, of compression (process time) to the time scale of heat conduction.
- To have identical outcomes, we need $\tau_{\text{conduction}}/\tau_{\text{compress}} << 1$ for both cases

LET'S APPLY DIMENSIONAL ANALYSIS TO A FLUID FLOW PROBLEM

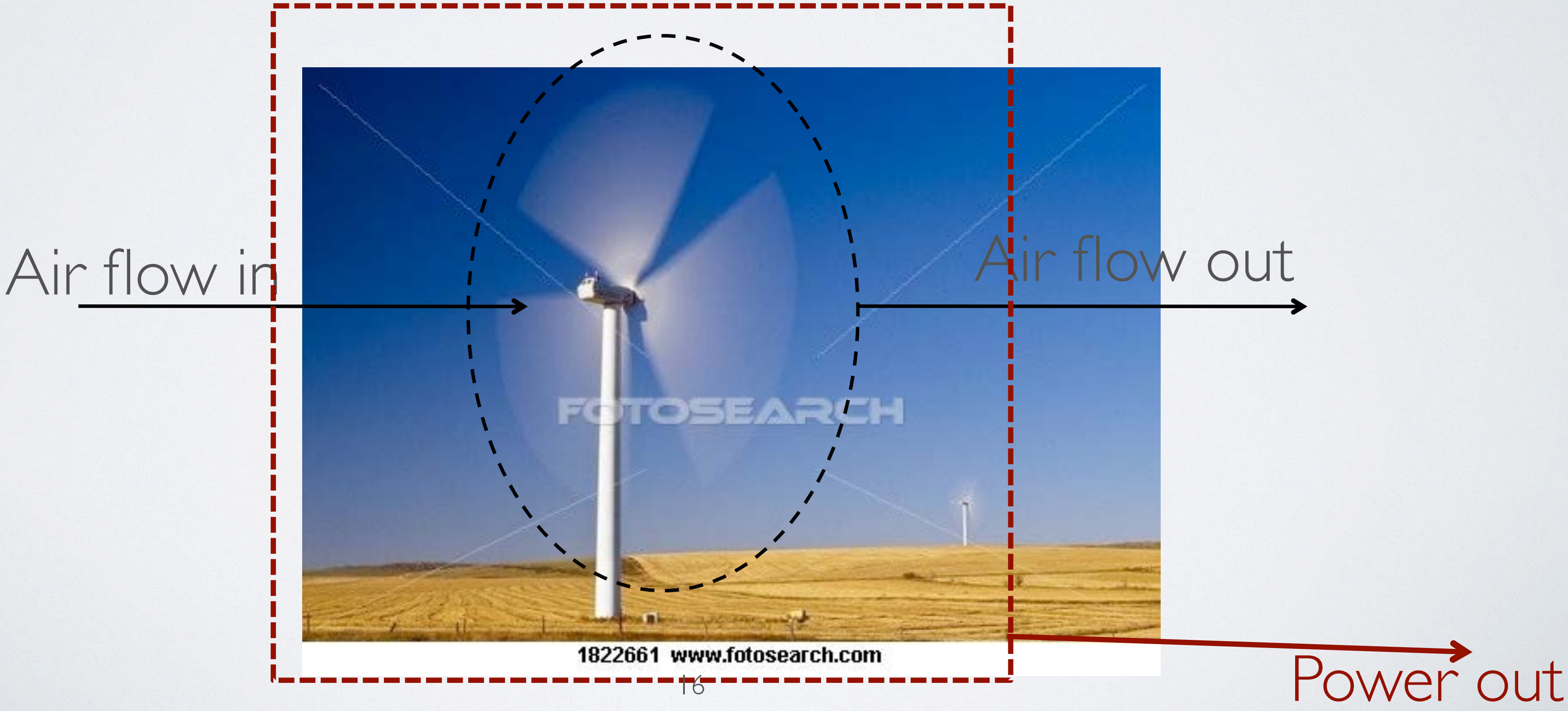
- A "field" of 40 wind turbines covers about 1400 acre
- This field is producing 56 MW of power for a wind speed of 10 m/s (22 mph) — which is about the optimal/maximal value
  - This is .04 MW/acre
    - A coal fired power plant would produce about 10 MW/acre!
- If the wind speed drops to 5m/s, how much power will the field produce?
  - With no reference to "formulas" is it possible to get an answer?
  - Does engineering analysis have to be really complex?

ENGINEERS LIKE TO COMPARE THINGS

- If I asked: ".. how far is it to Chicago?"
    - would you answer?
        - "a couple of hours" or...
        - "about 90 miles"
- If I asked: ".. is a meter a long distance?" what would you say
    - "No", compared to the distance to Chicago
    - "Yes", compared to a micron
- For our conclusion to be valid we need to
    - **compare** like (same dimensions) quantities.

POWER AND WIND SPEED?

- How does the power generated by the windmill change with wind speed?
  - How is power being generated?
    - Wind flows through area swept by blades
    - Windmill converts this kinetic energy to electric power



POWER AND WIND SPEED?

- How does the power generated by the windmill change with wind speed?
  - Let's see if we can figure this out based on dimensional reasoning
    - Power is work/time which is force * distance/time which is mass* acceleration *distance/time
    - Thus we could write

$$power = m\ l/t^2 l/t = \frac{ml^2}{t^3}$$

    - What variables could be used?

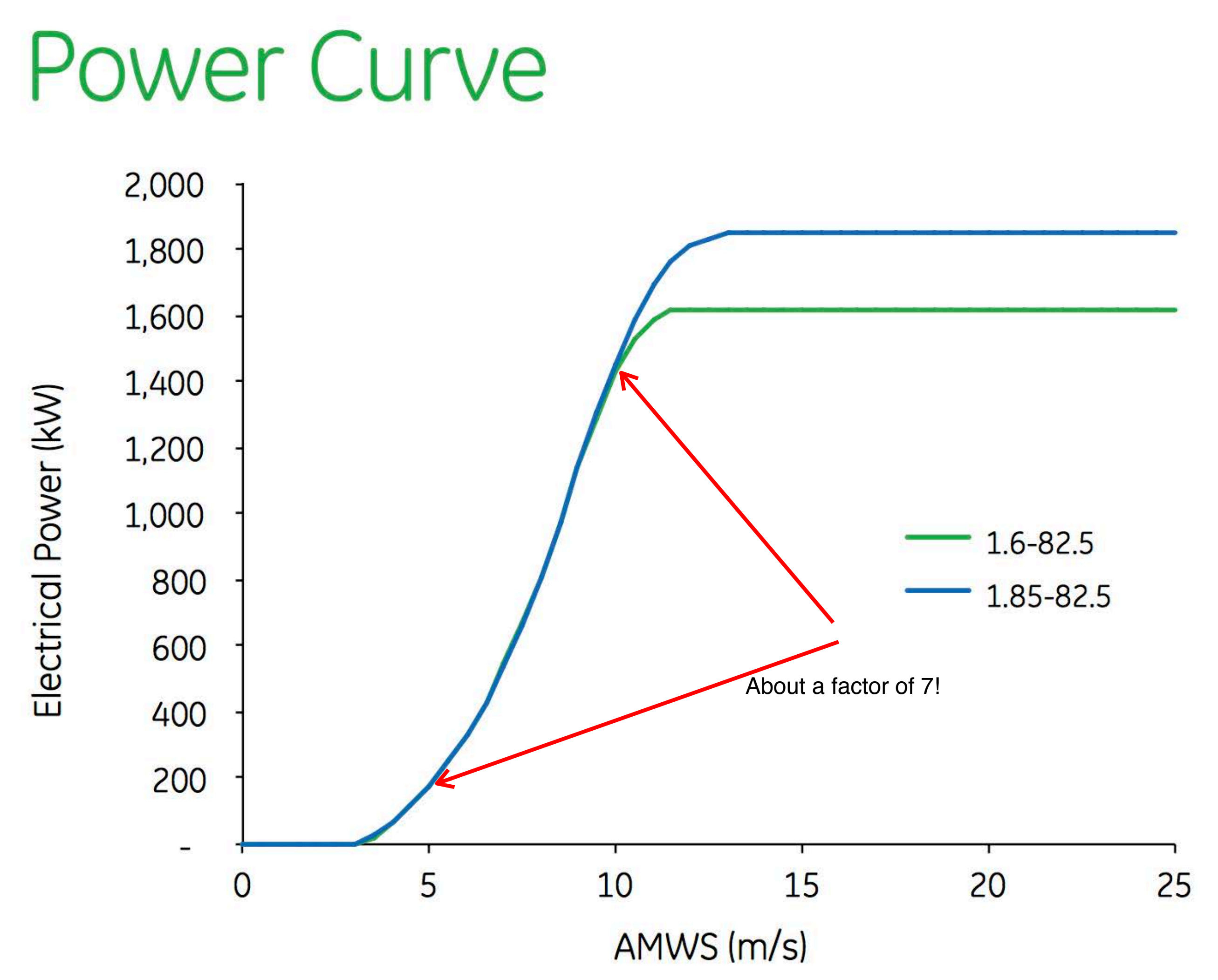
EQUATION FOR POWER FROM WIND

- Windspeed, blade diameter, air density
  - v [=] l/t
  - d, r [=] l
  - Density of air ρ [=] m/l^3
  - Arrange these variables to get dimensions of power:

$$power \sim \rho v^3 d^2 [=] \frac{ml^2}{t^3}$$

  - If the wind speed is cut in half, the power reduced to 1/8!
  - So our 40 wind turbines will produce about….
    - 7 MW!

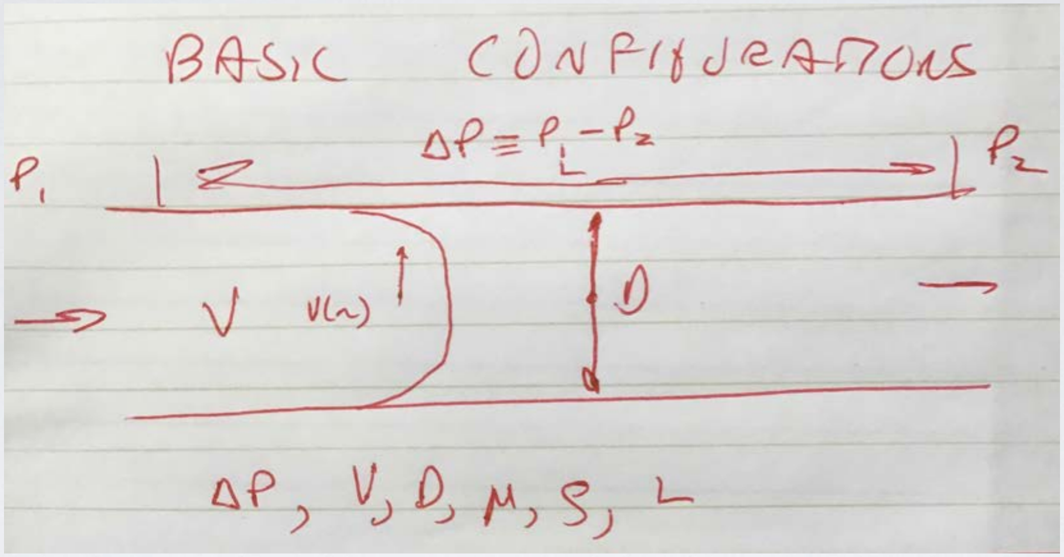
WIND TURBINE POWER



About a factor of 7!

https://www.gerenewableenergy.com/content/dam/gepower-renewables/global/en_US/downloads/brochures/wind-onshore-turbine-1.85-82.5-gea18755g-r1.pdf

FUNDAMENTAL FLUID MECHANICS



- For steady flow in a pipe, the forcing from the pressure difference is exactly balanced by the friction from the fluid viscosity

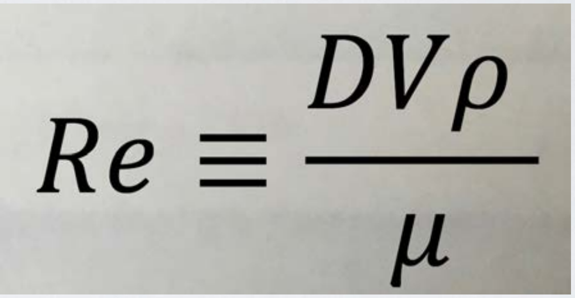
- An equivalent way to think of this is that the work being done to move the fluid is all being converted to heat.

DIMENSIONAL REASONING APPLIED TO PIPE FLOW

- The variables that describe flow in a pipe are, **μ**, **ρ**, **Δ**p, D, V, L
- We might worry that to formulate and solve a problem in fluid flow that the result would be different for each combination of values of these variables
- However, by applying dimensional reasoning to this problem using a more formal process of "Dimensional Analysis" we determine that these variables can be arranged into two "dimensionless groups" (the dimensional comparisons are built it) which should describe the behavior for this problem.
- The result is:

DIMENSIONLESS PARAMETERS FOR FLUID FLOW

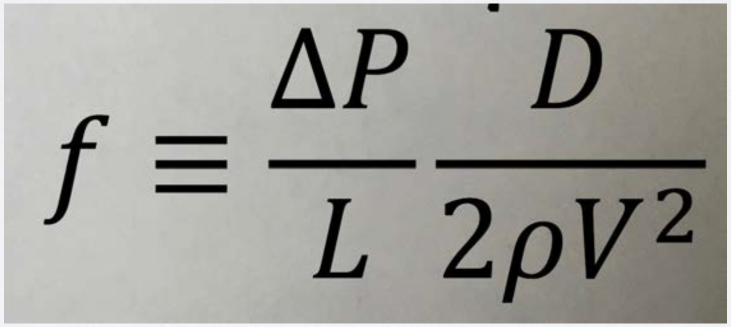
- Reynolds number:



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

  - ratio of inertia to viscous forces

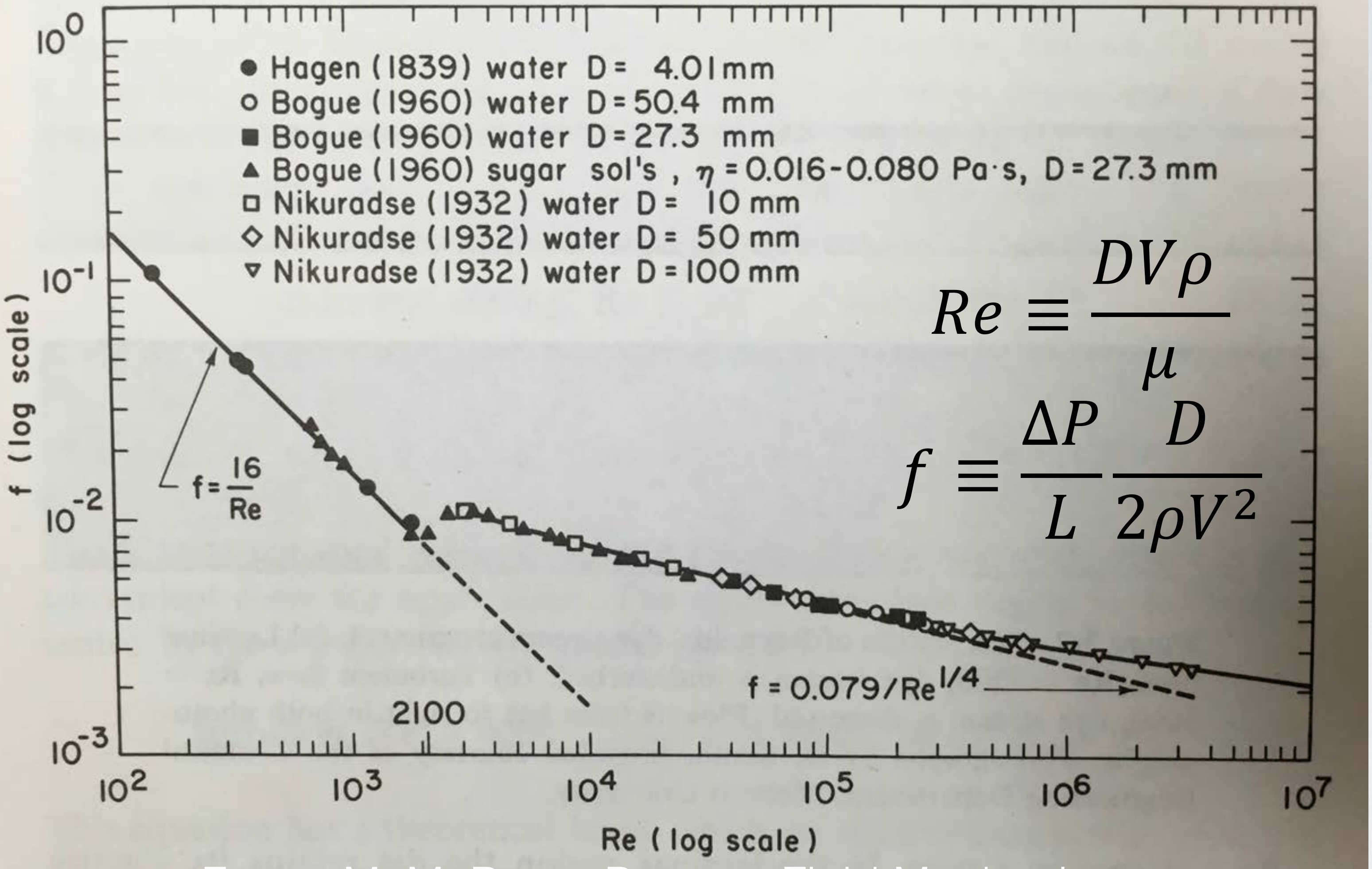
- Friction factor:



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

  - ratio of pressure forces to inertia

THIS FORMULATION WORKS!
DATA FOR LAMINAR AND TURBULENT PIPE FLOW

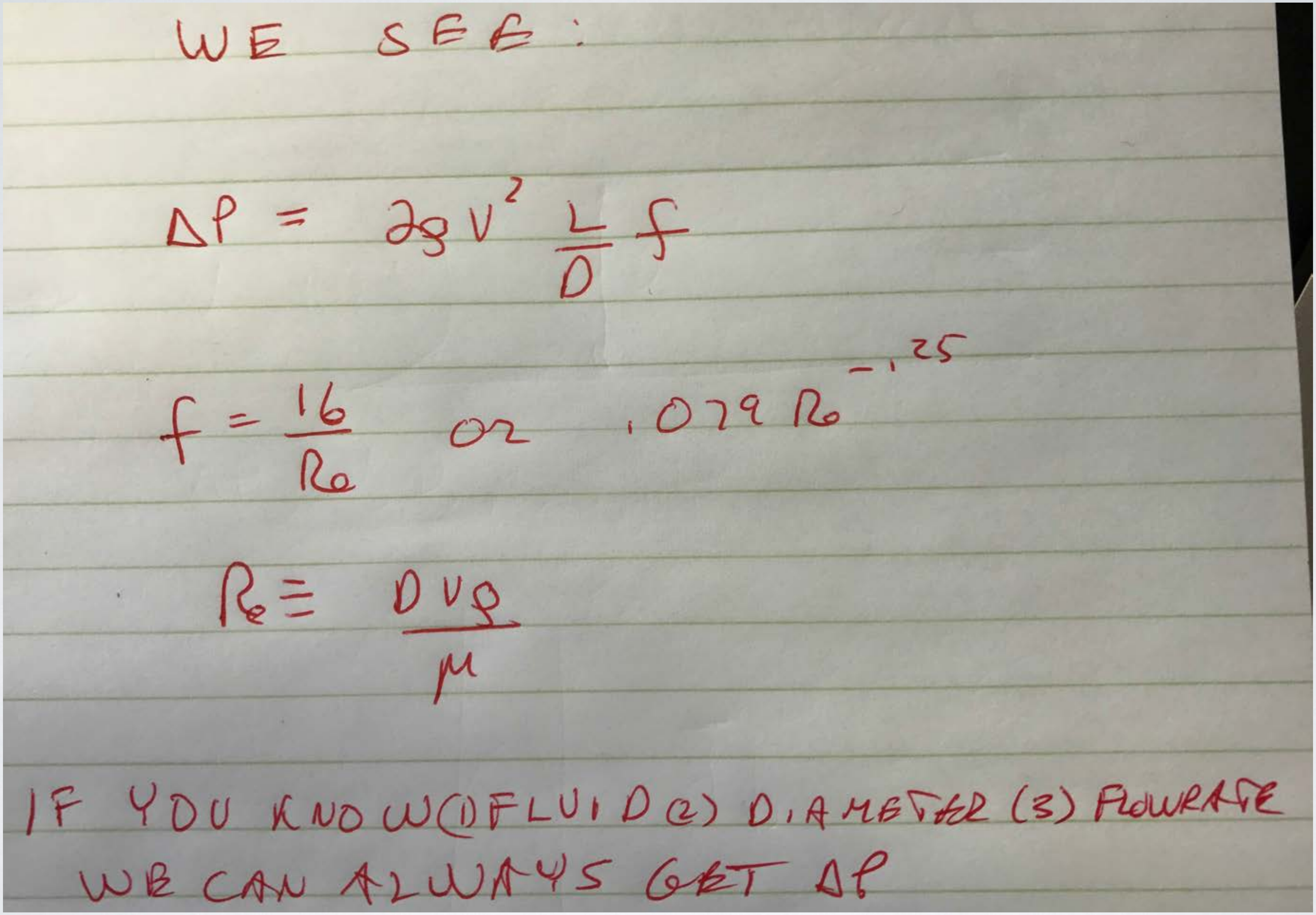


$$Re \equiv \frac{DV\rho}{\mu}$$

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

From: M. M. Denn, Process Fluid Mechanics

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



WE SEE:

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

$$f = \frac{16}{Re} \quad \text{or} \quad .079\, Re^{-.25}$$

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

IF YOU KNOW (1) FLUID (2) DIAMETER (3) FLOWRATE WE CAN ALWAYS GET ΔP

BASIS OF DIMENSIONLESS PARAMETERS

- If you have water flowing in a 1 cm pipe or a 2 cm pipe, we might expect that the physics of these two situations is exactly the same even if the "numbers" are different.
- Similarly, suppose we have the same pipe and we have a flow of water compared to water with a sugar solution. We might again expect the same physics with just a quantitative difference.
- This idea is substantially strengthened when we take the differential equations for fluid motion (derived from $\boldsymbol{F} = m\,\boldsymbol{a}$), solve them and then do some analysis to show exactly the simplifications that be obtained mathematically.
- If this done you get an exact result that
    - $f = 16/Re$

“REGIMES OF PIPE FLOW”

- “Laminar”
  - Straight streamlines
  - “Viscous” (molecular) transmission of momentum/stress in radial direction
- “Turbulent”
  - Irregularity of the flow causes increased pressure drop
    - “Convective” transport of momentum/stress
- “You” don’t get to choose. The system and conditions determine which will occur!

DYE STREAK EXPERIMENT

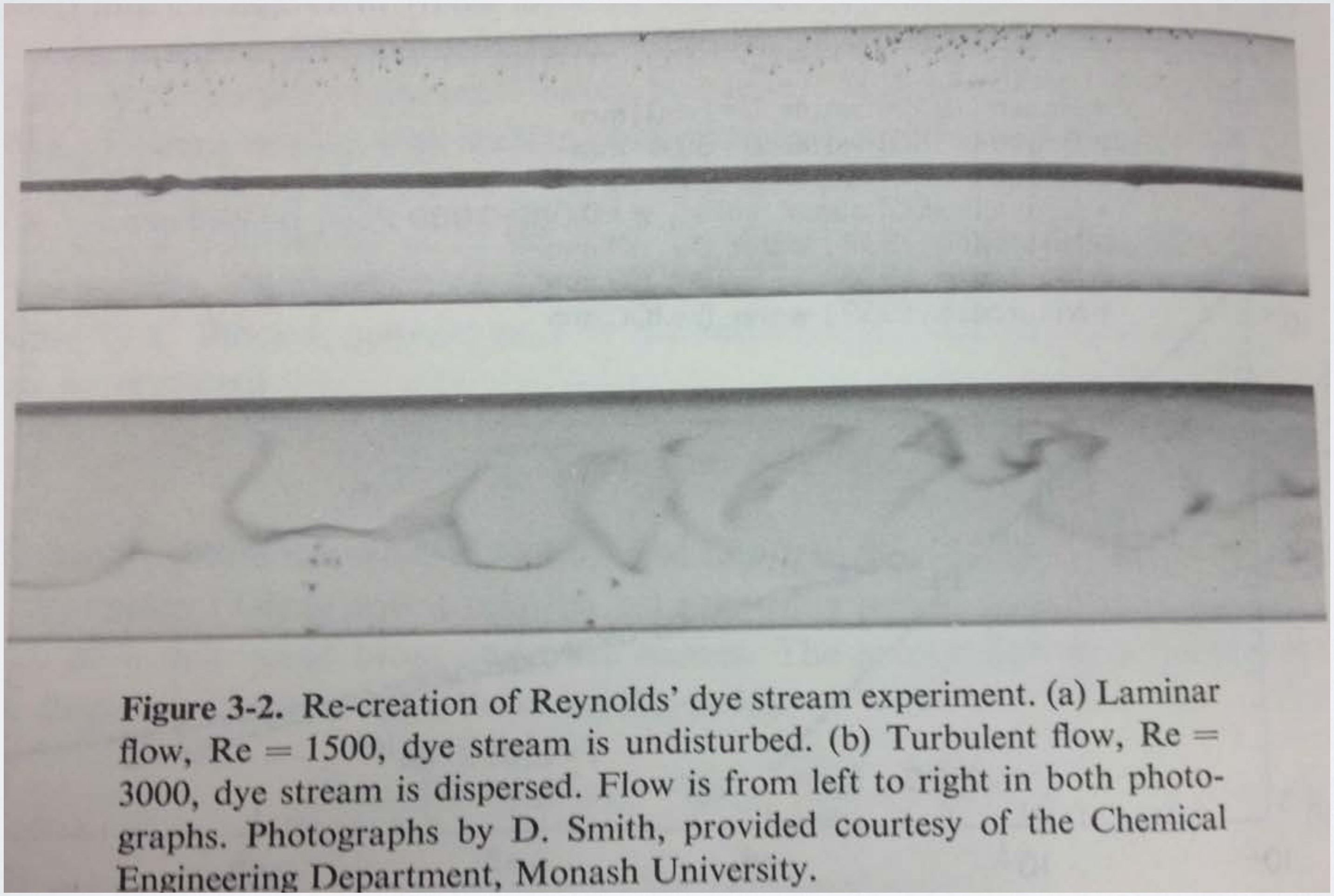
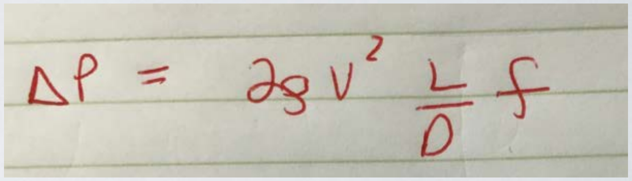


Figure 3-2. Re-creation of Reynolds' dye stream experiment. (a) Laminar flow, Re = 1500, dye stream is undisturbed. (b) Turbulent flow, Re = 3000, dye stream is dispersed. Flow is from left to right in both photographs. Photographs by D. Smith, provided courtesy of the Chemical Engineering Department, Monash University.

TYPICAL CALCULATION



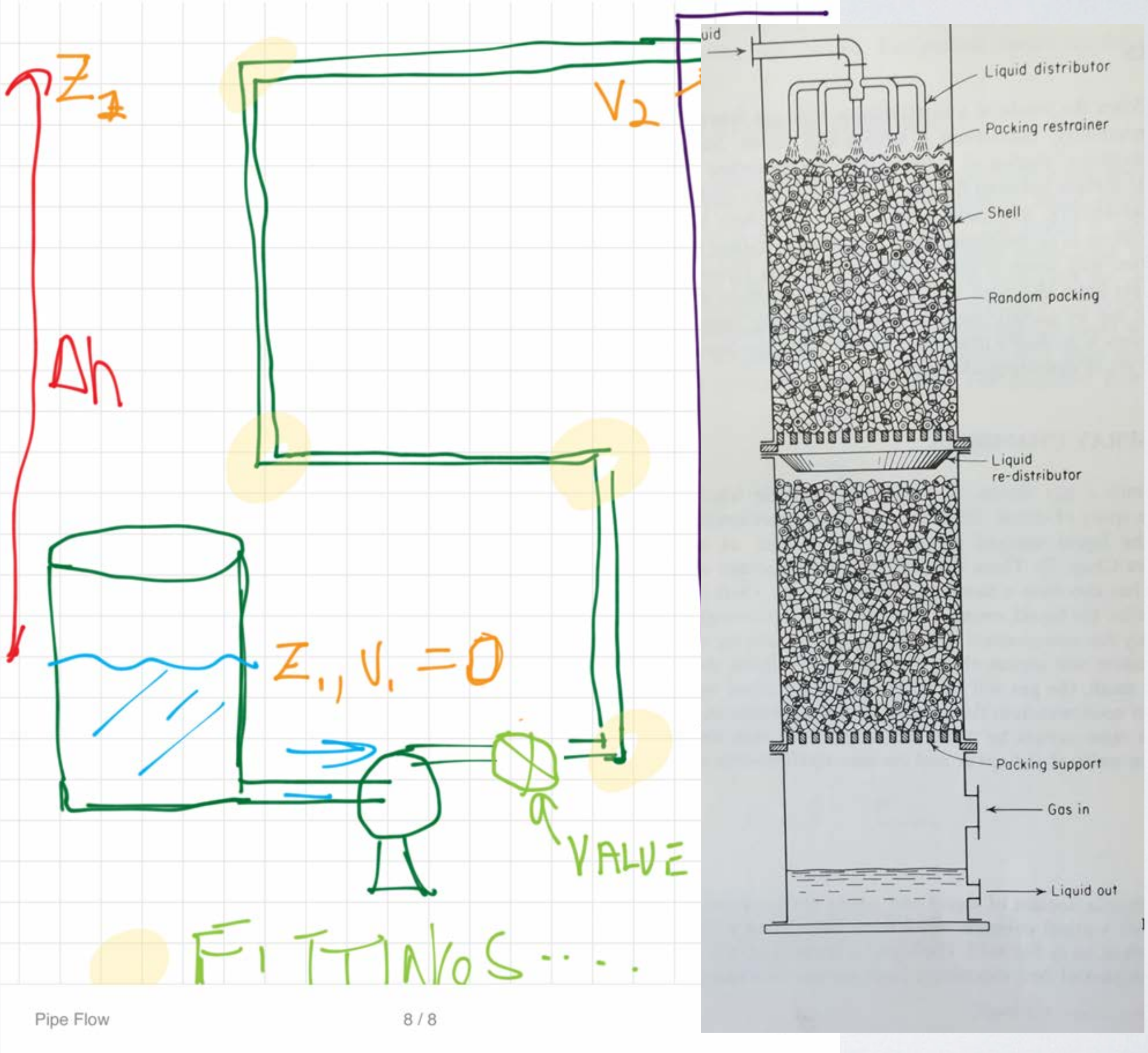
$$\Delta P = 2\rho v^2 \frac{L}{D} f$$

- What is the pressure change over 30 m of pipe, if the flow rate is 0.001 m^3/s, the diameter is 0.03 m and liquid is water, **μ** = 0.001 kg/(m-s), **ρ** = 1000 kg/m^3?
- About 22000 $kg/(m\text{-}s^2)$ =~ 0.2 ATM or 3 PSI.
- This is probably acceptable. If we made the pipe just 20% smaller, the pressure change would be 63,000 $kg/(m\text{-}s^2)$ and the power necessary to pump would increase from 20W to 60W!

NUMBER CHECK

HOW BIG SHOULD THE PUMP BE?

- Perhaps we are really asking the power that will be necessary to pump the liquid



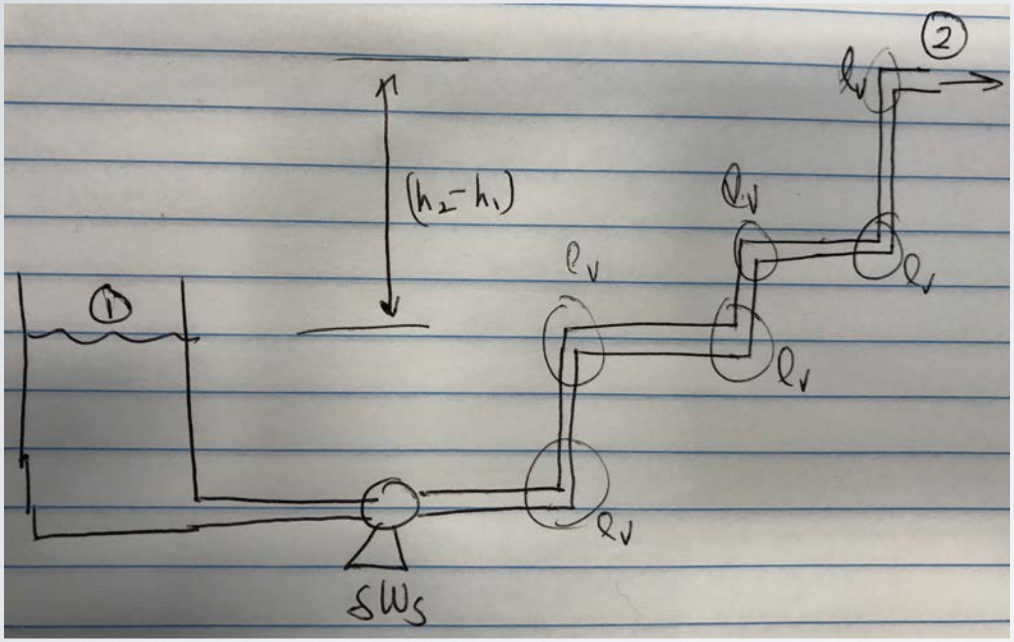
BERNOULLI EQUATION

- 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.

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

TYPICAL CALCULATION

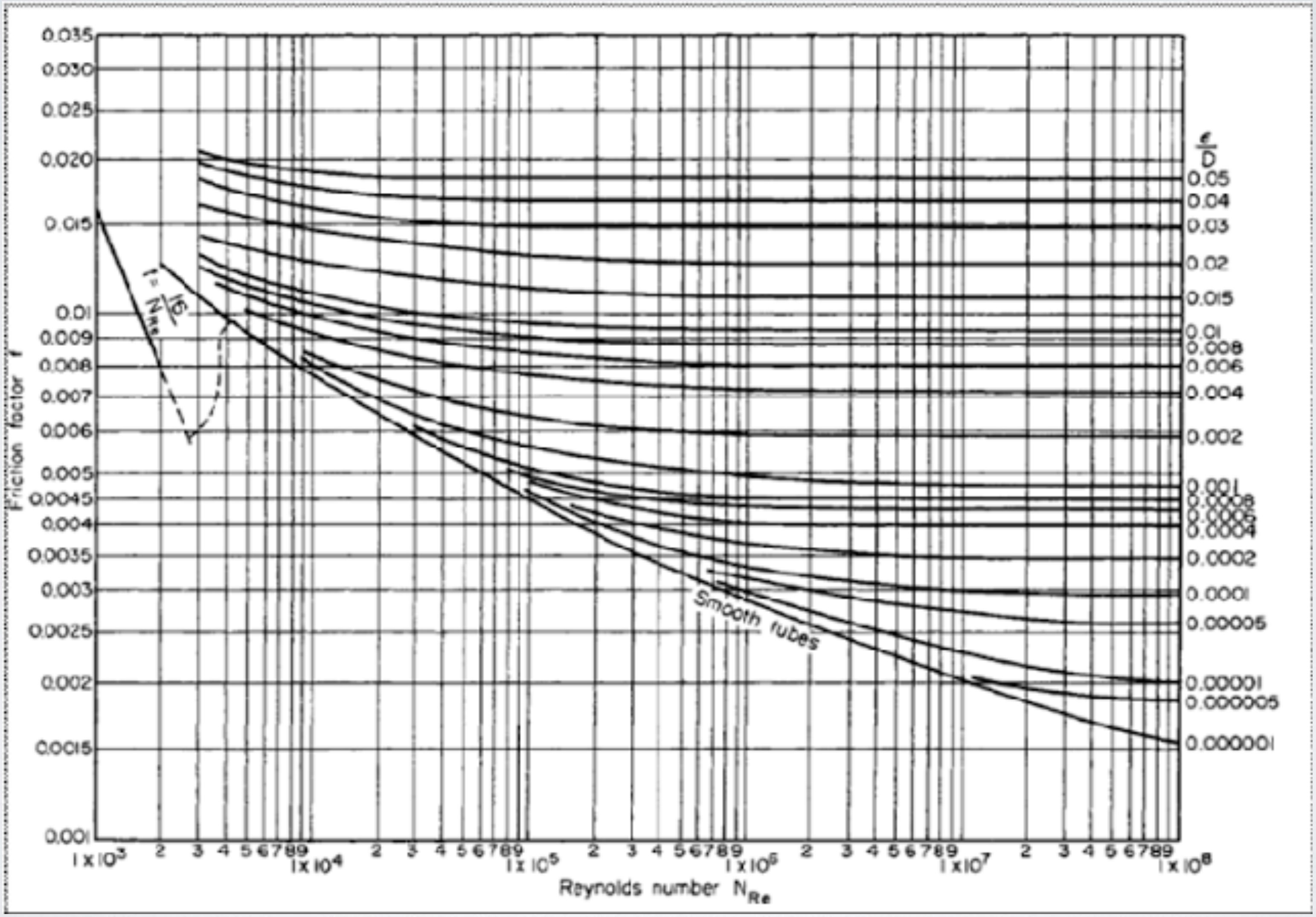


- Suppose that the flow rate is still 1 l/s of water, the total length of the pipe is still 30 m, the rise is 10 m and there are 6 elbows and a tank inlet

- Now what is the pumping power?
  - Note we would do the calculation from "1" to "2" and if so, Δp is 0!
  - The result is that it would take about 125 W. About 100 W is to pump against gravity, 20W for the straight pipe and only about 5W because of the fittings.

NUMBER CHECK

FRICTION FACTOR — REYNOLDS NUMBER CHART "ROUGHNESS", ε/D, ADDS AN ADDITIONAL PARAMETER

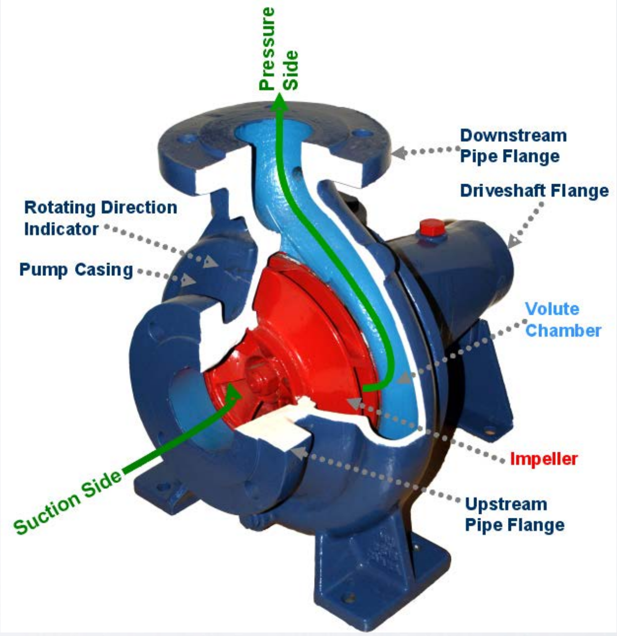


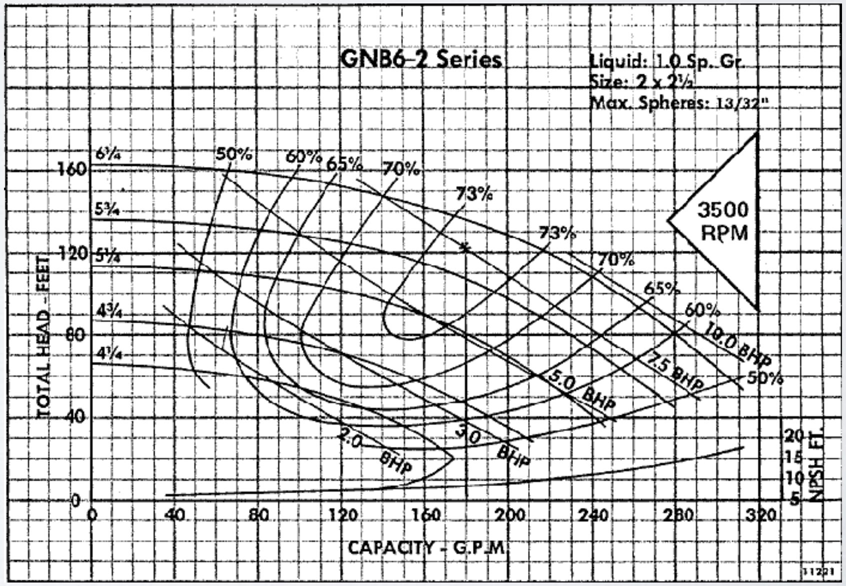
PUMPING FLUIDS

- Blowers and compressors are used for gases
- For low and moderate viscosity liquids, low to very high volumetric flow rates…
    - Centrifugal pumps are most common.
        - The Imperial College pilot plant is a special case… they use mostly positive displacement pumps with direct motor drive.
- The other key word is "positive displacement"
    - This means that specific volumes of fluid are forced through the pump/compressor/blower (with no back flow) so that the flow rate must be controlled by the speed of the motor/driving coupling.

CENTRIFUGAL PUMP

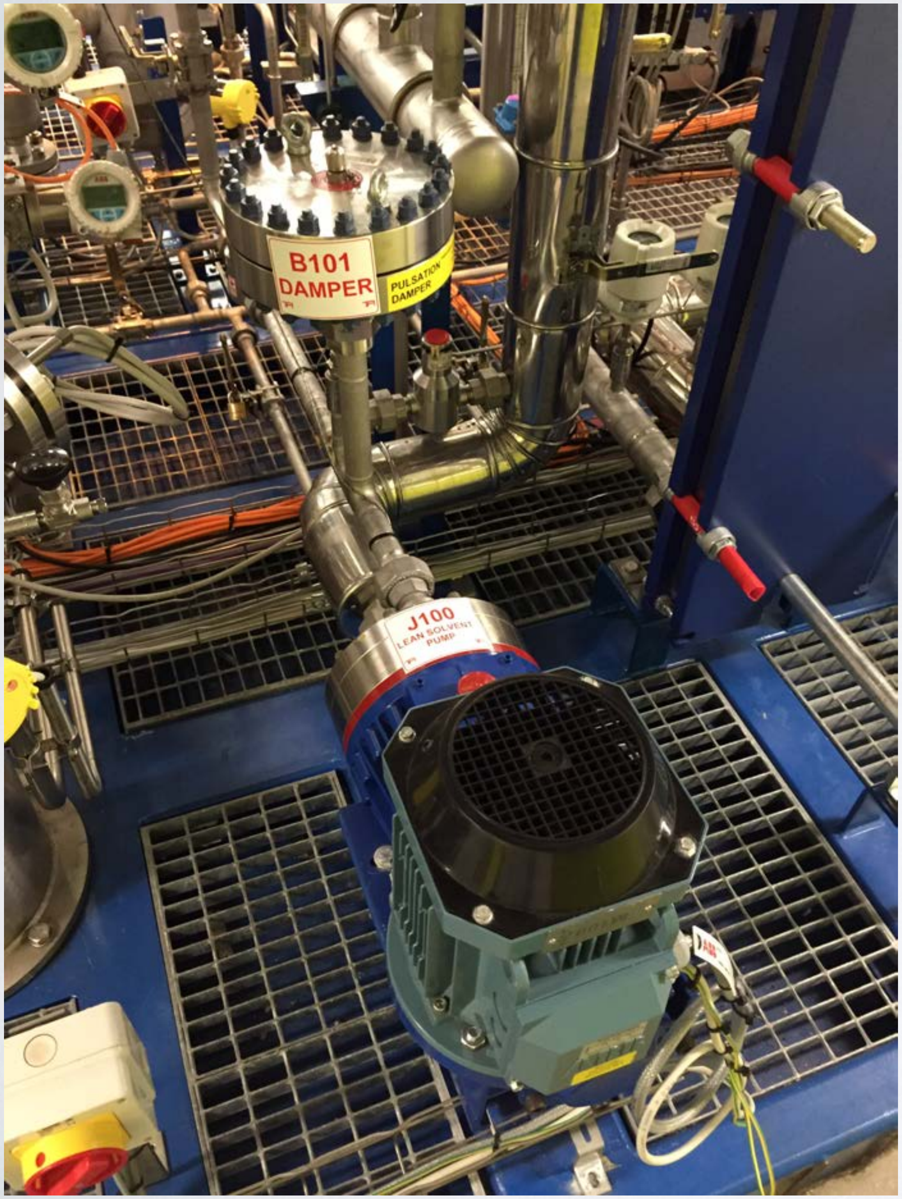
- Not positive displacement. A valve at the outlet can control the flow rate.
  - These can be throttled down quite a bit without causing any damage.





Pump Curves

DIRECT DRIVE POSITIVE DISPLACEMENT PUMPS



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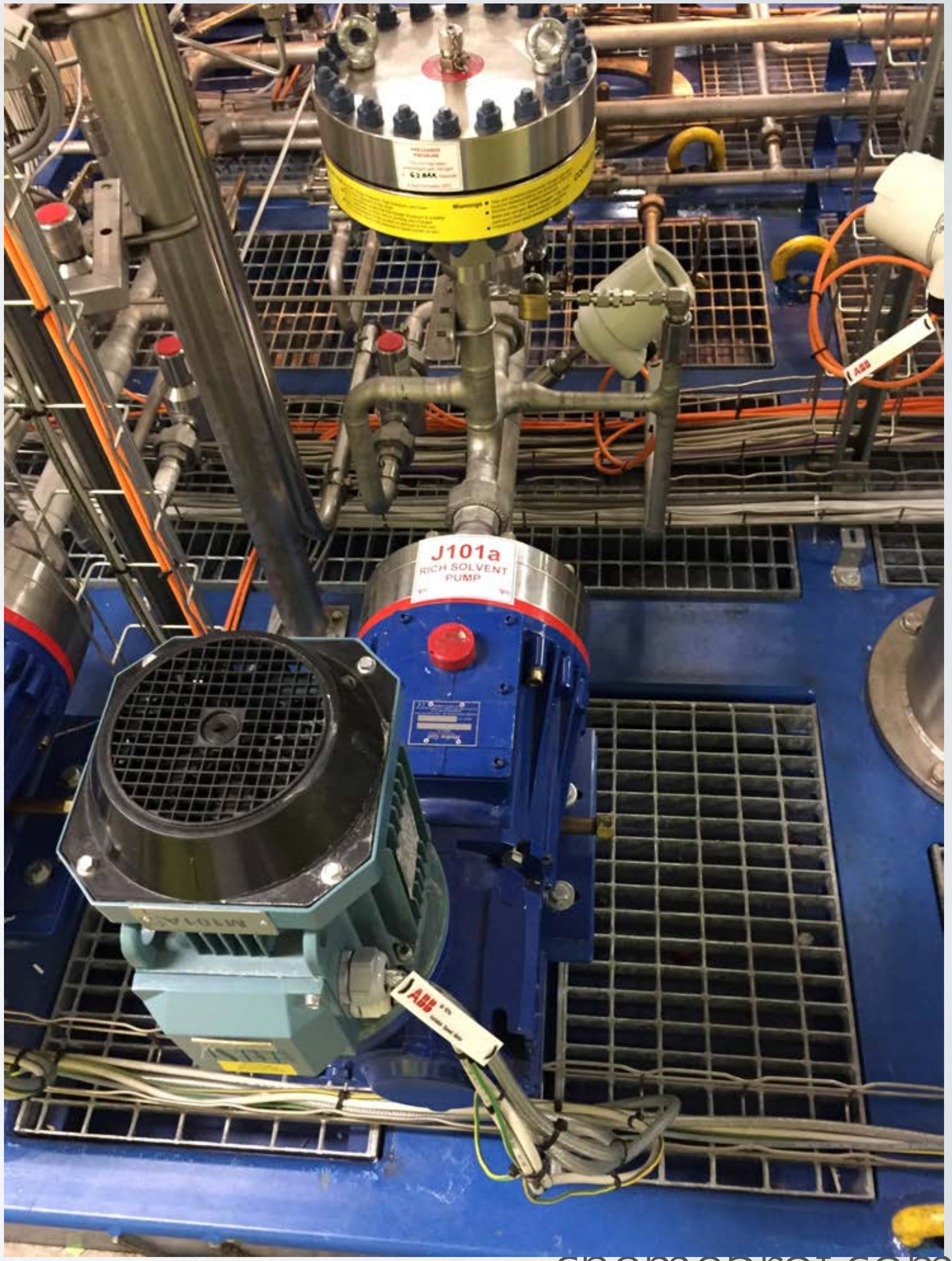

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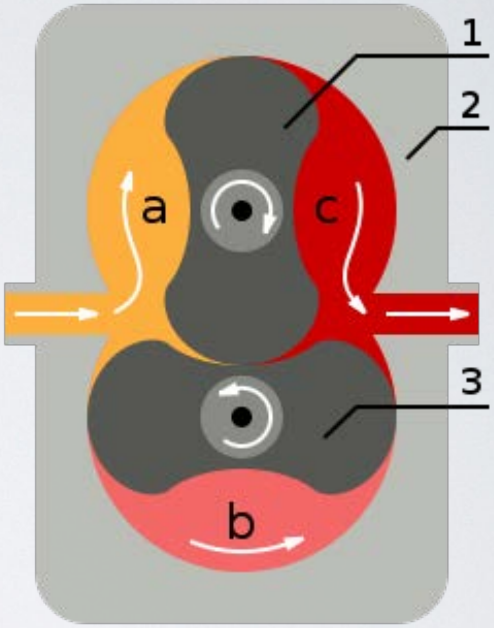
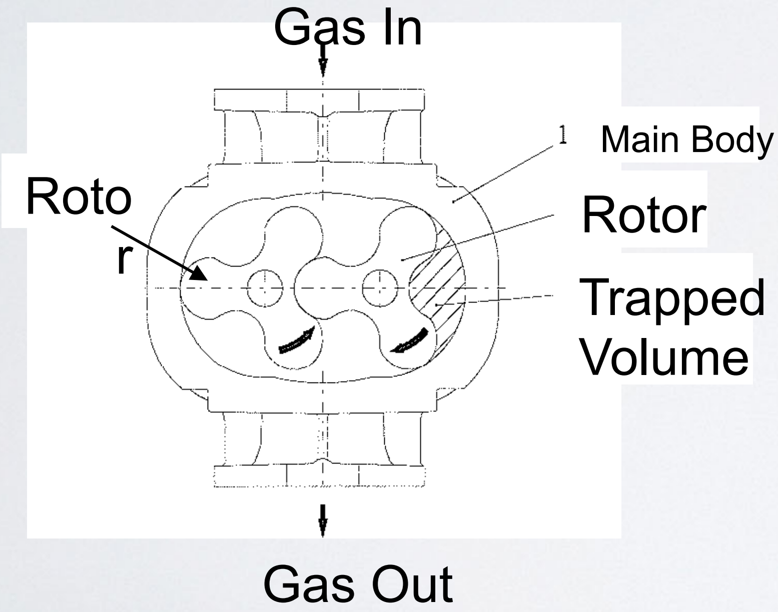
“BLOWER”



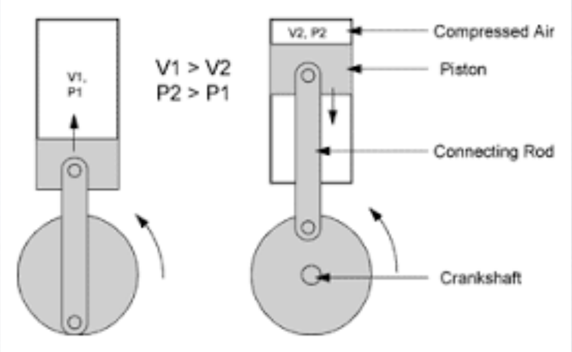
- Gases are pumped using blowers and compressors.
- Imperial has a “lobe” blower for the N2 recycle.
- Blowers usually provide some modest increase in pressure, but handle large volumes of air efficiently.


Gas In
1
Main Body
Roto
r
Rotor
Trapped
Volume
Gas Out


K102
KNOCK OUT
POT
J102
GAS BLOWER
M102
ABB

COMPRESSOR

- Compressors usually provide some “ratio” increase in pressure.
- Hence the power requirements are significant.
- Come in all sizes
- Reciprocating compressors are generally used for smaller scale flows (<50 HP).
- Imperial Compressor is a single-stage (“piston”) reciprocating compressor.

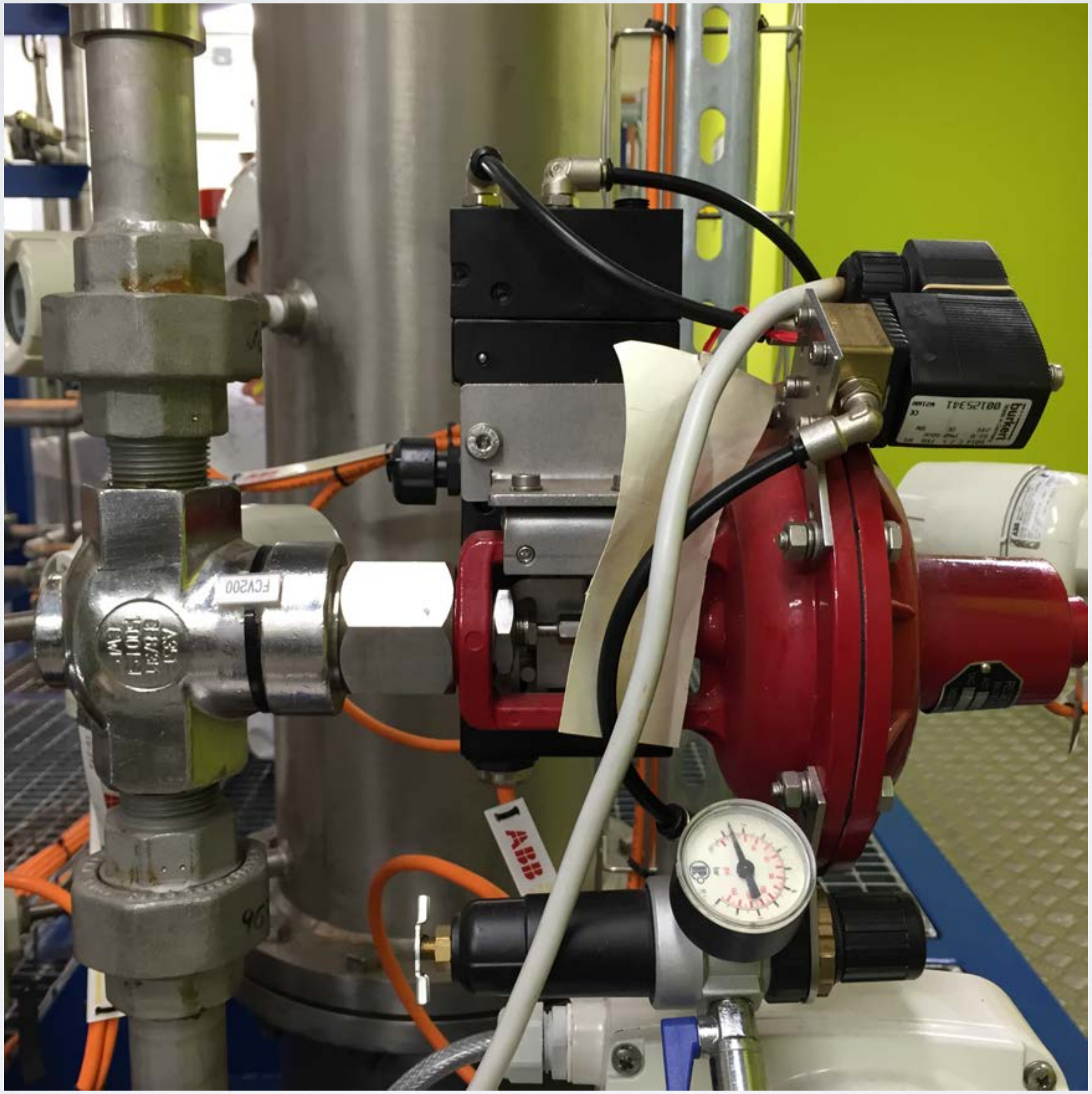


Pistons on top

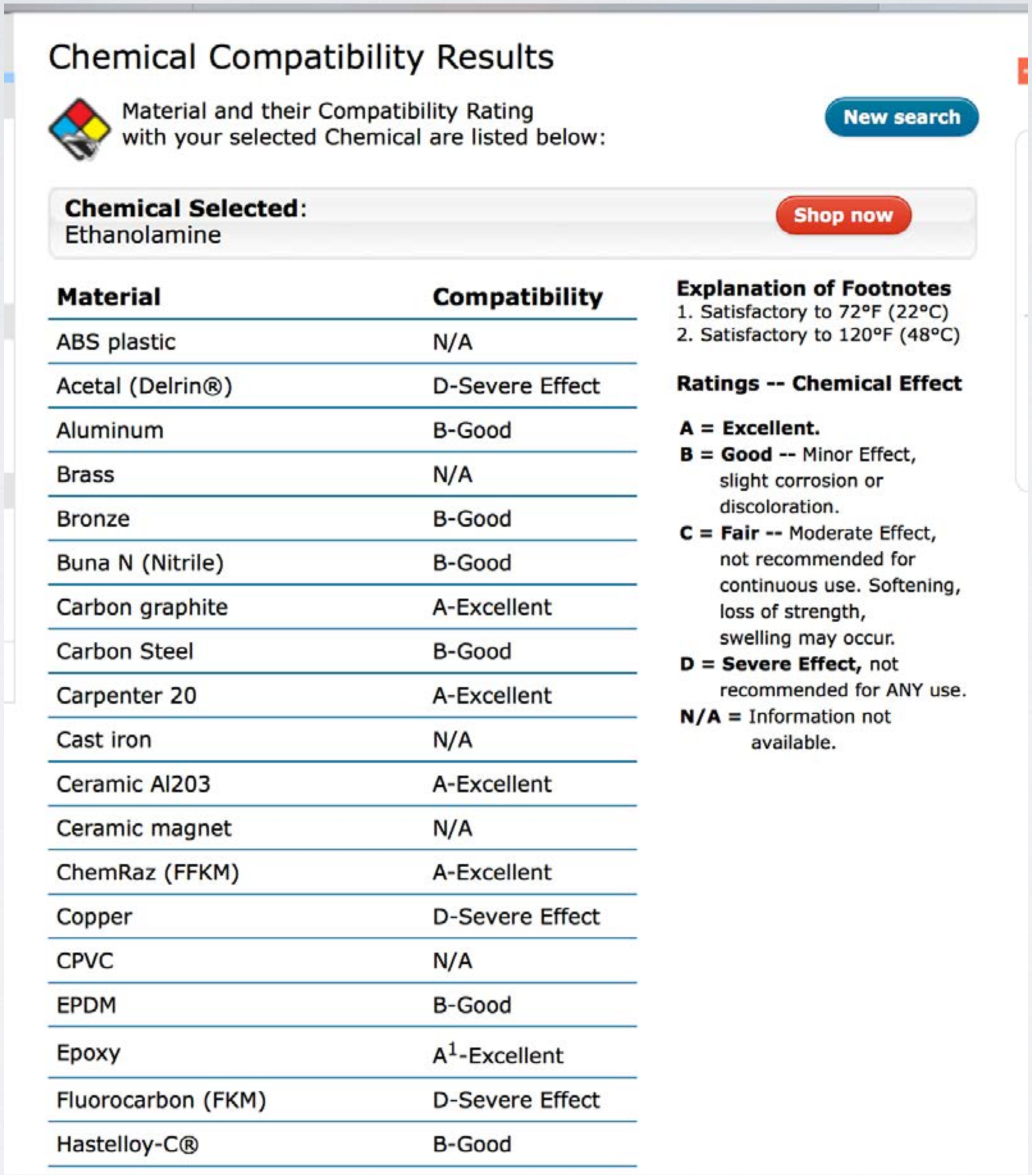
PIPE FITTINGS

WELDED JOINTS/BOLTED FLANGES

PIPE THREADS



CHEMICAL COMPATIBILITY



Chemical Compatibility Results

Material and their Compatibility Rating
with your selected Chemical are listed below:

Chemical Selected:
Ethanolamine

Material	Compatibility
ABS plastic	N/A
Acetal (Delrin®)	D-Severe Effect
Aluminum	B-Good
Brass	N/A
Bronze	B-Good
Buna N (Nitrile)	B-Good
Carbon graphite	A-Excellent
Carbon Steel	B-Good
Carpenter 20	A-Excellent
Cast iron	N/A
Ceramic Al203	A-Excellent
Ceramic magnet	N/A
ChemRaz (FFKM)	A-Excellent
Copper	D-Severe Effect
CPVC	N/A
EPDM	B-Good
Epoxy	A[1]-Excellent
Fluorocarbon (FKM)	D-Severe Effect
Hastelloy-C®	B-Good

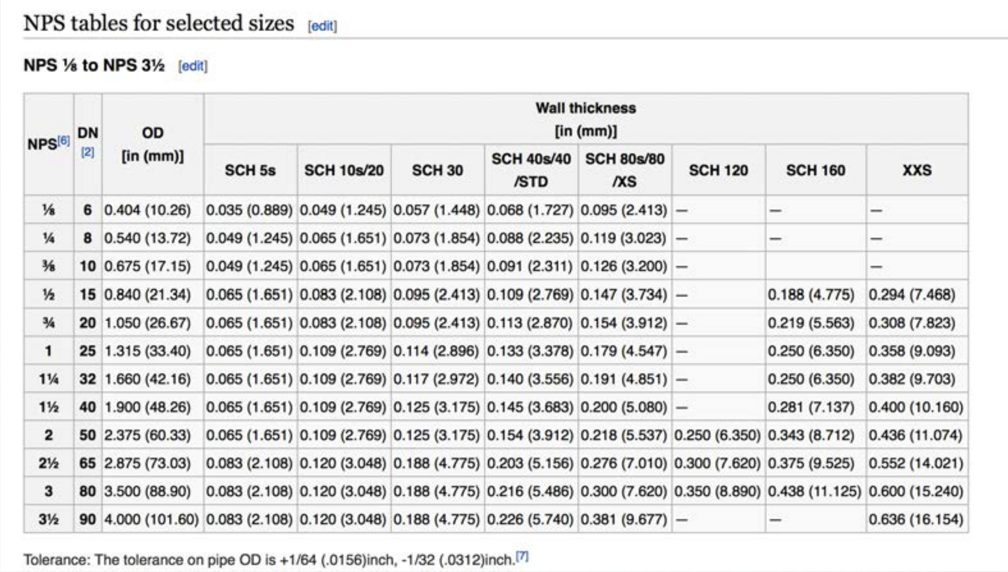
Explanation of Footnotes
1. Satisfactory to 72°F (22°C)
2. Satisfactory to 120°F (48°C)

Ratings -- Chemical Effect

A = Excellent.
B = Good -- Minor Effect, slight corrosion or discoloration.
C = Fair -- Moderate Effect, not recommended for continuous use. Softening, loss of strength, swelling may occur.
D = Severe Effect, not recommended for ANY use.
N/A = Information not available.

PIPES

- Standard sizes of fabrication
  - "schedule"… relates to wall thickness
- Chose material for appropriate compatibility
  - 304 Stainless is fine for MEA

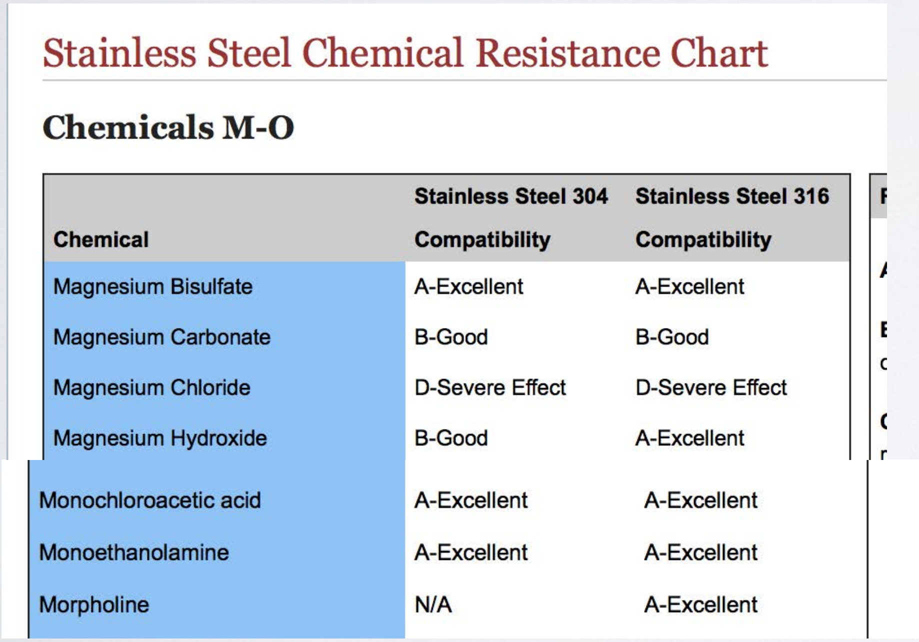


NPS tables for selected sizes [edit]

NPS ⅛ to NPS 3½ [edit]

NPS[6]	DN [2]	OD [in (mm)]	Wall thickness [in (mm)]							
			SCH 5s	SCH 10s/20	SCH 30	SCH 40s/40 /STD	SCH 80s/80 /XS	SCH 120	SCH 160	XXS
⅛	6	0.404 (10.26)	0.035 (0.889)	0.049 (1.245)	0.057 (1.448)	0.068 (1.727)	0.095 (2.413)	—	—	—
¼	8	0.540 (13.72)	0.049 (1.245)	0.065 (1.651)	0.073 (1.854)	0.088 (2.235)	0.119 (3.023)	—	—	—
⅜	10	0.675 (17.15)	0.049 (1.245)	0.065 (1.651)	0.073 (1.854)	0.091 (2.311)	0.126 (3.200)	—		—
½	15	0.840 (21.34)	0.065 (1.651)	0.083 (2.108)	0.095 (2.413)	0.109 (2.769)	0.147 (3.734)	—	0.188 (4.775)	0.294 (7.468)
¾	20	1.050 (26.67)	0.065 (1.651)	0.083 (2.108)	0.095 (2.413)	0.113 (2.870)	0.154 (3.912)	—	0.219 (5.563)	0.308 (7.823)
1	25	1.315 (33.40)	0.065 (1.651)	0.109 (2.769)	0.114 (2.896)	0.133 (3.378)	0.179 (4.547)	—	0.250 (6.350)	0.358 (9.093)
1¼	32	1.660 (42.16)	0.065 (1.651)	0.109 (2.769)	0.117 (2.972)	0.140 (3.556)	0.191 (4.851)	—	0.250 (6.350)	0.382 (9.703)
1½	40	1.900 (48.26)	0.065 (1.651)	0.109 (2.769)	0.125 (3.175)	0.145 (3.683)	0.200 (5.080)	—	0.281 (7.137)	0.400 (10.160)
2	50	2.375 (60.33)	0.065 (1.651)	0.109 (2.769)	0.125 (3.175)	0.154 (3.912)	0.218 (5.537)	0.250 (6.350)	0.343 (8.712)	0.436 (11.074)
2½	65	2.875 (73.03)	0.083 (2.108)	0.120 (3.048)	0.188 (4.775)	0.203 (5.156)	0.276 (7.010)	0.300 (7.620)	0.375 (9.525)	0.552 (14.021)
3	80	3.500 (88.90)	0.083 (2.108)	0.120 (3.048)	0.188 (4.775)	0.216 (5.486)	0.300 (7.620)	0.350 (8.890)	0.438 (11.125)	0.600 (15.240)
3½	90	4.000 (101.60)	0.083 (2.108)	0.120 (3.048)	0.188 (4.775)	0.226 (5.740)	0.381 (9.677)	—	—	0.636 (16.154)

Tolerance: The tolerance on pipe OD is +1/64 (.0156)inch, -1/32 (.0312)inch.[7]



Stainless Steel Chemical Resistance Chart

Chemicals M-O

Chemical	Stainless Steel 304 Compatibility	Stainless Steel 316 Compatibility
Magnesium Bisulfate	A-Excellent	A-Excellent
Magnesium Carbonate	B-Good	B-Good
Magnesium Chloride	D-Severe Effect	D-Severe Effect
Magnesium Hydroxide	B-Good	A-Excellent
Monochloroacetic acid	A-Excellent	A-Excellent
Monoethanolamine	A-Excellent	A-Excellent
Morpholine	N/A	A-Excellent

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.
- The material selected must be compatible with the fluids being pumped, but cost, weight and strength are also factors that must be considered.