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INDUSTRIAL DEVELOPMENT ORGANIZATION

COMPRESSED AIR SYSTEM OPTIMIZATION

EXPERT TRAINING

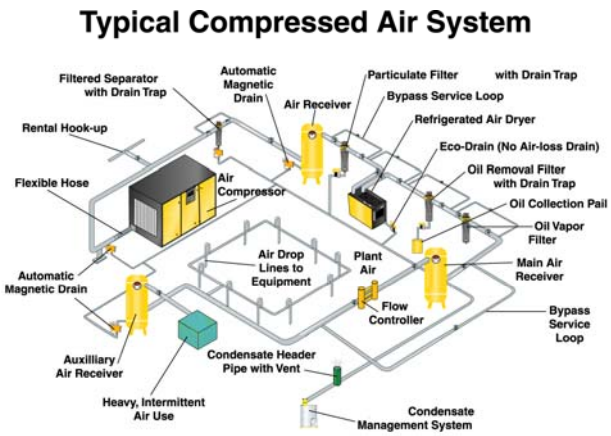
Introduction to Compressed Air

1. Introduction to Compressed Air Systems

- **Compressed air has 3 primary uses**
  - **Power**
    - **As an energy source to perform work**
  - **Process**
    - **Air becomes part of a process**
  - **Control**
    - **To stop, start or regulate the operation of a machine**

1. Introduction to Compressed Air Systems

- **A compressed air system includes both the supply side components and the demand side components.**



1. Introduction to Compressed Air Systems

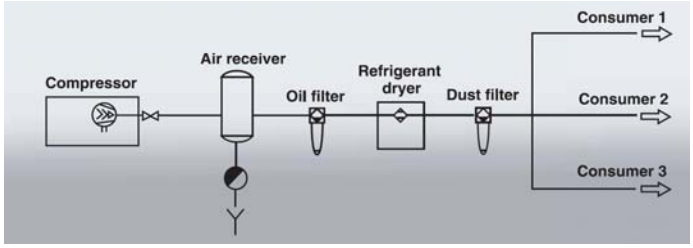
- **Old Management Technique**
  - **Plant production is #1 priority**
  - **Plant compressed air system must always be maintained**
  - **Over supply of compressed air is acceptable, under supply is not acceptable**
  - **Minimum pressure must be maintained. Higher pressure is acceptable**
- **New Management Technique**
  - **Plant <u>productivity</u> is the #1 priority**
  - **The plant air <u>demand</u> must always be supplied**
  - **The compressed air system must be in <u>balance</u> with demand. Both over supply and under supply are unacceptable**
  - **Compressed air pressure must be <u>stable</u>. Pressures higher than required are unacceptable as are pressures lower than required.**

Compressed Air System Optimisation Defined

There are three basic ways to optimise the consumption of a compressed air system:

1. Produce compressed air more efficiently
2. Consume less compressed air
3. Utilise the heat of compression

Source: ASME EA-4



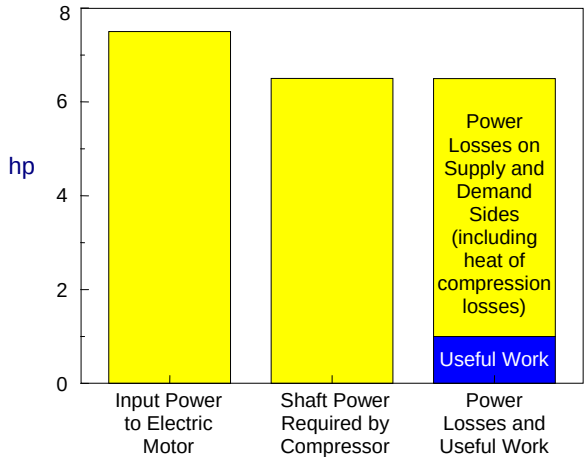
Compressed Air System Efficiency

Fact: Compressed air is an inefficient source of energy and should be used wisely.

Consider this:

- An air motor with 0,68 kW shaft output consumes 50 m^3/hr
- An air compressor consumes about 5.6 kW to produce 50 m^3/hr at 7 bar, or 8 times as much!

Compressed Air System Efficiency



Source: Compressed Air Challenge

Compressed Air System Cost

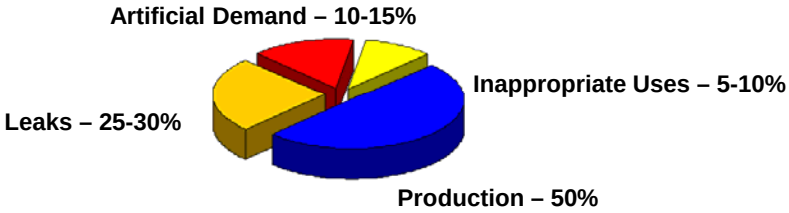
Compressed air power is costly

- The 0,68 kW compressed air motor shaft output costs RM 16 000 per year at 8 760 hours operation.
- An electric motor with a similar shaft output would consume about 0,85 kW and cost RM 2 430 per year to operate.

Compressed Air System Costs

System losses further increase the costs:

Typically 35 to 45% of compressed air is wasted to leakage and artificial demand before it gets to the user. And 10%+ may be wasted through inappropriate uses.



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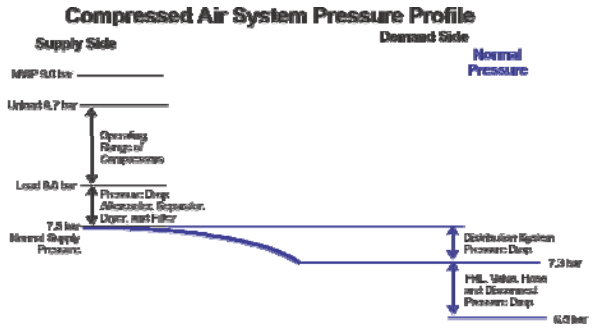
Compressed Air System Costs

System losses further increase the costs:

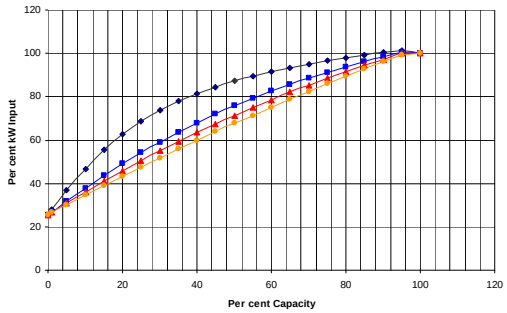
Pressure differentials typically reduce end use pressure by 1 or 2 bar forcing discharge pressures higher. Compressor power increases 6 to 7% per unit output for every bar increase.



Compressed Air System Costs

System losses further increase the costs:

Air compressors often do not run at full efficiency due to poor control and lack of storage receiver capacity



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The Systems Approach

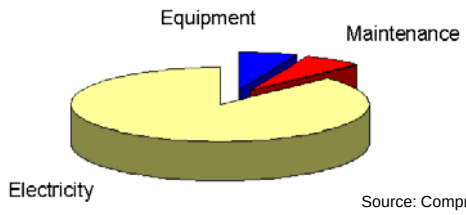
Application of a systems approach to a compressed air system assessment and resulting energy measures directs the focus towards total system performance rather than individual component efficiency

- Understand compressed air point of use as it supports critical plant production functions
- Correct existing poor performing applications and those that upset system operation
- Eliminate wasteful practices, leaks, artificial demand, and inappropriate use
- Create and maintain an energy balance between supply and demand
- Optimize compressed air energy storage and air compressor control

Source: ASME EA-4

Life Cycle Costs

Typically over 75% of the lifetime costs of compressed air are energy related



Source: Compressed Air Challenge

Based on 30 cen per kWh blended rate 55 kW fully loaded compressor at 4200 hours over ten years.

Typical Compressor Operating Cost

Item: Typical 160 kW air cooled screw compressor
Duty: Full load at 7.5 bar, 4 200 hours per year
Rate: 30 cen per kWh blended

Power at full load:	182.5 kW
Flow:	505 l/sec
Specific Power:	36.1 kW/ 100l/s

Energy Cost = kW x hours x rate

Energy Cost =	RM 229 950 per year
Purchase Price =	RM 189 540

Comparing Energy Usage and Efficiency

Compressed Air System Comparisons

Three 160 kW compressed air systems are being evaluated in an existing plant :

1. Existing fixed speed air cooled load/unload compressor, standard refrigerated dryer, standard filter and small receiver
2. A new fixed speed load/unload compressor, new refrigerated dryer, oversized filter and large receiver
3. A VSD compressor, cycling refrigerated dryer, oversized filter and medium receiver

Compressed Air System Comparisons

Air cooled compressor, 8 bar 8 760 hour operation, peak flow 330 l/s, average flow 175 l/s , cost 0,3 cen per kWh

Option 1 – Existing unit – Base Case

Ave Compressor Power	= 134,5 kW
Dryer Power	= 6,0 kW
Total Energy	= 1 230 780 kWh
Specific Power	= 80,3 kW/100 l/s
Electrical Cost	= RM 369 200

Compressed Air System Comparisons

Air cooled compressor, 7 bar 8 760 hour operation, peak flow 268 l/s, average flow 133 l /s, cost 0,3 cen per kWh

Option 2 – New more efficient load/unload , larger storage, lower pressure, cycling refrigerated dryer, leak reduction

Ave Compressor Power	= 85,1 kW
Dryer Power	= 1,7 kW
Total Energy	= 760 400
Specific Power	= 65,3 kW/100 l/s
Electrical Cost	= RM 228 100
Saved	= RM 141 100 or 38%
Project Cost	= RM 400 000

Compressed Air System Comparisons

Air cooled compressor, 7 bar 8 760 hour operation, peak flow 268 l/s, average flow 133 l /s, cost 0,3 cen per kWh

Option 3 – New VSD unit, medium storage, lower pressure, cycling refrigerated dryer, leak reduction

Ave Compressor Power	=	46,0 kW
Dryer Power	=	1,7 kW
Total Energy	=	417 850 kWh
Specific Power	=	35.9 kW/100 l/s
Cost	=	RM 125 400
Saved	=	RM 243 800 or 66%
Project Cost	=	RM 485 000

Compressed Air System Payback

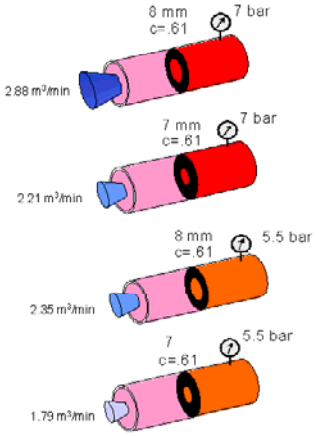
Option	Project Cost	Savings	Payback
O1 - Base	0	0	0
O2 - New load/unload	RM 400 000	RM 141 100	2.8
O3 - New VSD	RM 485 000	RM 243 800	2.0

Compressed Air System Incremental Payback

Option	Project Incremental Cost	Savings	Payback Years
O1 - Base	RM 235 000	0	0
O2 - New load/unload	RM 165 000	RM 141 100	1.2
O3 - New VSD	RM 250 000	RM 243 800	1.0

Artificial Demand

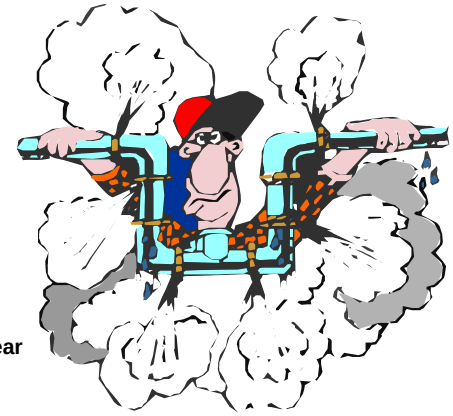
- If the required pressure is 5.5 bar
- Operating at 7 bar creates 2.8 m3/min of artificial demand
- 20% of the air that is supplied to the system is wasted.



1. Introduction to Compressed Air Systems

Finding leaks

- soap connections
- locate source of noise
- ultra-sound device



Example:
hole diameter: 3 mm
air loss: 0.5 m^3/min (6 bar gauge)
0.5 m^3/min x 60 min/h = 30 m^3/h
30 m^3/h x 8000 h/year = 240,000 m^3/year
240,000 m^3/year x cost/m^3 = ????

1. Introduction to Compressed Air Systems

Leakage losses

Hole diameter	Air consumption at 6 bar (g) m^3/min	Loss kW
1 mm	0.05	0.3
2 mm	0.21	1.3
4 mm	0.83	5.2
6 mm	2.12	13.5

At RM 0.30/kWh, a 6 mm leak costs over
RM 35,478
/year in power plus additional service on the compressed air equipment.

Class exercise: Calculate the cost over 4,000 hours.

1. Introduction to Compressed Air Systems

Leakage losses

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At RM 0.30/kWh, a 6 mm leak costs over
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Class exercise: Calculate the cost over 4,000 hours.
13.5 kW x 4,000 x 0.30 = RM 16,200
Question: How much if at 7 bar?

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1. Introduction to Compressed Air Systems

Leakage losses

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6 mm	2.12	13.5

At RM 0.30/kWh, a 6 mm leak costs over
RM 35,478
/year in power plus additional service on the compressed air equipment.

Class exercise: Calculate the cost over 4,000 hours.
13.5 kW x 1.06 x 4,000 x 0.30 = RM 17,170
Question: If this leak was repaired how much would be saved?

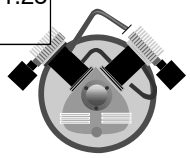
1. Introduction to Compressed Air Systems

Measuring leakage losses

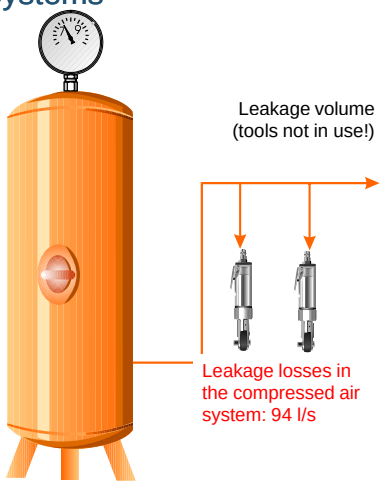
by exhausting an air receiver

$$V_L = \frac{V_R \times (p_I - p_F)}{T} \times 1.25$$

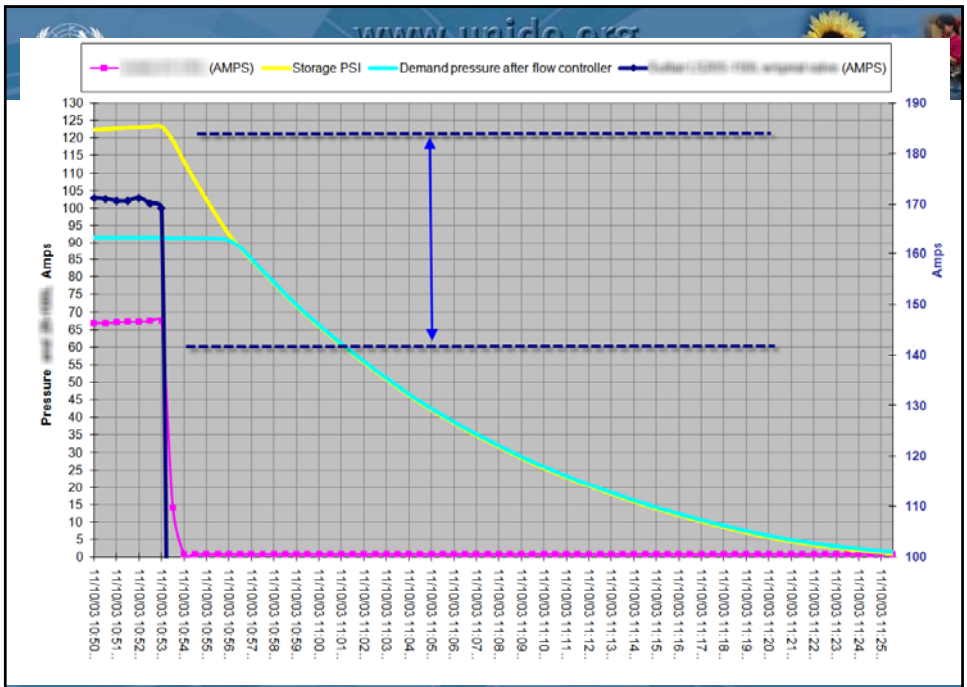
V_L = Leakage volume
V_R = Receiver volume
P_I = Initial receiver pressure
P_F = Final receiver pressure
T = Measuring period



Example:
V_R = 500 litres
p_I = 9 barg
p_F = 4.5 barg
T = 30 sec



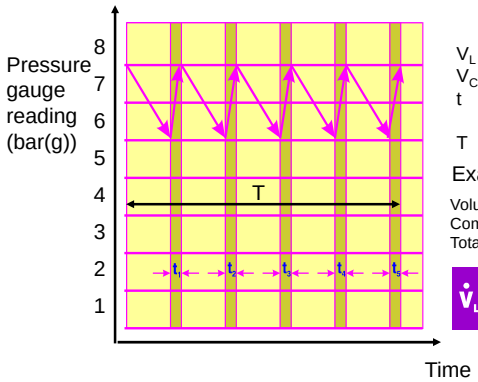
$$V_L = \frac{500\ l \times (9 - 4.5)}{30\ sec} = 75 \times 1.25 = 94\ l/s$$



1. Introduction to Compressed Air Systems

Measuring leak losses

by measuring loaded time of the compressor with end users shut off



V_L = Leakage volume in m^3/min
V_C = Compressor volumetric flow rate in m^3/min
t = Time units during which the compressor ran on load
T = Total time of the measurement procedure

Example:

Volumetric compressor flow rate	$\dot{V}$ =	3 m^3/min
Compressor time on load	$t = t_1+t_2+t_3+t_4+t_5$ =	120 sec
Total measurement time	T =	600 sec

$$\dot{V}_L = \frac{\dot{V}_C \times t}{T} \qquad \frac{3 \times 120}{600} = 0.6\ m^3/min = 20\%$$

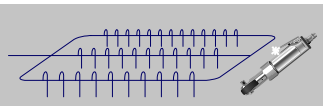
1. Introduction to Compressed Air Systems

Leak measurement of the consumers

In factories where a large number of air tools, machines and equipment are used, hose connectors and valves often cause considerable leak losses.

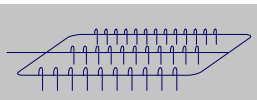
Using the two methods described previously, two measurements are carried out:

A



Tools, machines and equipment are connected for normal operation (total leakage)

B



The shut-off valves upstream of the connectors of the consumers are closed (air distribution leakage)

The difference between A and B represents the losses in the pneumatic tools, etc. and their fittings.

Key Learning Points

- Compressed air is a necessary utility for industrial plants.
- For some production uses compressed is a process variable.
- Many systems waste 50% of more of the compressed air that is consumed.
- System management must focus on productivity rather than traditional goals.
- The Systems Approach is an integrated approach, not component efficiency.
- Generating compressed air is an inefficient energy conversion.

Key Learning Points

- Using air only when other alternatives are not available.
- Eliminating inappropriate uses of compressed air.
- Reducing delivered pressure to the system eliminates Artificial Demand.
- Reducing the amount of leakage loss in the system.
- Minimize Irrecoverable Pressure Loss.
- Operating compressed air systems at the lowest practical pressure.
- Optimize compressor control with a properly implemented control strategy.

For more information:

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2. Understanding Compressed Air

2. Understanding Compressed Air

What is compressed air?

Compressed air is ...

- ... compressed atmospheric air
- ... a mixture of gases
- ... compressible
- ... an energy carrier

grid system user
Power station transformer

Air center air main
air treatment user

Proportional relationship between pressure, temperature and volume:

$$p \sim \frac{T}{V} \qquad p \times V \sim T$$

still valid:

$$p = \frac{F}{A}$$

2. Understanding Compressed Air

Basic units

m = Meter	kg = Kilogram
s = Second	A = Ampere
K = Kelvin	mol = Molar mass

Derived units

N = Newton	Pa = Pascal
bar = Bar	Ω = Ohm
J = Joule	W = Watt
C = Celsius	Hz = Hertz

2. Understanding Compressed Air

Physical laws

COMPRESSED AIR is atmospheric air under pressure.
That means energy is stored in the air.

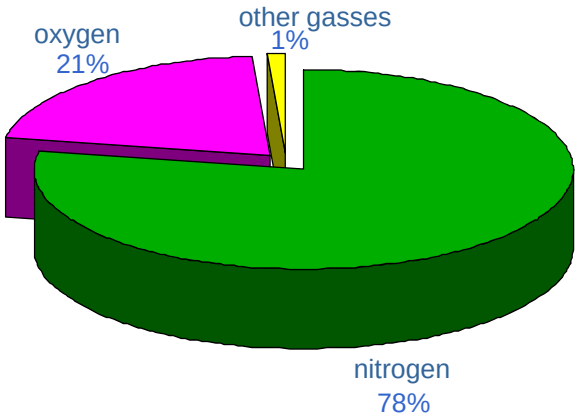
When the compressed air expands again
this energy is released as WORK.

pressure (energy)

EXPANSION

2. Understanding Compressed Air

Components of air

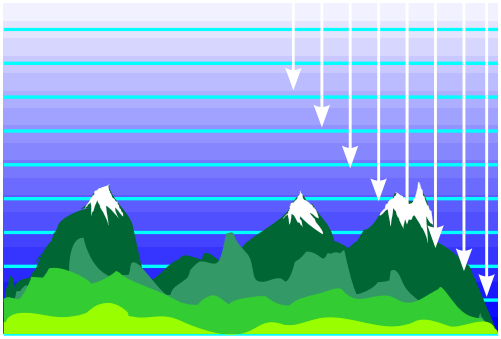


2. Understanding Compressed Air

Atmospheric pressure...

...is generated by the weight of the atmosphere.
It is dependent on the DENSITY of the air and the height:

The normal atmospheric pressure at sea level is 1.013 bar (760 mmHg (Torr))



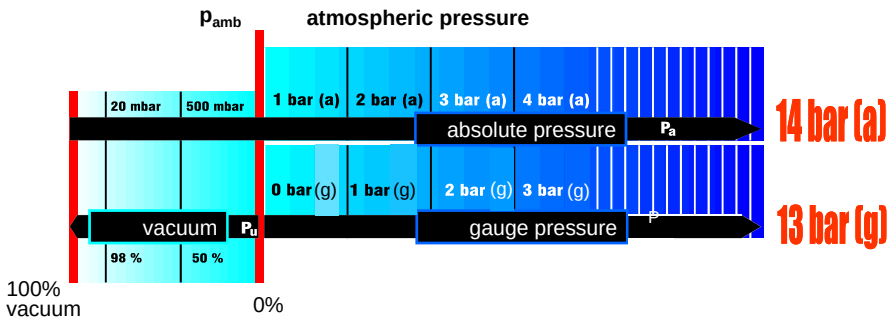
2. Understanding Compressed Air

Absolute pressure ...

... is the pressure measured from absolute zero.
It is used for all theoretical calculations and is required in vacuum and blower applications.

Gauge pressure ...

... is the practical reference pressure and is based on atmospheric pressure.



2. Understanding Compressed Air

Definition of pressures

Generally:

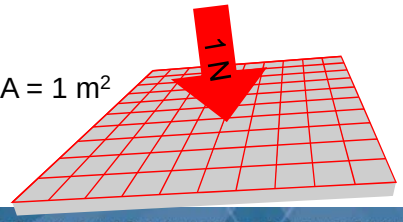
$$\text{Pressure (p)} = \frac{\text{Force (F)}}{\text{Area (A)}}$$

Dimensions:

$$\text{1 Pascal (Pa)} = \frac{\text{1 Newton (N)}}{\text{1 m}^2\text{ (A)}}$$

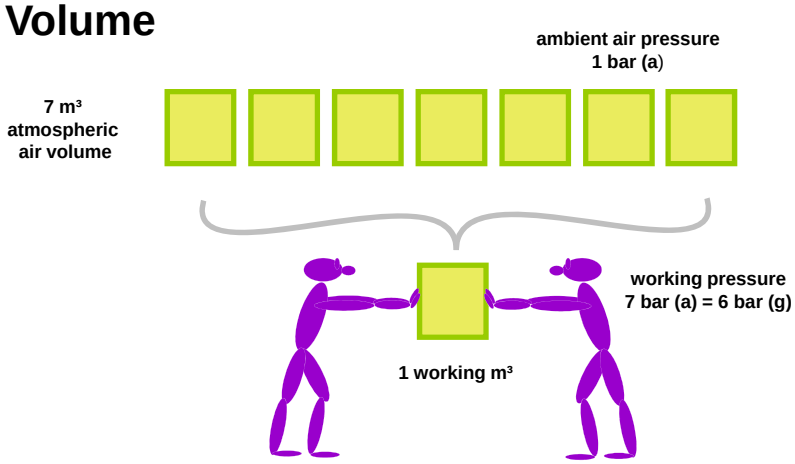
Equivalents		
10^5 Pa	=	1 bar
1 MPa	=	10 bar
1 hPa	=	0.001 bar
Gauge pressure 1 bar	=	14.5 psi(g)
1 bar	=	10197 mmWC
1 bar	=	750.062 Torr

A = 1 m²



2. Understanding Compressed Air

Volume



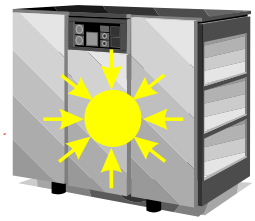
2. Understanding Compressed Air

Volume

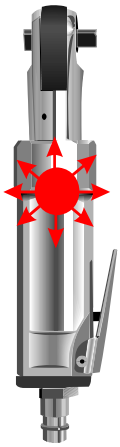
Expansion:

Working pressure
7 bar (a)
= 6 bar (g)

Working
pressure
p_1, V_1



Ambient air pressure p_0, V_0



The volume of atmospheric air decreases
at an inverse ratio to the respective absolute
pressures (at constant temperature,
without taking humidity into account)

$$\frac{V_1}{V_0} = \frac{p_0}{p_1}$$

2. Understanding Compressed Air

Definition of volumes

	Temperature	Pressure	Relative humidity	Density
Volume according to DIN 1343 (normal physical state)	0°C = 273.15K	1.01325 bar	0%	1.294 kg/m³
Volume according to DIN/ISO 2533	15°C = 288.15K	1.01325 bar	0%	1.225 kg/m³
Volume related to atmosphere (normal state)	atmospheric temperature	atmospheric pressure	atmospheric humidity	variable
Volume related to operating state	working temperature	working pressure	variable	variable

2. Understanding Compressed Air

Conversion of normal volume to volume according to DIN 1343

$$V_N = \frac{V_I \times T_N \times (p_I - (H_{rel} \times p_D))}{p_N \times T_I}$$

V_N = Normal volume to DIN 1343
V_I = Volume at inlet conditions
T_N = Temperature to DIN 1343, T_N = 273.15K
T_I = Maximum temperature at the installation in K
p_N = Air pressure to DIN 1343, p_N = 1.01325 bar
p_I = Lowest air pressure at the installation in bar
H_{rel} = Maximum relative humidity in the air at the installation
p_D = Saturation pressure of the water vapor contained in the air in bar, dependent on the temperature of the air

2. Understanding Compressed Air

Extract from the table for the saturation pressure of water vapour at saturation

Saturation pressure p_D (bar) at air temperature t (° C)

-10	0.00260
-9	0.00280
-8	0.00310
-7	0.00340
-6	0.00370
-5	0.00400
-4	0.00440
-3	0.00480
-2	0.00520
-1	0.00560
0	0.00610
1	0.00640
2	0.00710
3	0.00740
4	0.00810
5	0.00870
6	0.00940
7	0.01000
8	0.01070
9	0.01150

10	0.0123
11	0.0131
12	0.0140
13	0.0150
14	0.0160
15	0.0170
16	0.0182
17	0.0184
18	0.0206
19	0.0220
20	0.0234
21	0.0245
22	0.0264
23	0.0281
24	0.0298
25	0.0317
26	0.0336
27	0.0356
28	0.0378
29	0.0400

30	0.0424
31	0.0449
32	0.0473
33	0.0503
34	0.0532
35	0.0562
36	0.0594
37	0.0627
38	0.0662
39	0.0699
40	0.0738
41	0.0778
42	0.0820
43	0.0864
44	0.0910
45	0.0968
46	0.1009
47	0.1061
48	0.1116
49	0.1174
50	0.1234

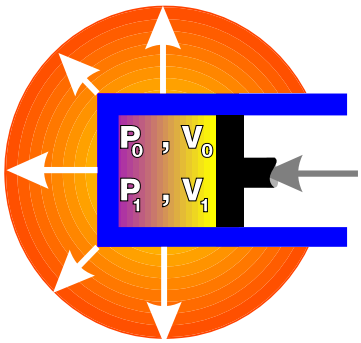
2. Understanding Compressed Air

Gas laws – Boyle's Law

Isotherms (constant temperature)

If the volume is reduced under constant temperature, the pressure increases.

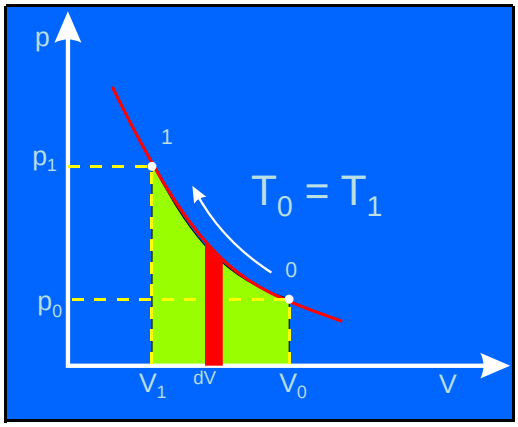
$$P_0 \times V_0 = P_1 \times V_1$$



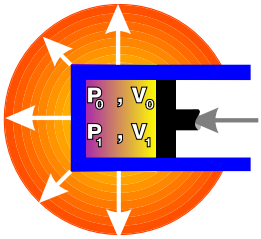
Heat dissipation

2. Understanding Compressed Air

Isotherms (constant temperature)



Heat dissipation



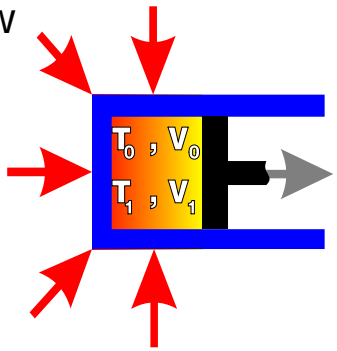
2. Understanding Compressed Air

Gas laws – Charles' Law

Isobars (constant pressure)

If heat is applied under constant pressure, The air volume behaves directly proportional to its absolute temperature.

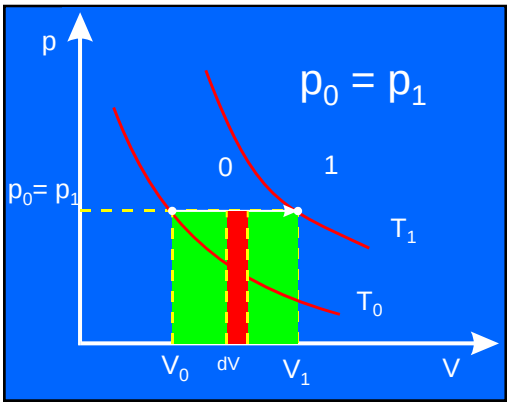
$$\frac{V_0}{V_1} = \frac{T_0}{T_1}$$



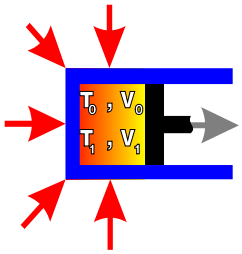
Application of heat

2. Understanding Compressed Air

Isobars (constant pressure)



Application of heat



2. Understanding Compressed Air

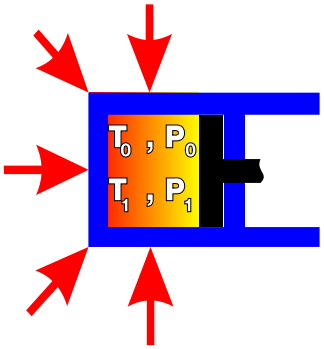
Gas laws – Amonton's Law

Isochors (constant volume)

If heat is applied with constant volume, the pressure behaves directly proportional to the absolute temperature.

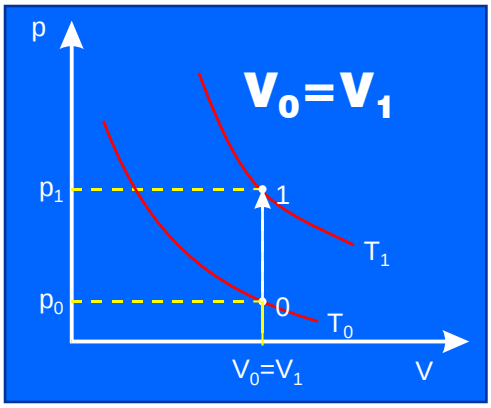
$$\frac{P_0}{P_1} = \frac{T_0}{T_1}$$

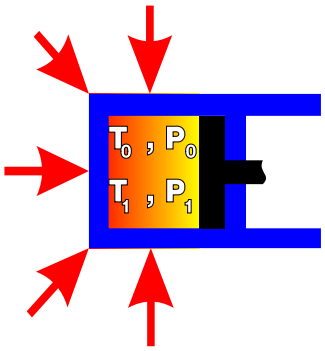
Application of heat



2. Understanding Compressed Air

Isochors (constant volume)





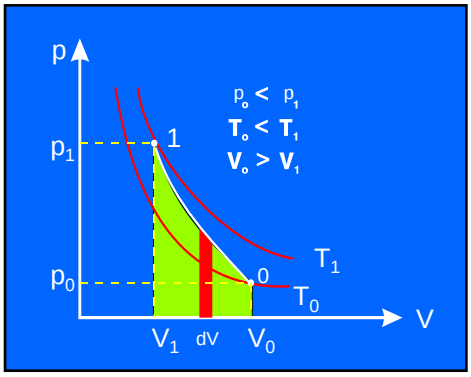
Application of heat

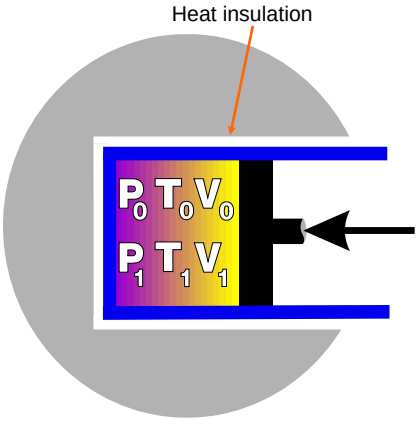
2. Understanding Compressed Air

Adiabatic or Isentropic

(no heat transfer)

If the volume is reduced and heat cannot be dissipated, temperature increases with the pressure





2. Understanding Compressed Air

Gas equation

Gas law relating to a closed system:

$$\frac{p_0 \times V_0}{T_0} = \frac{p_1 \times V_1}{T_1} = R = \text{constant}$$

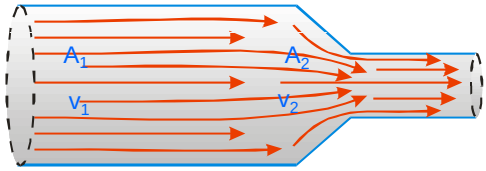
p	=	pressure (bar (absolute))
V	=	volume (m^3)
T	=	temperature (K)
R	=	special gas constants

e.g. $R = 28.96 \frac{bar \cdot m^3}{K} = 289.6 \frac{J}{kg \cdot K}$

for dry air

2. Understanding Compressed Air

Flow velocity in air lines



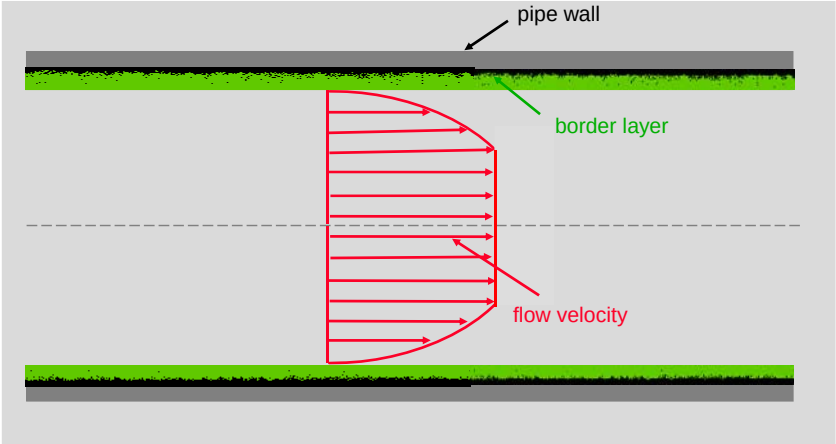
valid is:

$$\dot{V} = A_1 \times v_1 = A_2 \times v_2 \qquad \frac{A_1}{A_2} = \frac{v_2}{v_1}$$

$\dot{V}$	=	flow volume
v	=	velocity
A	=	pipe sectional area

2. Understanding Compressed Air

Flow profile

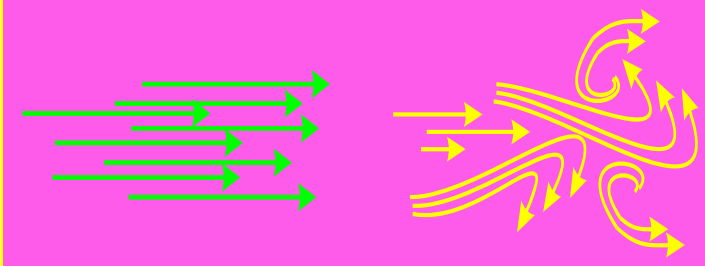


2. Understanding Compressed Air

Flow types

We differentiate between:

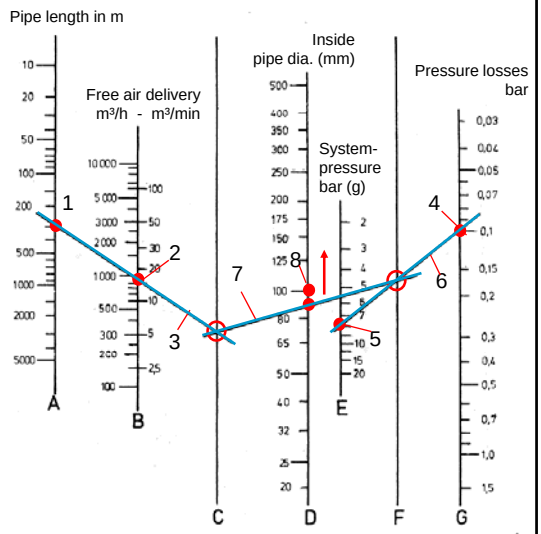
laminar (even) and turbulent *(swirling)* flow



2. Understanding Compressed Air

Straight-line graph

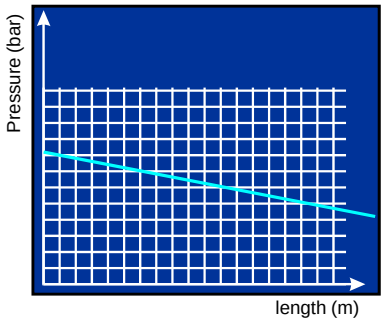
for determining inside pipe diameter (steps 1 to 8)



2. Understanding Compressed Air

Compressed air in motion

Pressure loss
is dependent on:
- sectional area
- velocity
- pipe length
- internal surface area of the pipe



2. Understanding Compressed Air

Pressure drop ...

... is caused by:

- high flow velocities
- turbulence
- internal friction (molecules)
- friction on the pipe walls

Pressure drop lowers the performance of the consumers, increases the cost of compressed air generation and thus production too!

	Performance	
Working press. bar (g)	%	kW
6.0	100	3.0
5.5	86	2.6
5.0	74	2.2
4.5	62	1.9
4.0	52	1.6

Performance loss caused by pressure drop

2. Understanding Compressed Air

Minimum diameters of pipes

FAD m^3/min	working pressure 7.5 bar (g)			
	length of pipeline			
	up to 50 m	up to 100 m	up to 200 m	over 200 m
up to 12.5	2 1/2"	2 1/2"	3"	see straight-line graph
up to 15,0	2 1/2"	2 1/2"	3"	
up to 17.5	2 1/2"	3"	DN100	
up to 20.0	3"	3"	DN100	
up to 25.0	3"	DN100	DN100	
up to 30.0	3"	DN100	DN100	
up to 40.0	DN100	DN100	DN 125	

2. Understanding Compressed Air

Flow resistance of fittings

expressed in equivalent pipe lengths

fitting example	equivalent pipe length in m						
	pipe inside diameter in mm						
	25	40	50	80	100	125	150
	6	10	15	25	30	50	60
	3	5	7	10	15	20	25
	0,3	0,5	0,6	1	1,3	1,6	1,9

Total pipe length: $L_{overall} = L_{straight} + L_{equivalent}$

or roughly: $L_{overall} = 1{,}6 \times L_{straight}$

2. Understanding Compressed Air

Pressure drop

If the normal working pressure of a pneumatic tool is 6 bar (g), any increase above that pressure costs money.

Example:
V = 30 m³/min demand at 7 bar (g) 160 kW
At 8 bar (g) approximately 6% more power is required, i.e. around 9.4 kW more

Costs:
9.4 kW x 0.05 $/kWh x 4000 h/year = 1880 $/year (13,160 ZAR) !

Air main:
On a well designed air piping system a pressure drop of 0.1 bar is normally expected.

The maximum pressure drop in the air piping system should be no more than 1.5 % of the working pressure

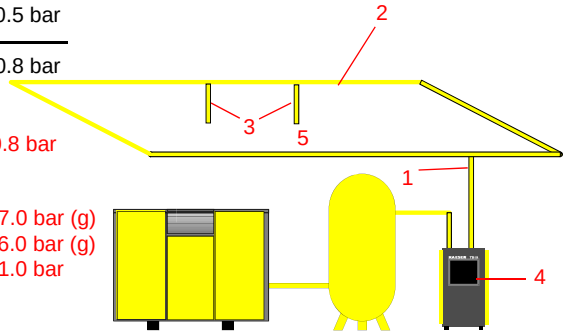
2. Understanding Compressed Air

Pressure drop

1. Main piping	0.03 bar
2. Loop main (distribution)	0.03 bar
3. Connecting lines	0.04 bar
4. Refrigeration dryer	0.2 bar
5. FRL unit and hose	0.5 bar
max.	0.8 bar

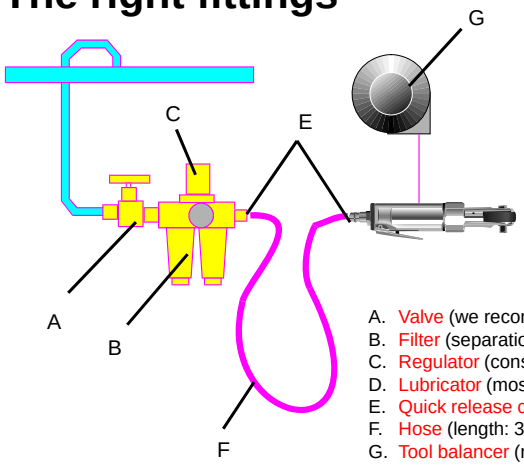
Overall pressure drop 0.8 bar

Max. pressure at compressor	7.0 bar (g)
Pressure at consumer	6.0 bar (g)
Difference	1.0 bar



2. Understanding Compressed Air

The right fittings



A. Valve (we recommend ball valves)
B. Filter (separation of water and rust)
C. Regulator (constant working pressure)
D. Lubricator (mostly oil mist lubricators)
E. Quick release couplings (flexibility at the workplace)
F. Hose (length: 3-5 m)
G. Tool balancer (reduction of work effort)

2. Understanding Compressed Air

Points to be observed when sizing and choosing air system piping:

Cross-section of the pipe

- Air consumption
- Length of the piping
- Working pressure
- Pressure drop
- Flow resistance

2. Understanding Compressed Air

Points to be observed when sizing and choosing air system piping:

Pipe layout

- **Loop/spur main**
- **Connecting lines**
- **Dead-end lines**
- **Pipe connections**
- **Fittings**

2. Understanding Compressed Air

Points to be observed when sizing and choosing air system piping:

Fittings and connections

- Types of outlets
- Shut-off valves
- Stopcocks
- Condensate separators
- Lubricators
- Particulate filters
- Oil filters
- Regulators
- Hoses
- Couplings

2. Understanding Compressed Air

Points to be observed when sizing and choosing air system piping:

Choice of materials

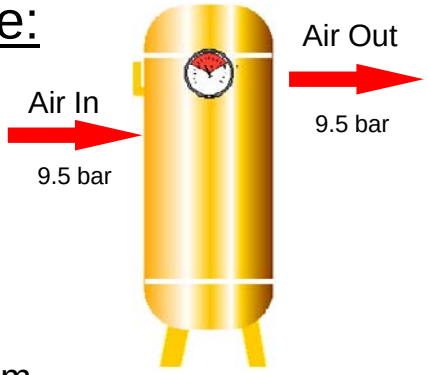
- Environmental conditions (humidity, temperature, chemical pollution of the air)
- Quality of the air (moisture content, oil content, temperature)
- Costs
- Expected working life

2. Understanding Compressed Air

Uncontrolled Storage:

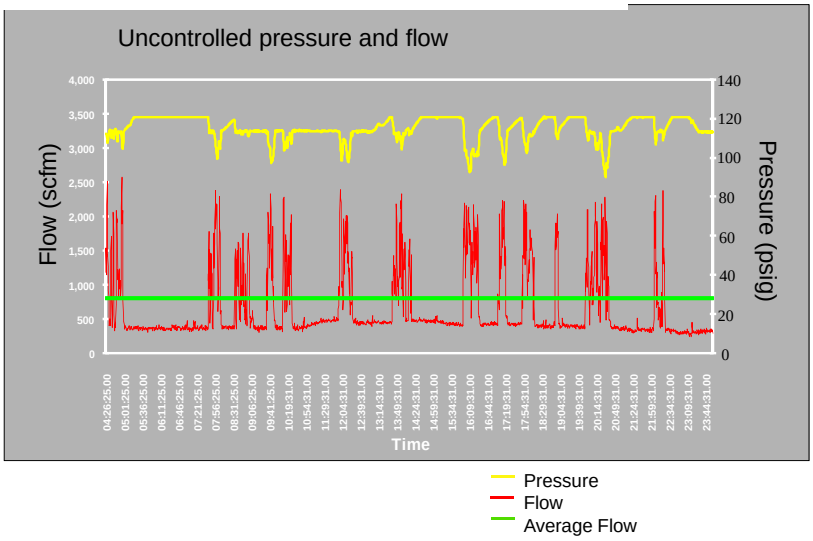
Without Pressure Differential

- ◆Quiet zone
- ◆Moisture separator
- ◆Protects downstream equipment from oil slugs
- ◆Prevents compressor from excessive cycling



No " Real" Storage

2. Understanding Compressed Air

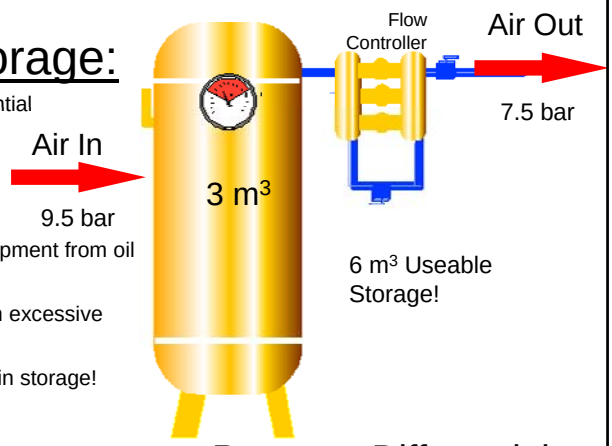


2. Understanding Compressed Air

Controlled Storage:

With Pressure Differential

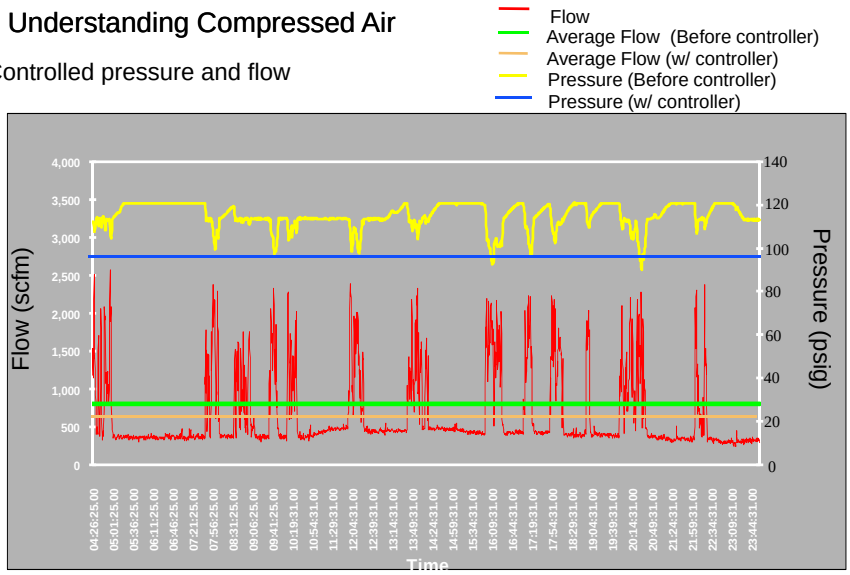
- ◆Quiet zone
- ◆Moisture separator
- ◆Protects downstream equipment from oil slugs
- ◆Prevents compressor from excessive cycling
- ◆PLUS 6 m^3 of useable air in storage!



Pressure Differential Creates Stored Energy!

2. Understanding Compressed Air

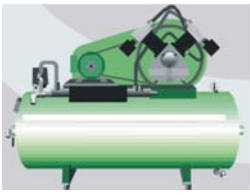
Controlled pressure and flow



2. Understanding Compressed Air

3. Understanding Compressors & Their Application

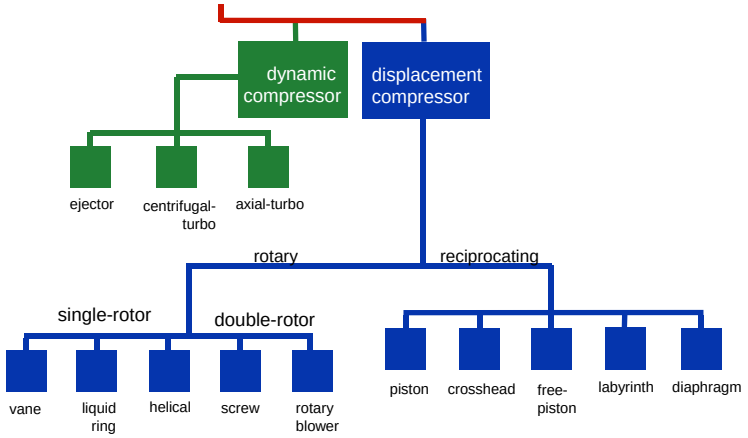
3. Understanding Compressors & Their Application



Types of Compressors

3. Understanding Compressors & Their Application

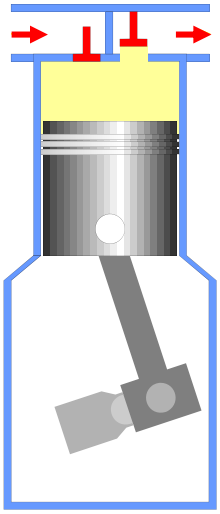
Compressor types



3. Understanding Compressors & Their Application

Reciprocating compressors

single / two stage



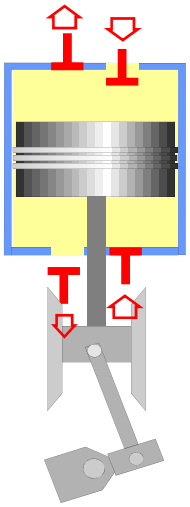
Note the difference:	- single / two stage - single acting / double acting
Installation:	- portable - stationary
Application: (single stage)	- common 10 bar - boosters 35 bar

3. Understanding Compressors & Their Application

Double-acting

with crosshead

Application:
High pressure, up to 1000 bar
in combination with screw compressors.
Compression of gas



3. Understanding Compressors & Their Application

Reciprocating compressor

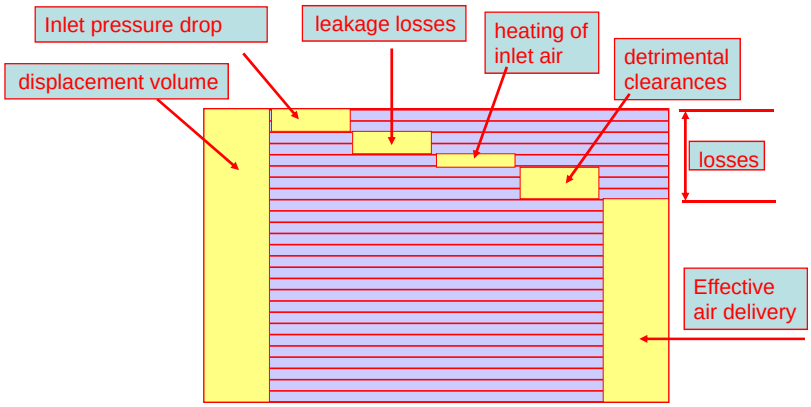
Clearances that affect efficiency

upper piston clearance (dead space)

- machining tolerances
- clearances in valves and valve recesses
- constructional peculiarities

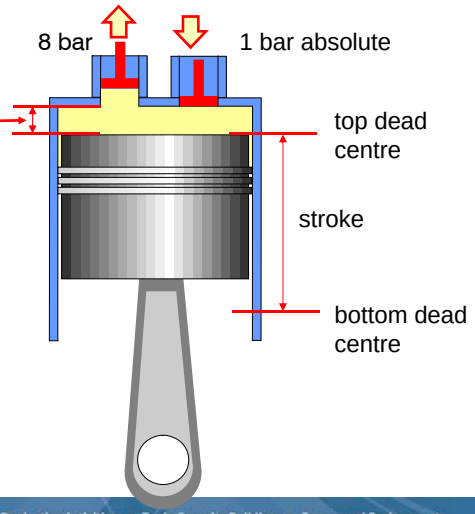
3. Understanding Compressors & Their Application

Effective air delivery with reciprocating compressors



3. Understanding Compressors & Their Application

Upper piston clearance (dead space)



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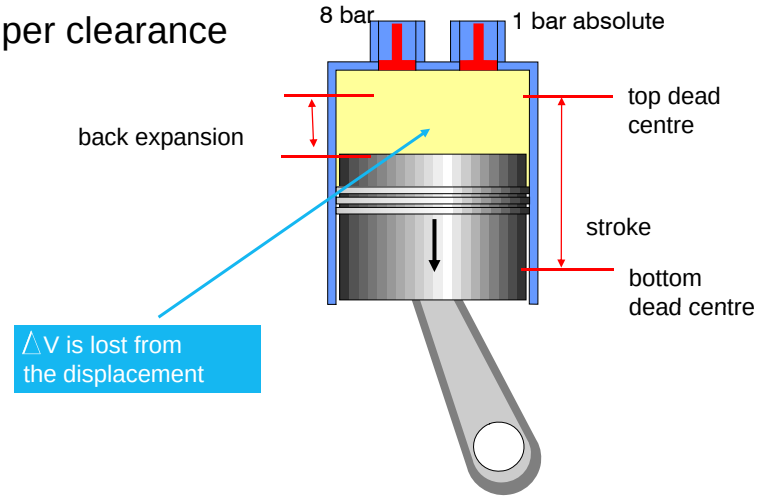
upper clearance



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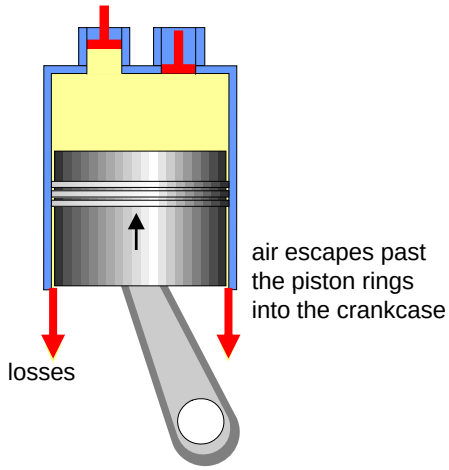
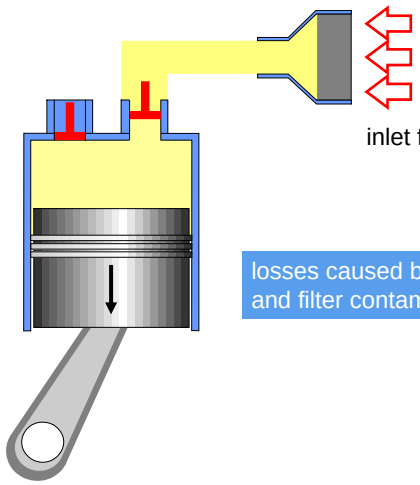
Compression



3. Understanding Compressors & Their Application

Suction



losses caused by throttling and filter contamination

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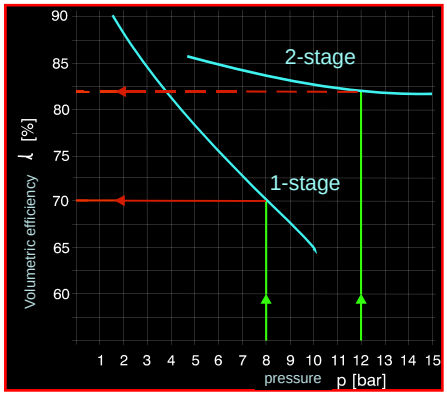
3. Understanding Compressors & Their Application

Reciprocating compressors

Volumetric efficiency of single and two stage compressors

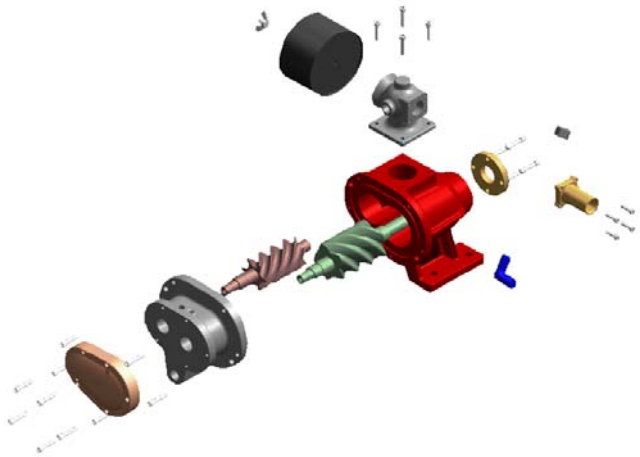


$$\text{Volumetric efficiency} = \frac{\text{free air delivery}}{\text{theoretical displacement}}$$

Poverty Reduction through Productive Activities • Trade Capacity Building • Energy and Environment 12

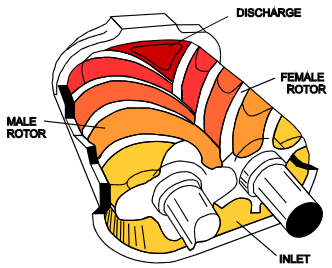
3. Understanding Compressors & Their Application

Rotary Screw compressors

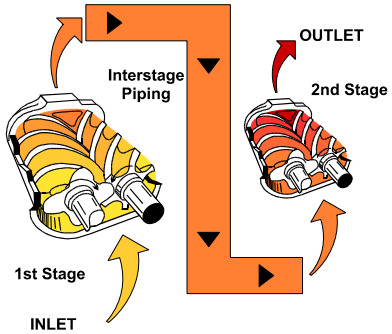


3. Understanding Compressors & Their Application

- Single Stage Rotary Screw



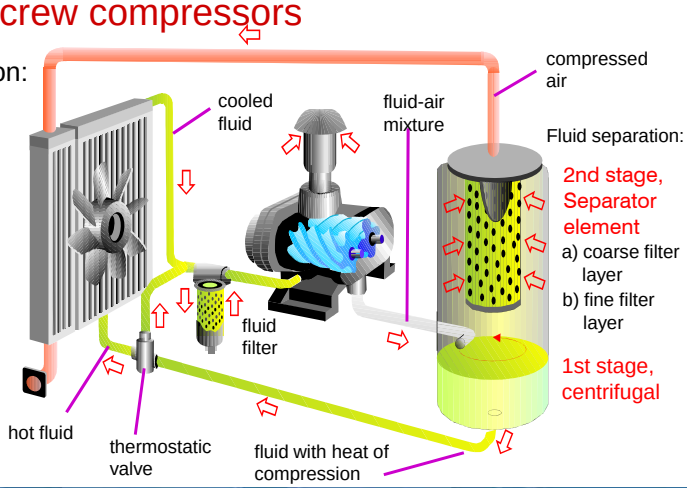
- Two Stage Rotary Screw



3. Understanding Compressors & Their Application

Rotary Screw compressors

Construction:



3. Understanding Compressors & Their Application

Efficiency - comparison of specific power consumption

$$\text{Specific power consumption*} = \frac{\text{power* in kW}}{\text{Effective FAD in m}^3\text{ / min}}$$

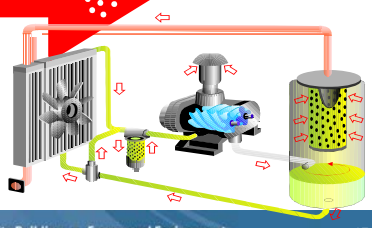
$$P_{spec} = \frac{P^*}{\dot{V}}$$

* depending on reference point:
- compressor shaft power
- motor output power
- electric power input

3. Understanding Compressors & Their Application

Function of the fluid in a lubricated rotary screw

First task:	heat transfer, discharge temperature approximately 75 - 80 ºC
Second task:	lubrication of bearings
Third task:	sealing the gap between rotors and casing, prevention of metallic contact
Fourth task	absorbing dust, sulphur, etc.



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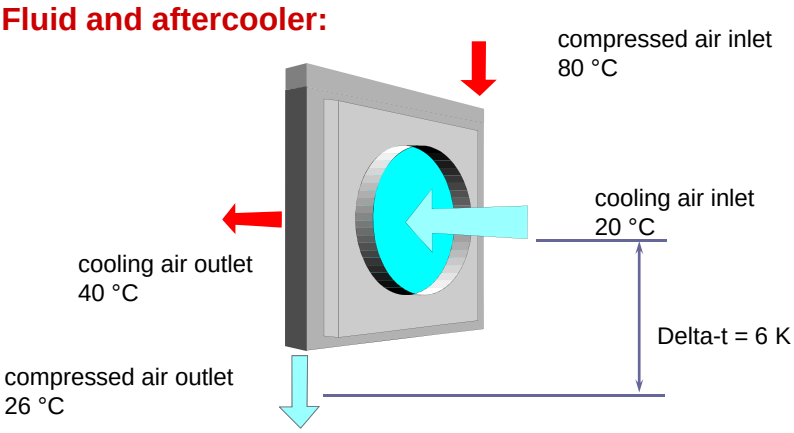
3. Understanding Compressors & Their Application

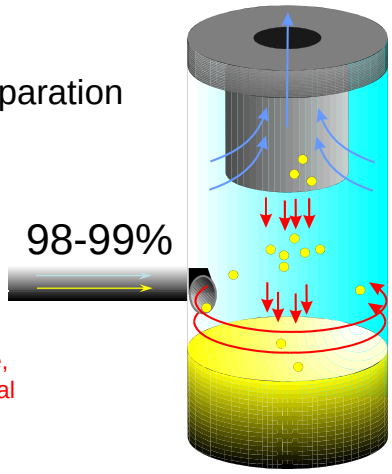
Fluid and aftercooler:



3. Understanding Compressors & Their Application

Fluid separation

98-99%



2nd stage, fluid separator element

a) coarse filter layer
b) fine filter layer

1st stage, centrifugal

3. Understanding Compressors & Their Application

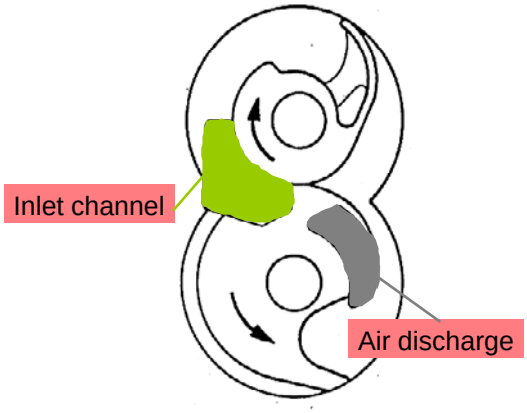
Rotary tooth compressors

Advantages:

quieter running than reciprocating compressors

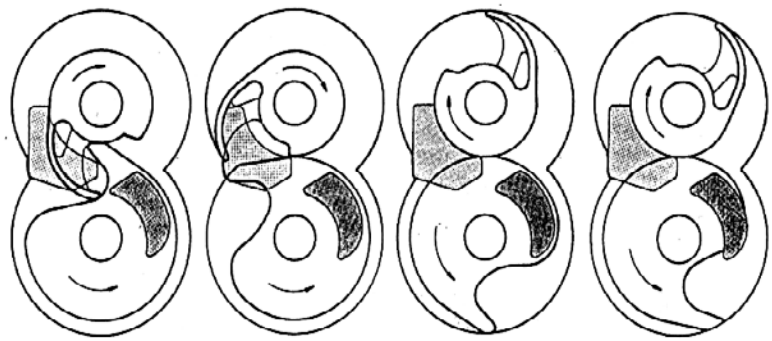
Disadvantages:

high power consumption
more expensive
8 bar max. gauge pressure



3. Understanding Compressors & Their Application

Rotary tooth compressor

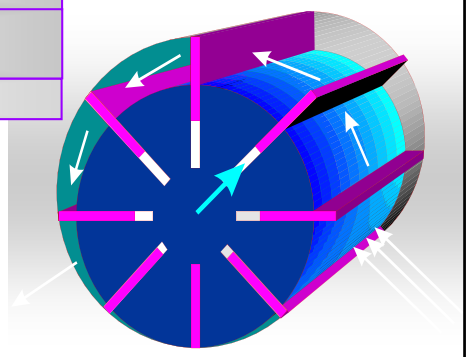


3. Understanding Compressors & Their Application

Rotary sliding vane compressors

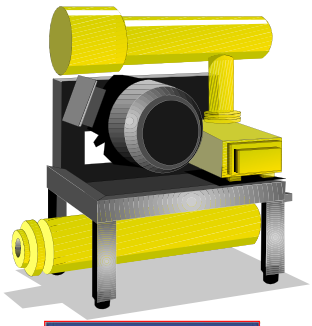
- single shaft rotary compressor
- high maintenance costs to maintain constant efficiency
- high remaining oil content with clean oil injection and oil mist separator
- poor efficiency at high pressures

Main applications:
2 - 5 bar
Vacuum down to 1 x 10^{-3} bar



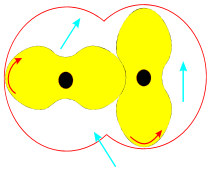
3. Understanding Compressors & Their Application

Rotary Blowers



Characteristics:

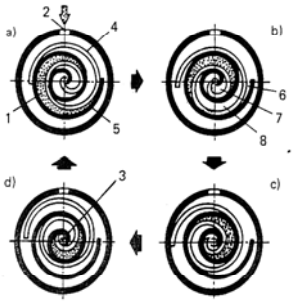
capacity: up to 1200 m^3/min
air flow: 2 or 3 pulsations per working cycle
pressure range: - 0.5 to +1 bar (g)
speed: 300 to 11000 min^{-1}



3. Understanding Compressors & Their Application

Scroll compressors

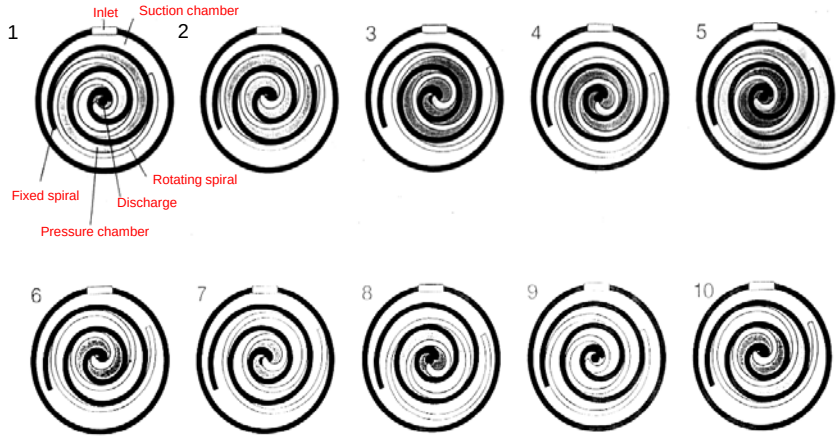
air delivery:	up to 0.5 m^3/min
air flow:	constant, no pulsation
pressure range:	up to 10 bar (g)
speed range:	up to 3100 min^{-1}



1 Gas chamber	4 Oscillating spiral	6 Suction	6 Suction
2 Inlet	5 Fixed spiral		7 Discharge
3 Discharge			8 Compression

3. Understanding Compressors & Their Application

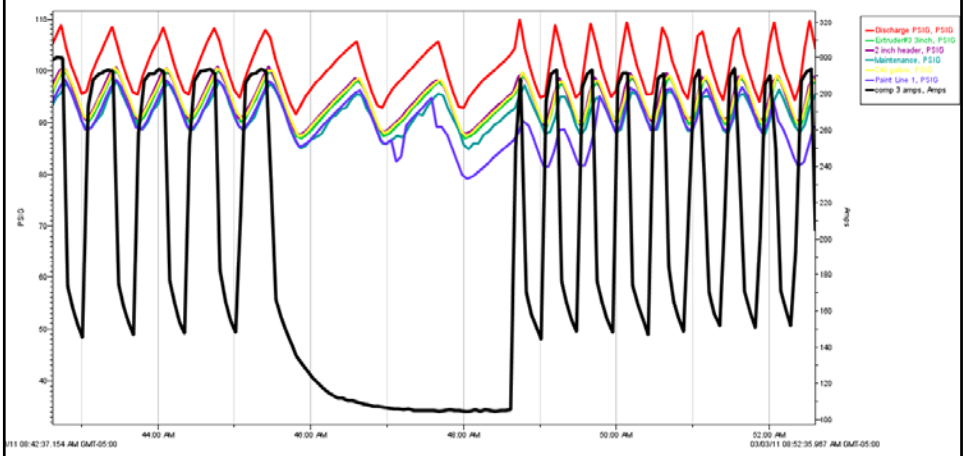
Scroll compressor



3. Understanding Compressors & Their Application

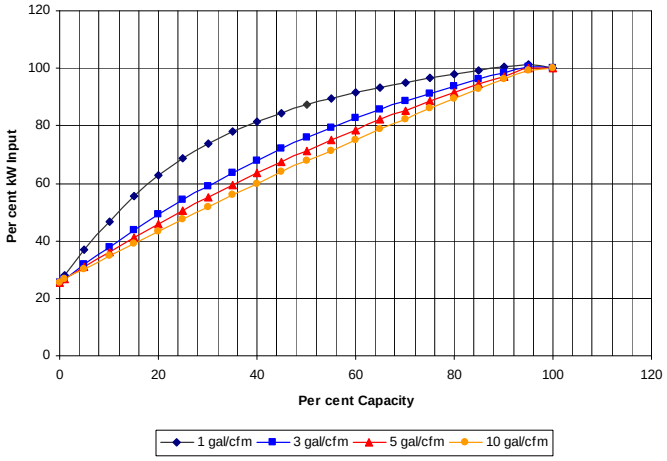
ROTARY SCREW COMPRESSOR CONTROLS

Load / Unload Control

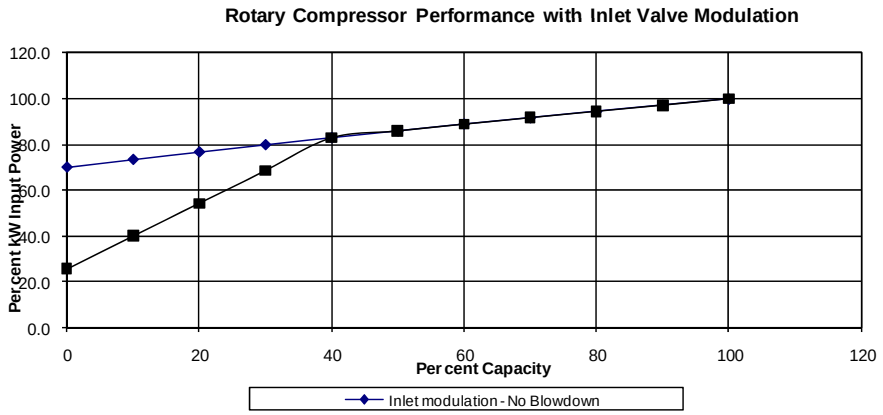


Load / Unload Control

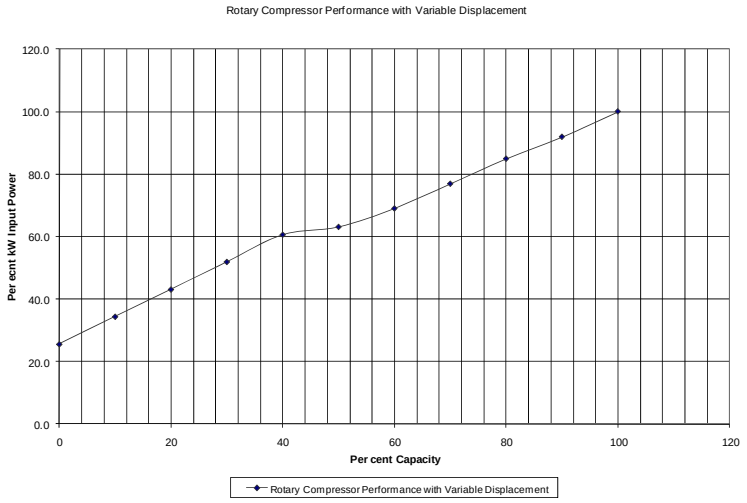
Average kW vs Average Capacity with Load/Unload Capacity Control



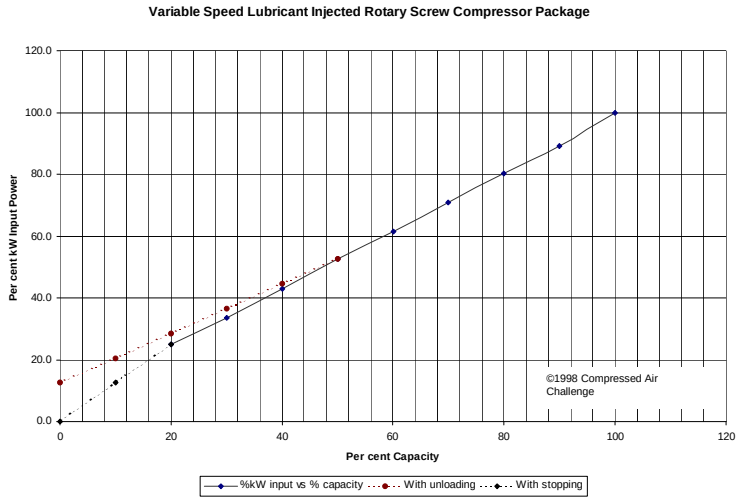
Inlet Valve Modulation Control



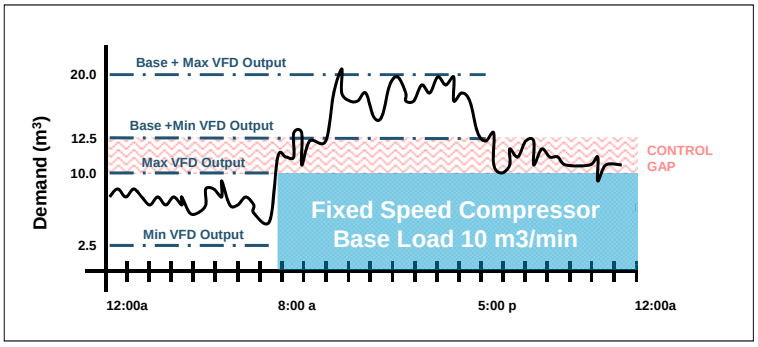
Variable Displacement Control



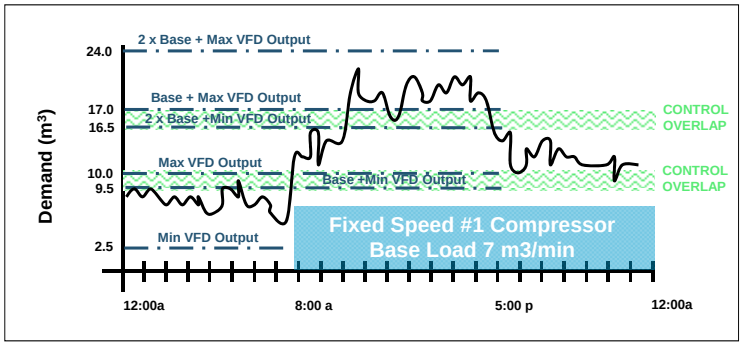
Variable Speed Control



Variable Speed Control "Control Gap"



Variable Speed Control Eliminating "Control Gap"



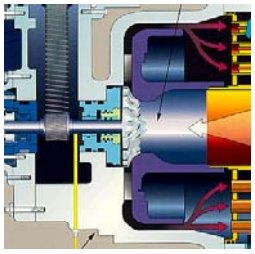
3. Understanding Compressors

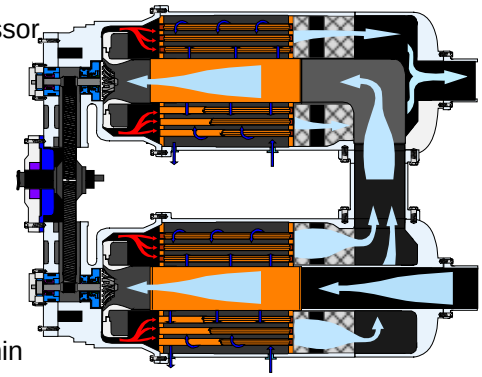
DYNAMIC AIR COMPRESSORS

3. Understanding Compressors & Their Application

Turbo compressors

Centrifugal turbo compressor



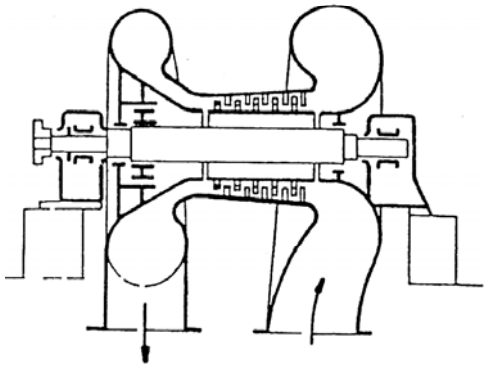


Characteristics:
Capacity: 35 - 1200 m^3/min
Stages: 1 - 6
Pressure range: 3 - 40 bar (g)
Speed range: 3000 - 80000 min^{-1}

3. Understanding Compressors & Their Application

Axial compressor

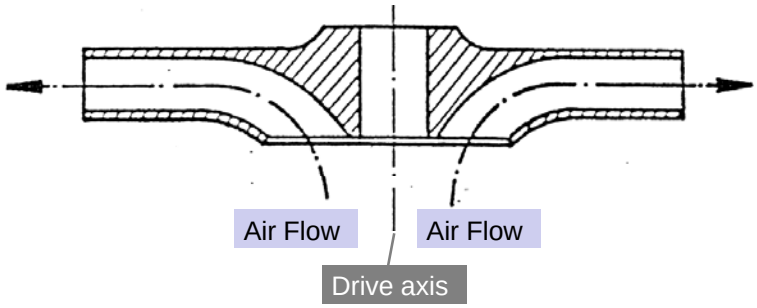
Characteristics:
Capacity: 600 - 30000 m^3/min
Stages: 10 - 25
Pressure range: 0 - 6 bar (g)
Speed range: 6000 - 20000 min^{-1}



3. Understanding Compressors & Their Application

Centrifugal turbo compressor

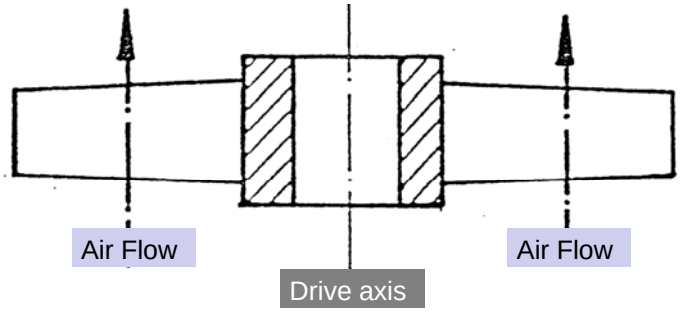
centrifugal impeller



3. Understanding Compressors & Their Application

Axial compressor

Axial impeller



Centrifugal Compressors

- Most Common Dynamic Compressor
  - Relatively easy to install
  - Attractive first cost esp. larger capacities
  - 500 Hp (2000 cfm) -> 15,000.. 20,000 cfm
  - Efficient operation
    - Low Specific Power while operating in turndown range
    - Very inefficient when operating in blow-off

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Centrifugal Compressors

- Smaller size centrifugals now available
  - Over lap in performance with large positive displacement compressors
  - More combined systems with a mix of positive displacement and centrifugal machines.
- Dynamic Control -> Constant Pressure
- Displacement Control -> Pressure Band
- Special Considerations when Controlling Mixed Systems

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Centrifugal Compressors

- Centrifugal Compressor Drivers
  - Range 200 Hp through 3,500+ Hp
  - Electric motors are common
    - 208, 230/460, & 575 volt / 3 phase / 60 Hz
    - 220, 380-400 volt / 3 phase / 50 Hz
    - Synchronous 1.0 or 0.85 leading optional > 500 Hp
    - Large compressor motors medium voltage
      - 2,300 or 4,160 volt / 60 Hz; 3600 volt / 50 Hz
      - Medium Voltage (1kV - 35 kV) * Medium Voltage - ANSI/IEEE 1585-2002 [It is assumed that this is ac.]
  - Other air compressor drivers
    - Engine drive, natural gas and diesel
    - Steam Turbine drive
    - Gas turbine drive in larger sizes

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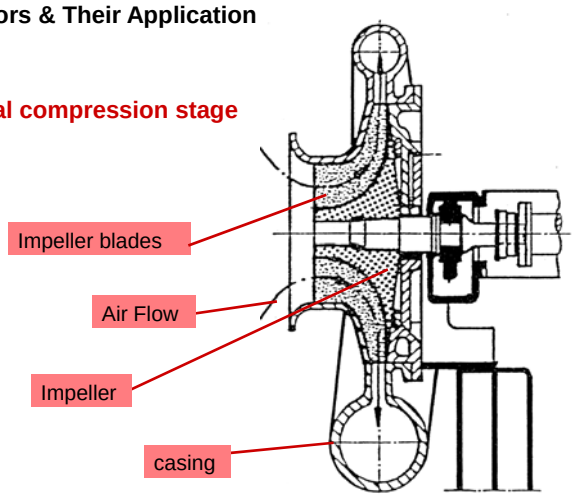
3. Understanding Compressors & Their Application

Construction of a Centrifugal compression stage

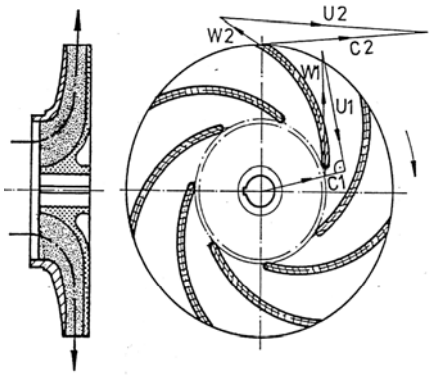


3. Understanding Compressors & Their Application

Centrifugal impeller velocities

At inlet
C1 = velocity of the air to be compressed
U1 = peripheral speed of the compressor impeller
W1= relative velocity between air and compressor impeller

At outlet
C2 = velocity of the air to be compressed
U2 = peripheral speed of the compressor impeller
W2 = relative velocity between air and compressor impeller



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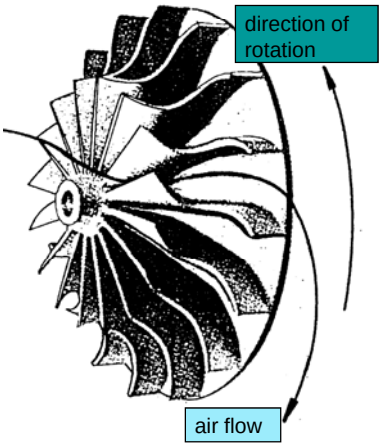
3. Understanding Compressors & Their Application

centrifugal impeller, singlesided

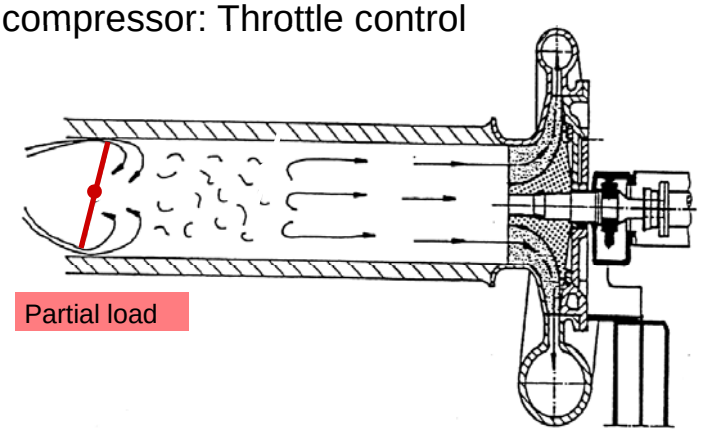
Impeller profile

backward-bent impeller vanes



3. Understanding Compressors & Their Application

Turbo compressor: Throttle control



Partial load

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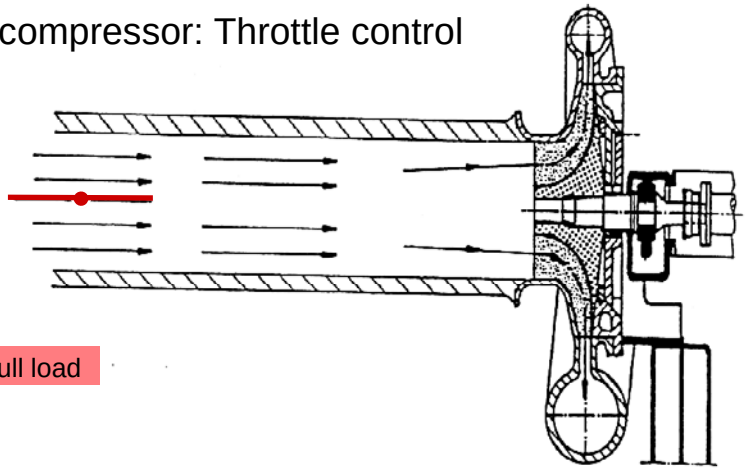
3. Understanding Compressors & Their Application

Turbo compressor: Throttle control

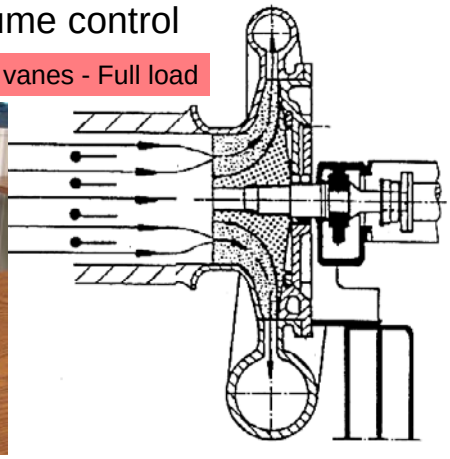


Full load

3. Understanding Compressors & Their Application

Turbo compressor: Volume control

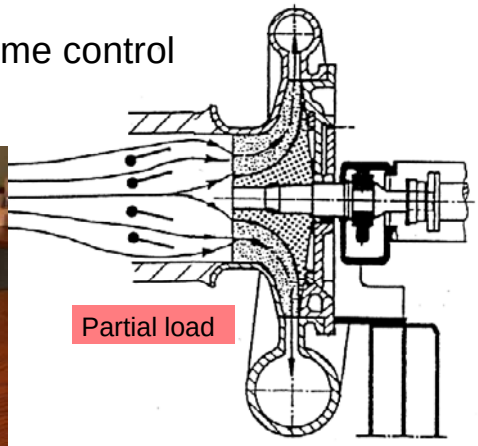
Inlet guide vanes - Full load



3. Understanding Compressors & Their Application

Turbo compressor: Volume control

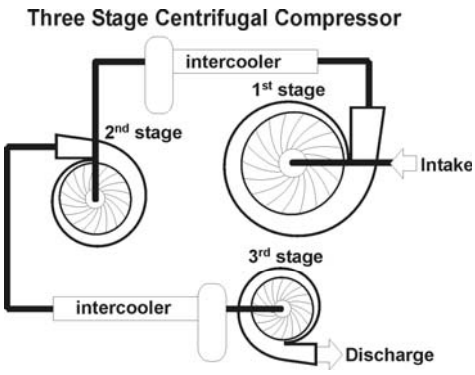
Inlet Guide Vanes – Closed



Partial load

Centrifugal Compressor Performance

- Dynamic Compression
  - Air enters the eye of the impeller
  - Velocity increases to the impeller tip
  - Air enters the diffuser and volute
  - Velocity decreases energy converts to pressure
  - Air exits to the inter-stage
  - The process repeats



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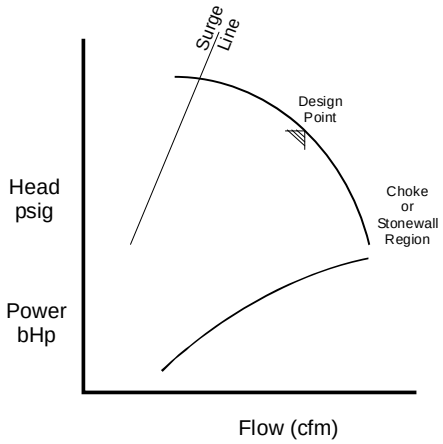
Centrifugal Compressor Performance



- Dynamic Compression
  - Flow –vs – Pressure – Power Curve

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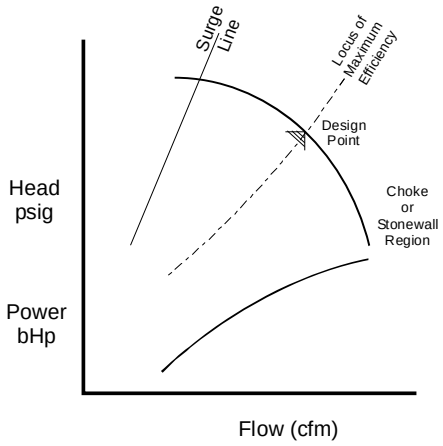
Centrifugal Compressor Performance



- Dynamic Compression
  - Flow –vs– Pressure
  - & Power Curve
  - with Locus of Maximum Efficiency

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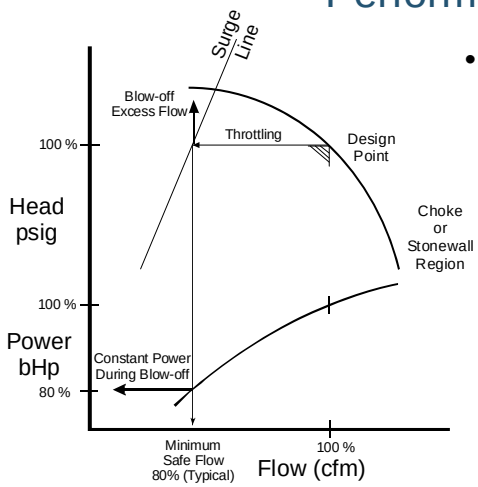
Centrifugal Compressor Performance



- Dynamic Compression
  - Throttling Range – Blow-off

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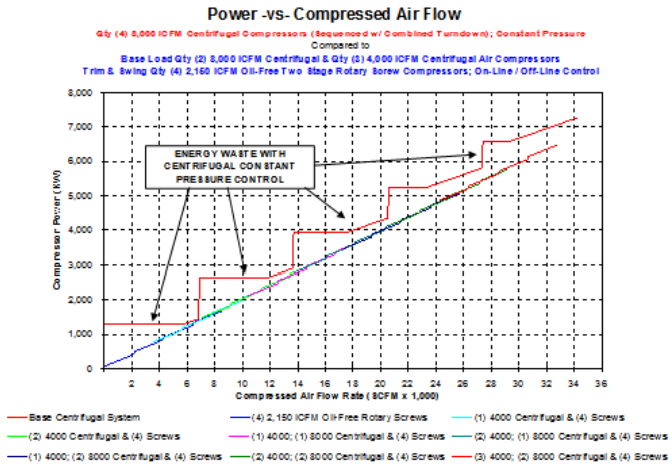
Centrifugal Compressor Performance



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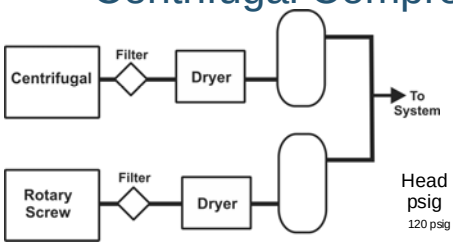
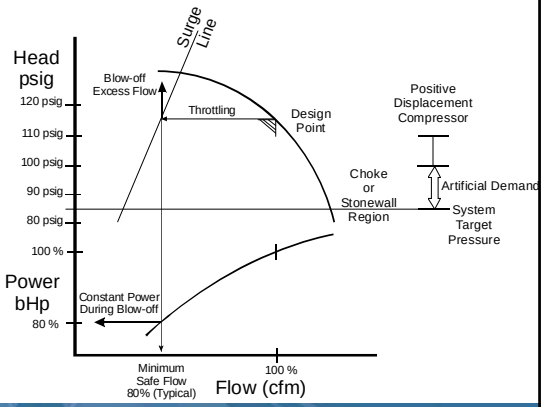
Centrifugal Compressor Performance





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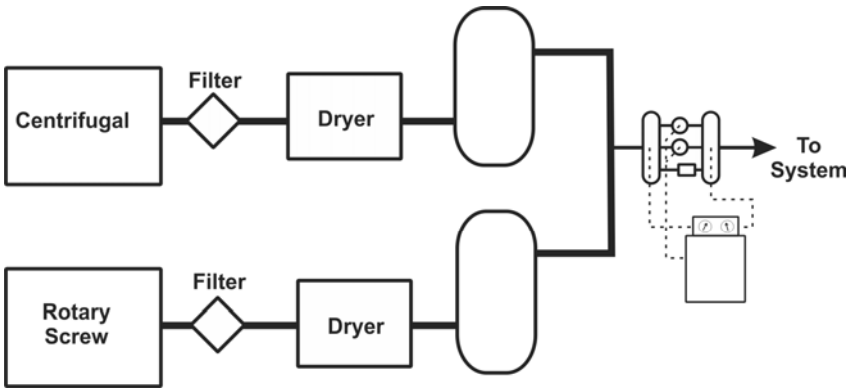
Centrifugal Compressor Performance



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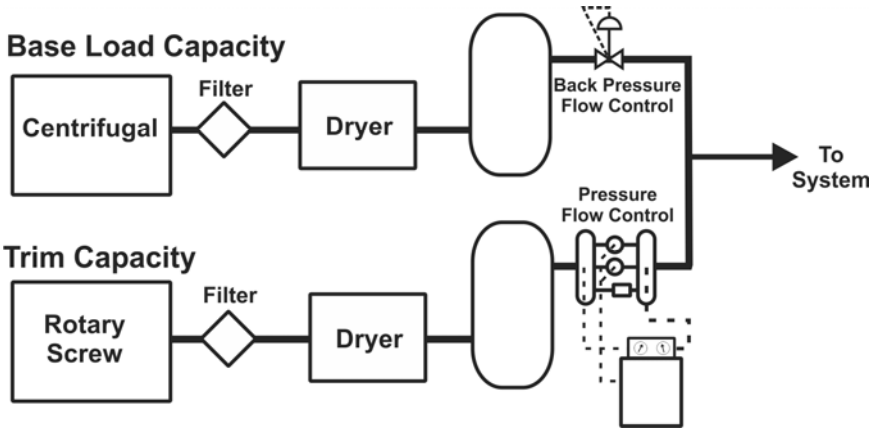
Centrifugal Compressor Performance



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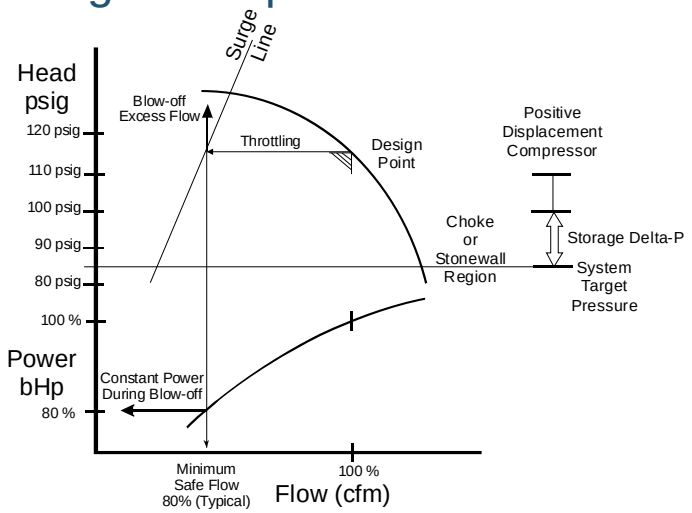
Centrifugal Compressor Performance



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Centrifugal Compressor Performance

- Major HVAC Equipment Manufacturer
  - Multi-building site 3.5 million sq. ft.
  - Power House multiple mixed compressors
  - 3 additional centrifugals in 3 locations
  - Operating with multiple machines in blow-off

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Centrifugal Compressor Performance

- Project Goals
  - Cost effective reduction in energy use
  - Improve system reliability
  - Consistent pressure to support production
  - Eliminate compressed air related downtime

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Centrifugal Compressor Performance

- Project Implementation
  - $ 23,000 Assessment
  - $ 68,000 (1) Flow & (3) backpressure controls
  - $ 8,000 reuse (2) 30,000 gal LP Tanks
  - $ 47,400 (14) Thermal mass flow transducers
  - $ 39,900 (4) microprocessors, BMS
  - $ 10,300 (10) Digital power kW / kWh meters
  - $ 96,800 Engineering, Installation, Training
  - **$ 293,600 Total Project Cost**
  - **36% Reduction in Energy Use**
  - **3.7 Mwh Annual Energy Savings**

Poverty Reduction through Productive Activities • Trade Capacity Building • Energy and Environment

Centrifugal Compressor Performance

- Project Life Cycle Cost
  - $ 293,600 Total Project Cost
  - $ 280,000 Annual Energy Savings
  - Simple Payback 1.05 years

  - 3.7 Megawatts Annual Energy Savings
  - 15 year project life $4.2 million total savings

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Centrifugal Compressor Performance

- Centrifugal Compressor Maintenance
  - Routine operational checks and maintenance items are critical.

  - Minor maintenance items that are not repaired can result in major failures.

  - Check capacity and surge controls, along with safety shutdowns

  - Other checks per the manufacturer's recommendations

Poverty Reduction through Productive Activities • Trade Capacity Building • Energy and Environment

Centrifugal Compressor Performance

- Centrifugal Compressor Maintenance
  - Centrifugal compressors are less forgiving than other designs.
  - Routing checks and maintenance are important epically in harsh environments.
  - If there is a history of marginally effective routine maintenance, consider alternatives.
  - Run to failure maintenance of centrifugal compressors is very expensive.

3. Understanding Compressors & Their Application

- Key Points
  - There are two broad categories of industrial air compressors, positive displacement and dynamic.
  - Reciprocating compressors are positive displacement compressors.
  - Rotary screw compressors are also positive displacement compressors.
  - Rotary screw compressors are the most common type of industrial air compressor.
  - There are many different types of part load capacity control for rotary screw compressors.
  - Different types of part load capacity control have different part load power characteristics.

3. Understanding Compressors & Their Application

- Key Points
  - Centrifugal air compressors are the most common type of dynamic compressor used by industry.
  - Aerodynamic design determines the head -vs- flow performance curve for centrifugal air compressors.
  - Operating centrifugal compressors with blow-off control can be extremely inefficient.
  - Operating in the stonewall (or choke) region of a centrifugal compressor's performance range is in efficient.

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3. Understanding Compressors & Their Application

- Key Points
  - When operating multiple centrifugal air compressors in a system it is preferable to throttle multiple compressor as opposed to operating in blow-off.
  - When operating a system using a combination of positive displacement and centrifugal compressors requires special attention to control strategy and the system's pressure profile.
  - Performing poor routine maintenance for centrifugal air compressors can lead to expensive failures of major air compressor components.

4. Understanding Air Treatment

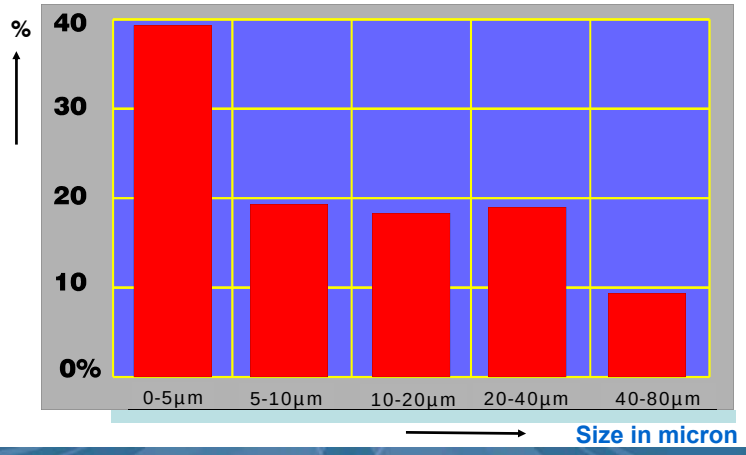
4. Understanding Air Treatment

Impurities in the air

Regardless of which type of construction, all compressors draw in the impurities in the air and concentrate them many times

4. Understanding Air Treatment

Solid particles in the air



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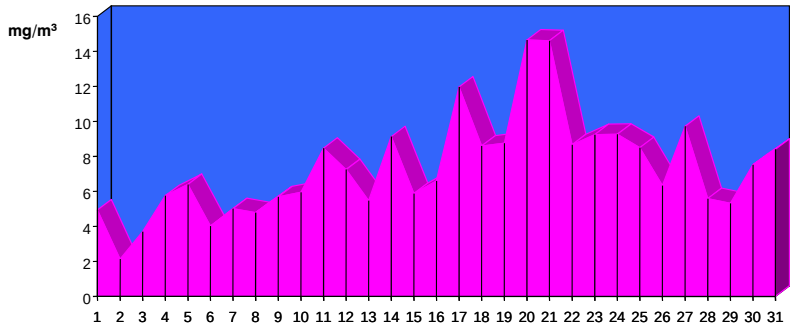
4. Understanding Air Treatment

Overall hydro carbon concentration

Mean daily value (mg/m³)

Location: a small German town

Period: July 1992

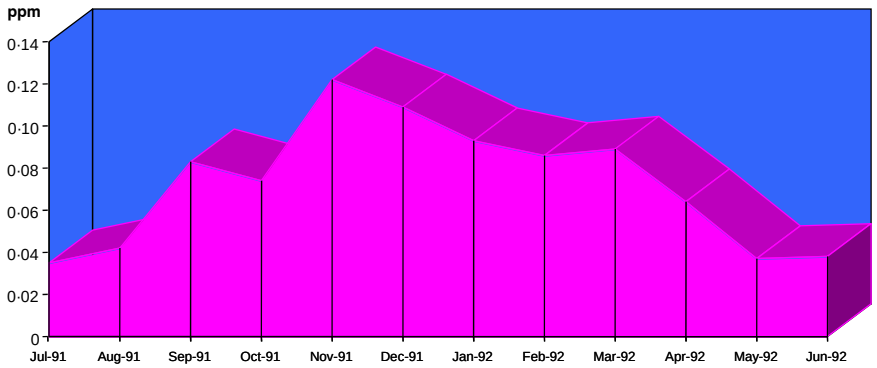


4. Understanding Air Treatment

Sulphur-dioxide (SO_2) concentration

Period: July 1991 - June 1992

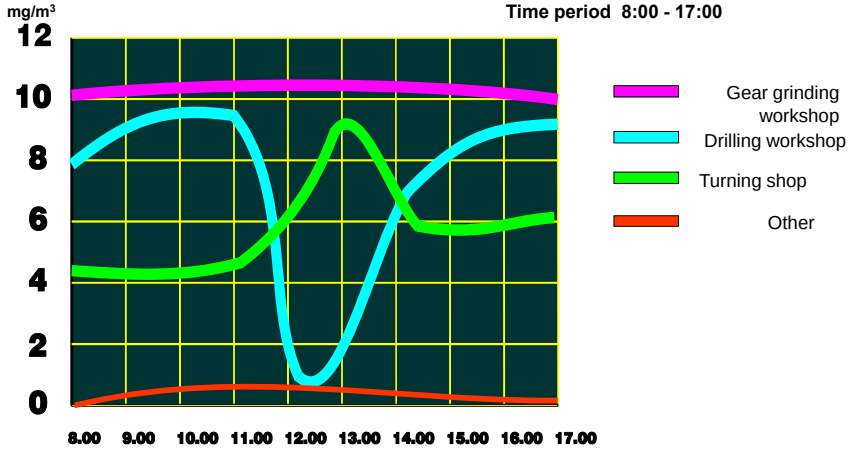
Location: a small German town



4. Understanding Air Treatment

Concentration in mg of mineral oil / m^3 air

Time period 8:00 - 17:00



4. Understanding Air Treatment

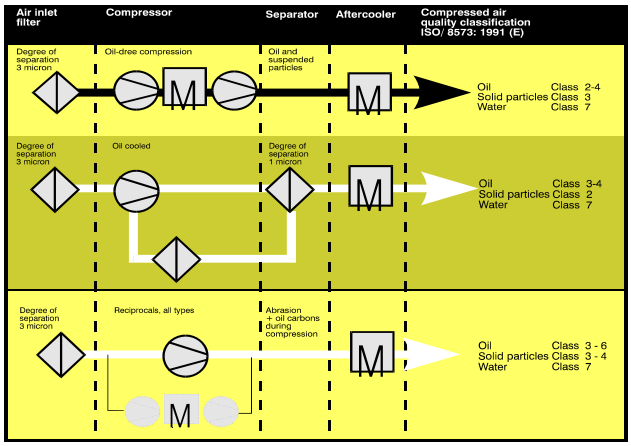
Quality classification of compressed air

to ISO 8573-1: 2001 (E)

ISO 8573-1 Class	Solid particle content						Moisture content	Oil content
	max. number of particles per m³ sized d [µm]				µm	mg/m³	PDP / (x=liquid water content g/m³)	mg/m³
	≤ 0,1	0,1< d ≤ 0,5	0,5< d ≤ 1,0	1,0< d ≤ 5,0				
0	as specified by the equipment user or supplier and more stringent than class 1							
1	-	100	1	0	-	-	≤ -70 °C	≤ 0,01
2	-	100.000	1.000	10	-	-	≤ -40 °C	≤ 0,1
3	-	-	10.000	500	-	-	≤ -20 °C	≤ 1,0
4	-	-	-	1.000	-	-	≤ +3 °C	≤ 5,0
5	-	-	-	20.000	-	-	≤ +7 °C	-
6	-	-	-	-	≤ 5	≤ 5	≤ +10 °C	-
7	-	-	-	-	≤ 40	≤ 10	*x ≤0,5*	-
8	-	-	-	-	-	-	*0,5 ≤ x ≤5,0*	-
9	-	-	-	-	-	-	*5,0 ≤ x ≤ 10,0*	-

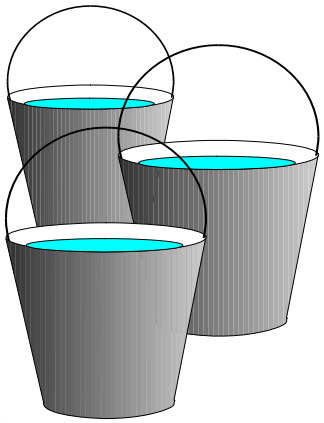
4. Understanding Air Treatment

Air quality downstream of the compressor



4. Understanding Air Treatment

CONDENSATE:

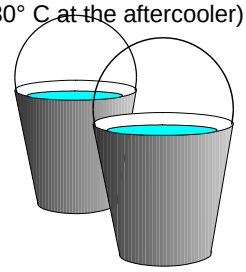


This compressor with an air delivery of 5 m^3/min (referred to +20° C, 70 % moisture carry-over and 1 bar absolute) transports around 30 litres of water into the air main during an 8 hour day

4. Understanding Air Treatment

CONDENSATE:

around 20 litres of this water accumulates in the aftercooler in the form of condensate (at 7 bar gauge working pressure and an outlet temperature of +30° C at the aftercooler)



4. Understanding Air Treatment

CONDENSATE:

As the air cools down further the remaining 10 litres accumulate at convenient points in the air main

the results are expensive maintenance, repairs and defects in production

4. Understanding Air Treatment

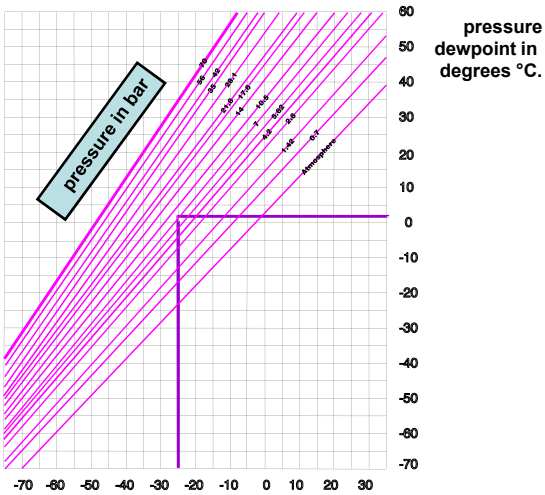
Water Content of Ambient Air

Dewpoint	g/m³	Dewpoint	g/m³
+100	588.208	+6	7.246
+90	417.935	+4	6.359
+80	290.017	+2	5.570
+70	196.213	+0	4.868
+60	129.020	-10	2.156
+50	82.257	-20	0.88
+40	50.672	-30	0.33
+30	30.078	-40	0.117
+20	17.148	-50	0.038
+10	9.356	-60	0.011
+8	8.342	-70	0.0033

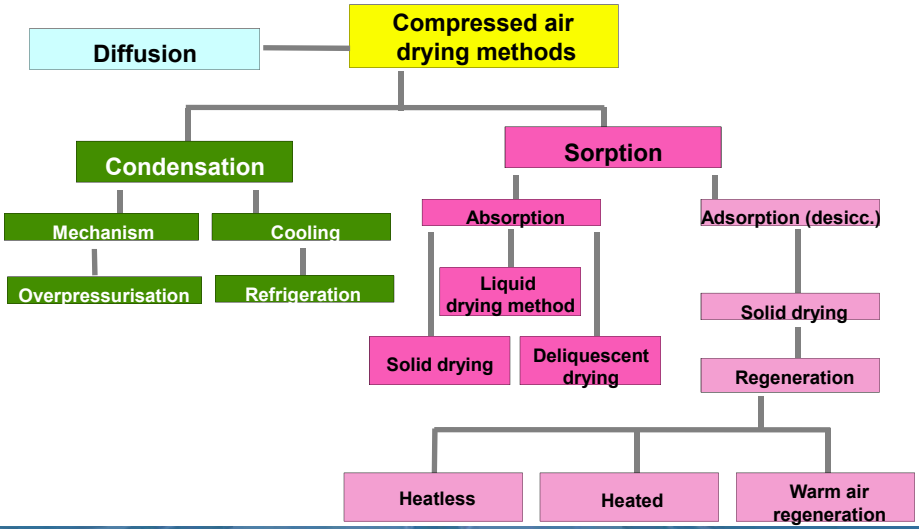
4. Understanding Air Treatment

Pressure dewpoint - atmospheric dewpoint

Example:
Pressure dewpoint: 2-3 °C.
Working pressure: 7 bar
Atmospheric dewpoint: - 25 °C.



4. Understanding Air Treatment



4. Understanding Air Treatment

Why Dry Compressed Air?

Untreated air	Problems in the air main	Problems with equipment
dirt	corrosion	contamination
oil aerosols	pressure loss	tool wear
moisture	contamination	scrap
	freezing	downtime
	maintenance	

COSTS

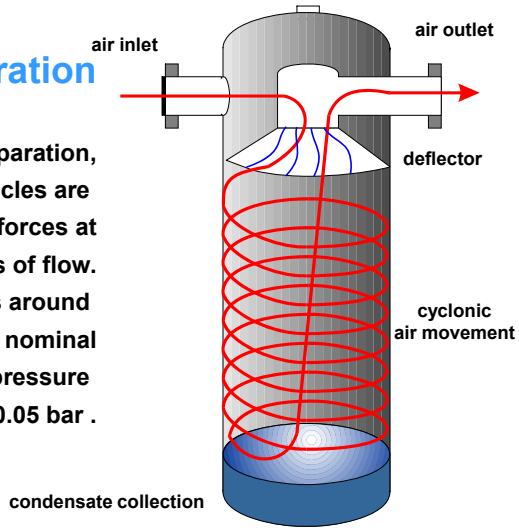
COSTS

4. Understanding Air Treatment

Condensate separation

To ensure sufficient separation, liquids and heavy particles are subjected to centrifugal forces at high rates of flow.

The degree of separation is around 95% at 6 bar, 20 °C and the nominal volumetric flow rate. The pressure drop is approximately 0.05 bar .



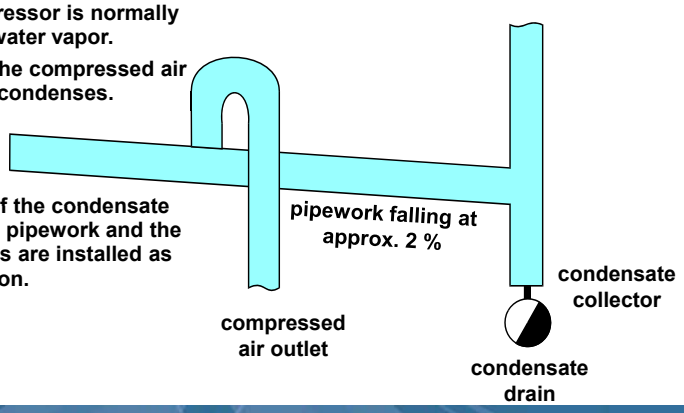
4. Understanding Air Treatment

Condensate separation

The compressed air discharged from the aftercooler of a compressor is normally 100% saturated with water vapor.

If the temperature of the compressed air falls, the water vapor condenses.

A coarse separation of the condensate can be achieved if the pipework and the compressed air outlets are installed as shown in the illustration.

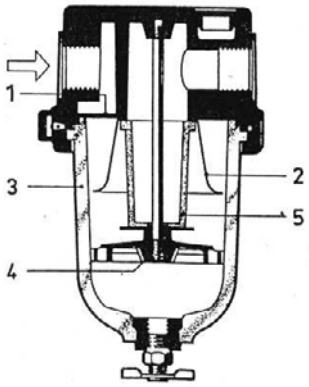


4. Understanding Air Treatment

Condensate separation

Fine filter

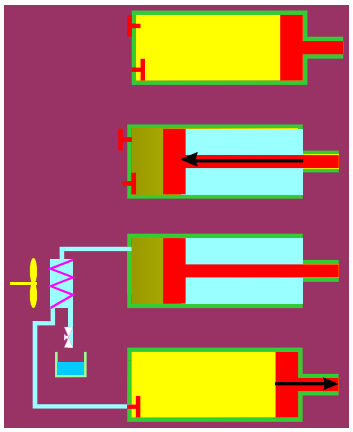
- used directly at the takeoff point
- mechanical filter
- rotating movement
- deflection plate
- condensate drain (important!)



4. Understanding Air Treatment

Over-compressing

Simplest method
Disadvantage: high energy requirement



Suction of atmospheric air,

high compression e.g. 300 bar (g),

cooling the air and separation of condensate,

decompression to 15 bar (g).

Example:

High-voltage safety switch
Working pressure 15 bar (g)
Preliminary compression to 300 bar (g)

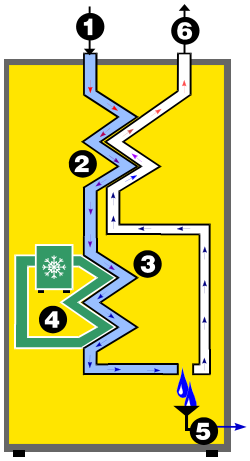
Manufacture of high pressure cable
Working pressure 0.5 bar (g)
Preliminary compression to 30 bar (g)

high humidity
low humidity

4. Understanding Air Treatment

Refrigeration drying

1. Air inlet
2. Air to air heat exchanger
3. Refrigerant to air heat exchanger
4. Refrigerant compressor
5. Condensate separation, automatic condensate drain
6. Compressed air outlet



4. Understanding Air Treatment

High Inlet Temperature Refrigerated Dryer

Description:

- **Air inlet temperatures up to 82 °C**
- **Centriflex separator system**
- **Automatic, float-controlled condensate drain**

Advantages:

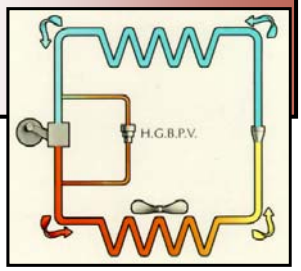
- **Ideal for reciprocating compressors**
- **Pressure dew point +10 °C : selected to suit the practical requirements of reciprocating compressor operation**
- **Hot gas-bypass valve for constant PDP**

4. Understanding Air Treatment

The hot-gas bypass controller allows high-pressure refrigerant gas to flow to the inlet of the refigerant compressor under fluctuating load.

This ensures constant temperature cooling of the compressed air.

> no pressure dew point fluctuations
> no danger of freezing



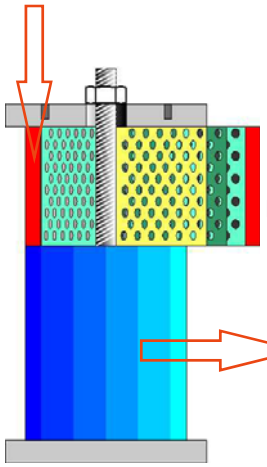
4. Understanding Air Treatment

Separator systems

for refrigeration dryers

Centriflex

First stage of separation:
A special stainless steel insert separates all particles larger than 10 micron, using the basic principle of centrifugal force and deflection.
The re-usable separator is fabricated as a cartridge and is easy to remove for cleaning.



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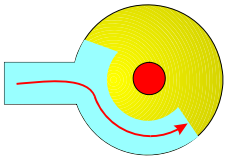
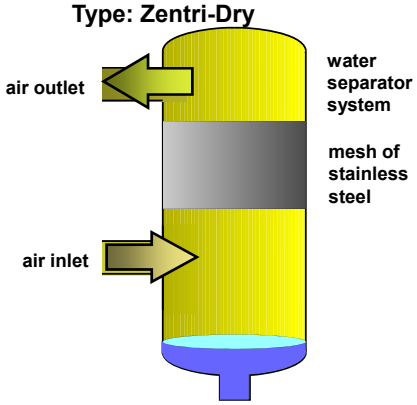
4. Understanding Air Treatment

Separator systems for compressed air dryers

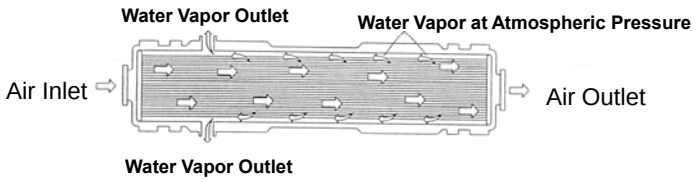


stainless steel housing

Type: Zentri-Dry



4. Understanding Air Treatment

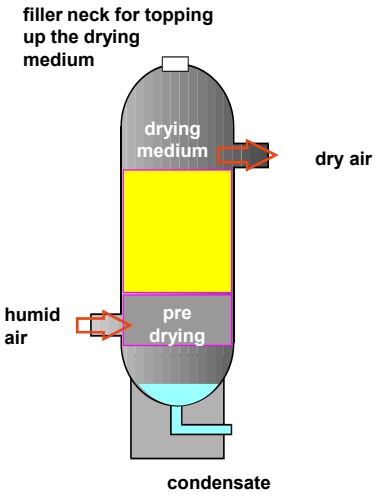


Membrane Dryer

4. Understanding Air Treatment

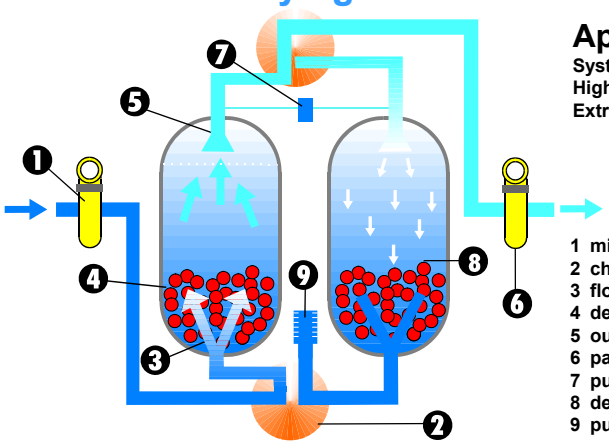
Absorption drying

Chemical process
Solid soluble drying medium
Deliquescent drying medium
Periodic renewal of the drying medium
Dewpoint: + 15 ° Celsius
Low compressed air inlet temperatures



4. Understanding Air Treatment

Desiccant drying - heatless



Application:

Systems subjected to freezing.
High ambient temperatures.
Extreme requirements of air quality.

1 microfilter (0.01 µm, 0.01 ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: moisture adsorption
5 outlet collector
6 particulate filter 1 µm
7 purge (regeneration) air valve
8 desiccant bed: regeneration
9 purge air exhaust silencer

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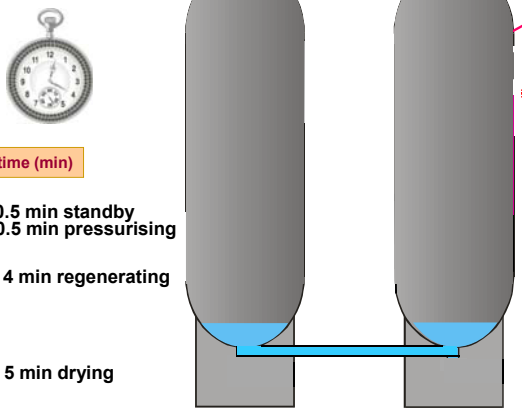
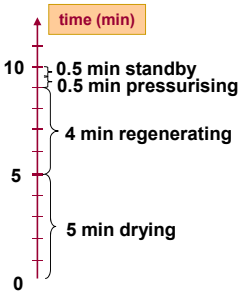
Design of the heatless regenerating desiccant dryers

Standard Cycle





100 % desiccant volume
100 % air flow
35 °C inlet temperature
7 bar (g)
pressure dew point - 40 °C

Regenerating air requirement:

average	14 %
+ chamber filling	1 %
total average	15 %

Regenerating air (max.)

$$\frac{15\ \% \times 5\ \text{min}}{4.5\ \text{min}} \approx 17\ \%$$

Conventional dryers

Standard Cycle

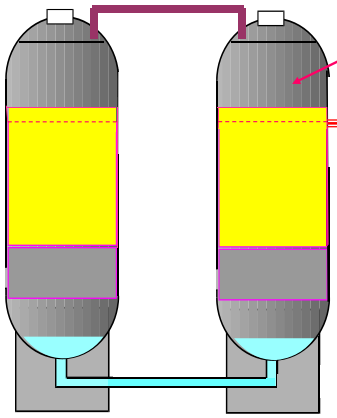
time (min)

10 — 0.5 min standby
0.5 min pressurising

4 min regenerating

5 — 5 min drying

0



80 % desiccant volume
100 % air flow
35 °C inlet temperature
7 bar (g)
pressure dew point - 40 °C

Regenerating air requirement:

average	17 %
+ chamber filling	1 %
total average	18 %

Regenerating air (max.)

$$\frac{18\ \% \times 5\ \text{min}}{4.5\ \text{min}} \approx 20\ \%$$

Economy Dryer

Economy Cycle

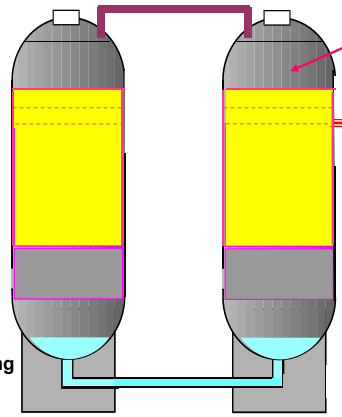
time (min)

10

5 — 0.25 min standby
0.25 min pressurising
2 min regenerating

2.5 min drying

0



60 % desiccant volume
100 % air flow
35 °C inlet temperature
7 bar (g)
pressure dew point - 40 °C

Regenerating air requirement:

average	22 %
+ chamber filling	2 %
total average	24 %

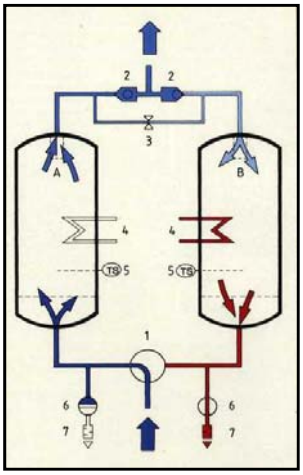
Regenerating air (max.)

$$\frac{24\% \times 2.5\ \text{min}}{2.25\ \text{min}} \approx 27\ \%$$

4. Understanding Air Treatment

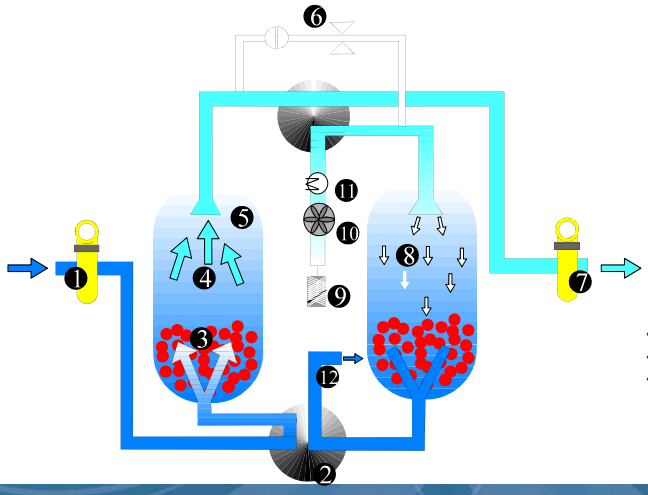
Desiccant drying - internally heated

- integrated heating rods (desiccant not heated evenly during regeneration)
- low purge air requirement (cooling, pressure build-up)
- constant dry, oil-free and clean compressed air



4. Understanding Air Treatment

Desiccant drying - externally heated

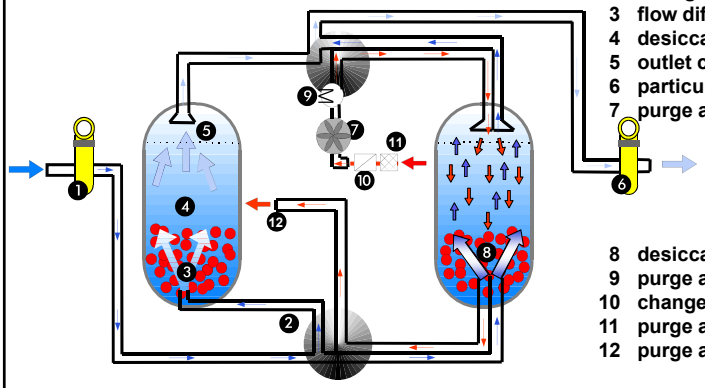


1 microfilter (0.01 µm, 0.01ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: adsorption
5 outlet collector
6 regeneration (purge) valve
7 particulate filter
8 desiccant bed: regeneration
9 purge air inlet
10 purge air blower
11 purge air heating
12 purge air outlet

4. Understanding Air Treatment

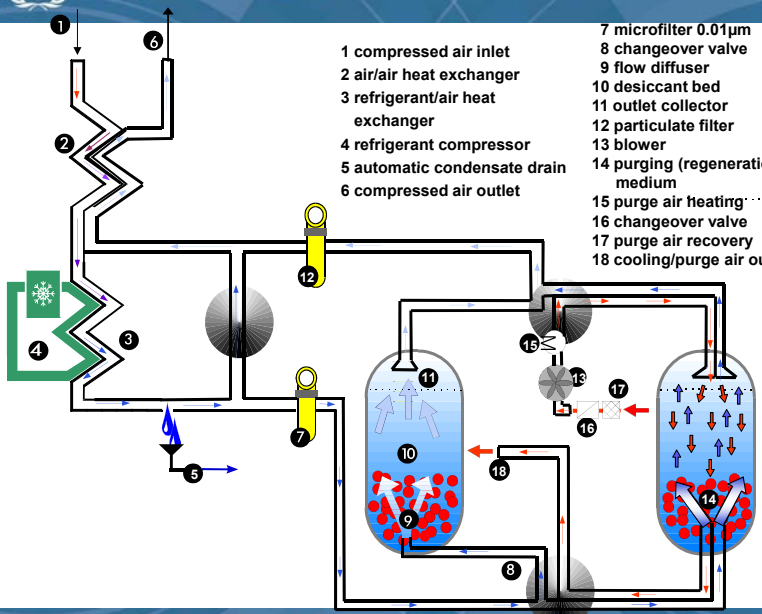
Desiccant drying, externally heat regenerated

Principle of no compressed air loss:



1 microfilter (0.01 µm, 0.01ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: adsorption
5 outlet collector
6 particulate filter
7 purge air blower

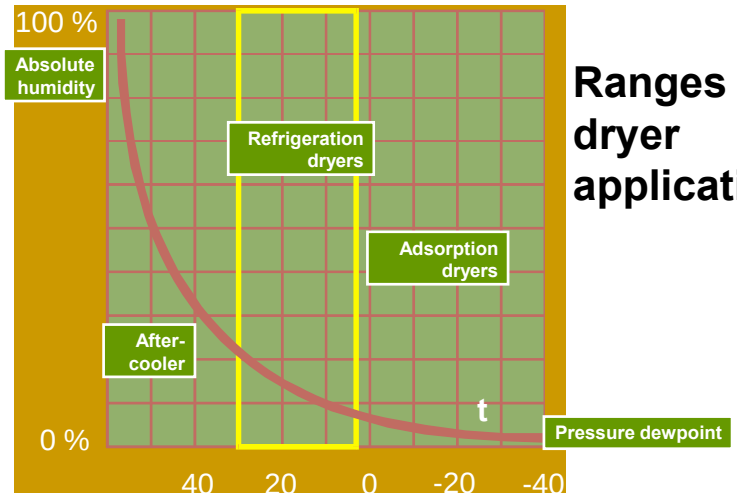
8 desiccant bed: regeneration
9 purge air heating
10 changeover valve
11 purge air inlet
12 purge air outlet



1 compressed air inlet
2 air/air heat exchanger
3 refrigerant/air heat exchanger
4 refrigerant compressor
5 automatic condensate drain
6 compressed air outlet

7 microfilter 0.01µm
8 changeover valve
9 flow diffuser
10 desiccant bed
11 outlet collector
12 particulate filter
13 blower
14 purging (regeneration) of drying medium
15 purge air heating
16 changeover valve
17 purge air recovery
18 cooling/purge air outlet

4. Understanding Air Treatment



Ranges of dryer application

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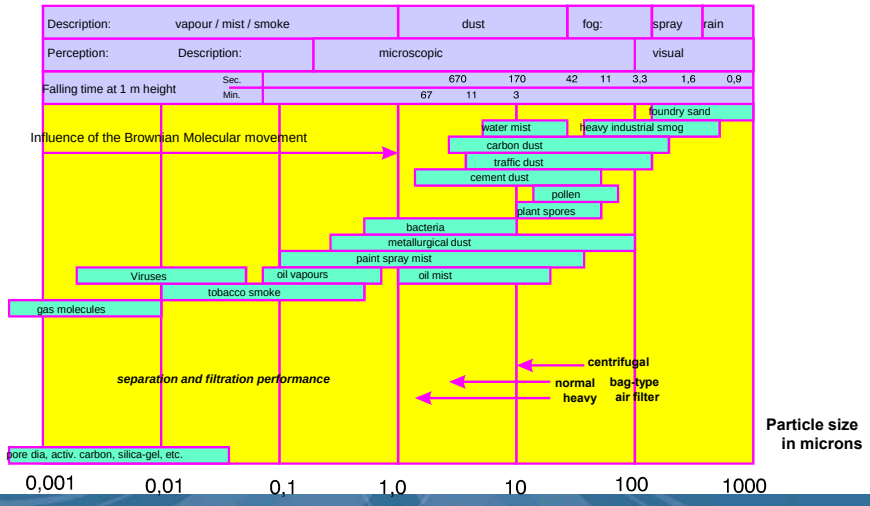
4. Understanding Air Treatment

Pressure dewpoints for some areas of application

Area of application	Required pressure dewpoint in °C
Workshop air - indoor pipework	10 to - 10
Paint spraying	10 to - 25
Instrument air	10 to - 40
Air motors	10 to - 40
Sand blasters	5 to 0
Pneumatic tools	5 to - 25
Packaging	5 to - 25
Plastics industry	5 to - 40

4. Understanding Air Treatment

How large are the impurities in the air?



Particle size in microns

4. Understanding Air Treatment

Permissible particle sizes

Compressed air usage	Permissible particle size in micron
rotary vane air motors percussion tools	40 - 20
cylinder controllers	20 - 5
control systems. instru-ments, spray guns	5 - 1
fluidic elements, phar-maceutics. electronics	< 1
pure breathing air	0.01

4. Understanding Air Treatment

Current hydro carbon carry-over limits for various applications

Application	Max. hydro carbon carry-over in compressed air in mg/m³
Working air Normal breathing air	< 5
Testing air	< 1
Pure breathing air	< 0.5
Oil-free air	< 0.003

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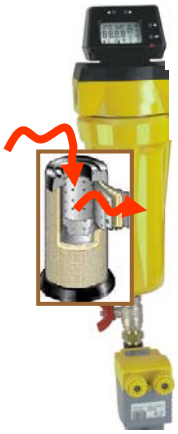
4. Understanding Air Treatment



Prefilter

used as a coarse filter for 100% saturated compressed air (or for water vapor components in the liquid phase)

Streamed from the inside to the outside.
Used as a liquid filter

Principle the same as all deep-bed filters

4. Understanding Air Treatment

Particulate filter

used as dust filter for dried air (e.g. downstream of a desiccant dryer)

Streamed from the outside to the inside.
Used as surface filter

4. Understanding Air Treatment

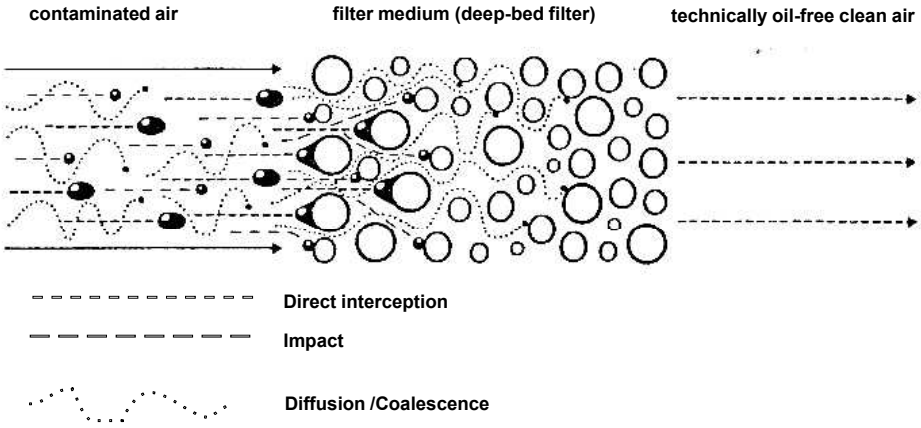
Microfilter

0.01 to 0.001 micron for liquids (aerosols) and particles

Streamed from the inside to the outside.
Used as a deep-bed filter

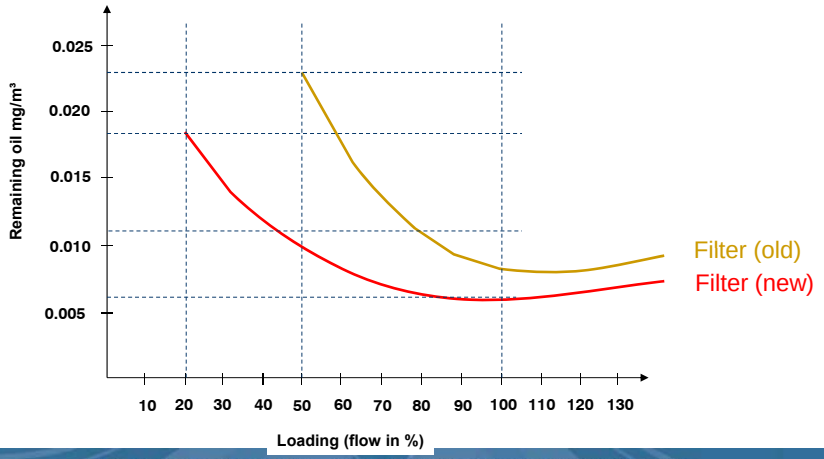
4. Understanding Air Treatment

How does the microfilter work?



4. Understanding Air Treatment

Coalescing filter behaviour in the partial load range



4. Understanding Air Treatment

Activated carbon adsorber

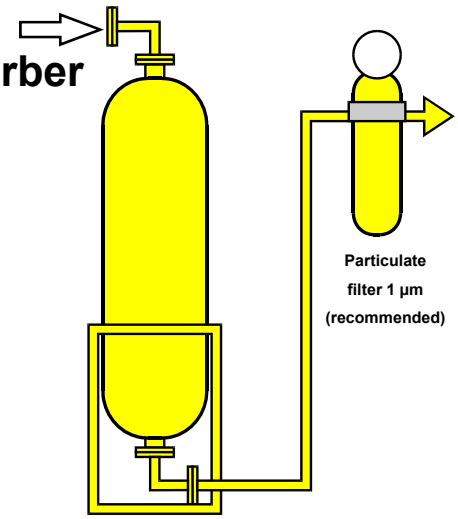
Quality of inlet air:

hydro carbon content <0.01 mg/m³
free of particles > 0.01 µm

- long contact time of the air and activated carbon bed
- long and reliable life
- hydro carbon indicator for continuous quality control

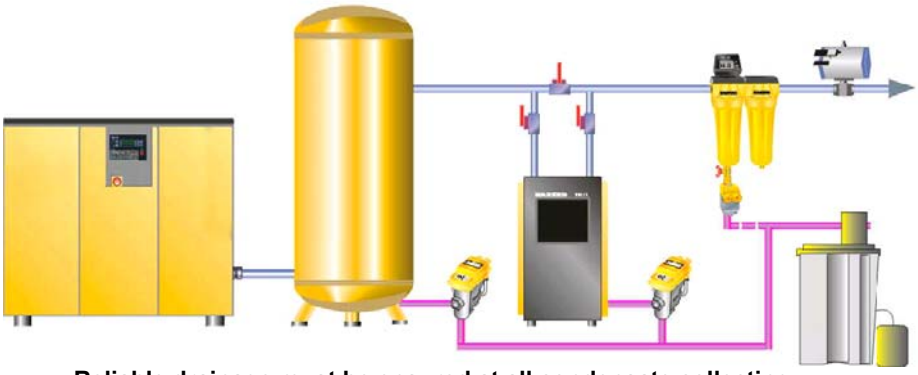
Quality of outlet air:

hydro carbon content 0.003 mg/m³



4. Understanding Air Treatment

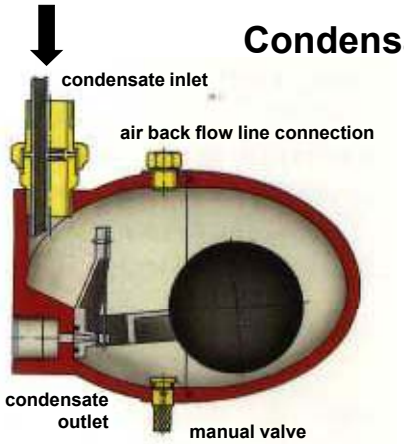
Condensate drainage



Reliable drainage must be ensured at all condensate collecting points of the air main

4. Understanding Air Treatment

Condensate drains: float type



Drainage occurs only when sufficient condensate has collected

No compressed air blowoff

Regular maintenance required

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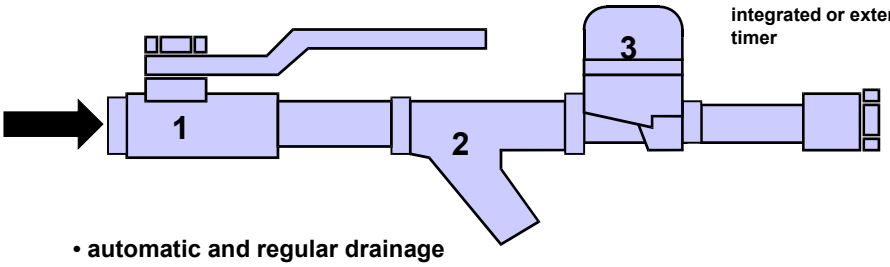
4. Understanding Air Treatment

Condensate drains: solenoid valve, timer controlled

1 ball valve
2 dirt trap
3 solenoid valve with integrated or external timer

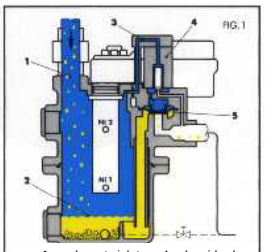


- automatic and regular drainage
- interval 1.5 to 30 min
- opening period 0.4 to 10 sec
- condensate can be directed into a disposal canister

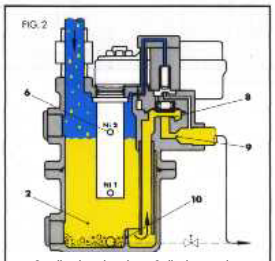
4. Understanding Air Treatment

Condensate drains: Electronic level-sensing type

Capacitive level sensing
Automatic pressure matching
Self-monitoring
Volt-free alarm contact



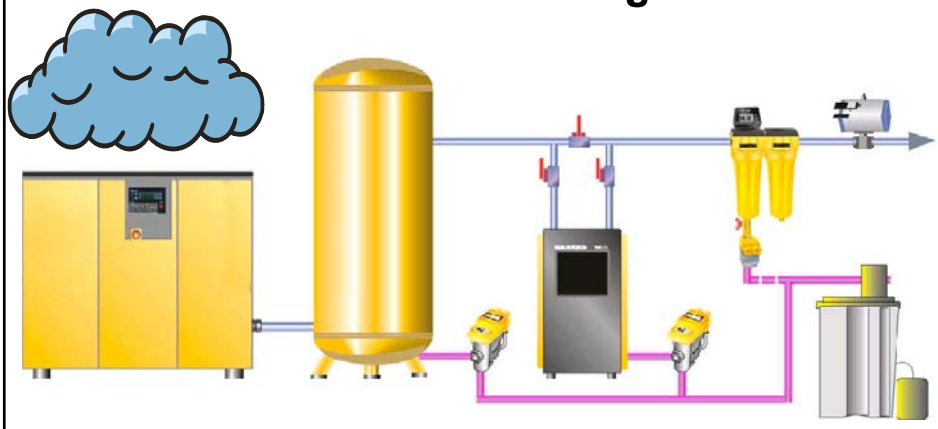
1 condensate inlet 4 solenoid valve
2 collection chamber 5 valve diaphragm
3 pressure balance line



2 collection chamber 9 discharge pipe
6 level sensor
8 valve seat

4. Understanding Air Treatment

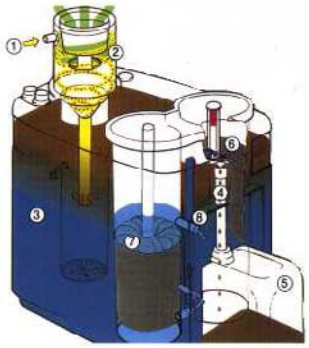
What's the reason for treating condensate?



Regardless of which type of construction, all compressors draw in the impurities in the air and contentrate them many times

4. Understanding Air Treatment

Condensate: Oil-Water separator



1 condensate inlet
2 expansion chamber
3 separating tank: gravitational separation
4 oil overflow drain
5 oil collector tank
6 prefilter: retention of solids
7 adsorption filter: retention of oil particles
8 water drain (clean water)

Used to separate condensate dispersions

4. Understanding Air Treatment

Pollutants in the condensate of oil-free and oil-cooled compressor units

Sample	HC mg/l	Ph	Cu mg/l	Zn mg/l	Cl mg/l	Pb mg/l	Fe mg/l	Na mg/l
oil-free	4.2	4.7	2.5	0.75	1.3	0.2	0.2	1.6
fluid-injected	7.1	6.6	1.1	1	1	0.2	0.2	0.12
oil-free	7	5.5	1.7	0.22	2.4	0.2	0.2	0.45
fluid-injected	0.1	7.1	0.11	0.04	1	0.2	0.2	0.64
oil-free		4.2	16	2	6.4	2.1	4	1.5
oil-free	5.3	6.2	0.11	2.2	1	0.2	0.2	0.76

HC .... Hydro carbon content
Ph .... ph value

4. Understanding Air Treatment

5. Understanding Systems

The Demand Side

5. Understanding Systems

Pneumatic Power

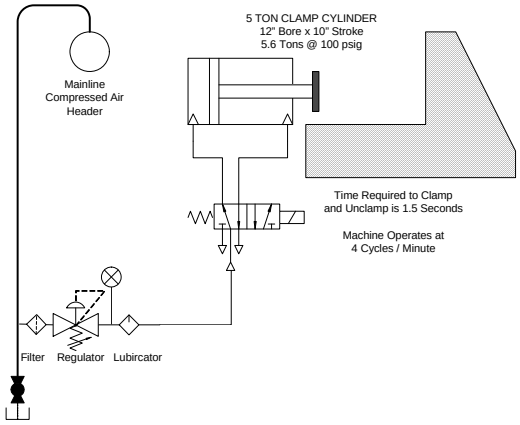
Air Flow > Mass or Weight of Air
Pressure > Potential Energy

Increasing – or – Decreasing
Flow – or – Pressure
Increase – or – Decrease
Power Delivered & Power Consumed

5. Understanding Systems

5 Ton Clamping Cylinder

- 1.5 seconds
- 4 cycles per minute
- 320mm Bore (45,000 Newtons @ 6.9 bar)
- 250mm Stroke Length



5. Understanding Systems

Cylinder Volume Calculation

$$V = \frac{\Pi\ r^2 \times l}{(1000)^3} = \frac{\Pi\ (160)^2 \times 250}{(1000)^3} = 0.02\ cubic\ meters$$

Cylinder Air Use

$$m^3 = V \times \frac{\Delta P + P_{atm}}{P_{atm}} = 0.02\ m^3 \times \frac{6.9 + 1}{1} = 0.158$$

5. Understanding Systems

Cylinder Average Air Demand (1 minute)

$$Average\ Air\ Flow\ (m^3) = 8\ \frac{Strokes}{Minute} \times 0.158\ \frac{m^3}{Stroke} = 1.264\ m^3 (1\ Minute\ Average)$$

What Size Components?

Air Line Size _____

Filter, Regulator, Lubricator _____

Valve Size _____

5. Understanding Systems

Cylinder Peak Dynamic Flow Rate

$$Dynamic\ Airflow\ Rate\ (m^3/min) = \frac{1.164\ m^3}{12\ seconds} \times \frac{60\ seconds}{1\ minute} = 6.32\ m^3/min$$

What Size Components Now?

Air Line Size _____

Filter, Regulator, Lubricator _____

Valve Size _____

5. Understanding Systems

- When does the Peak Air Flow Occur?
- When is the High Pressure Required?
- What Size Components Now?

5. Understanding Systems

- Flow Static Demand
  - Peak air flow and minimum pressure required do not occur simultaneously.
- Flow Dynamic Demand
  - Peak airflow rate and minimum pressure required must occur simultaneously.

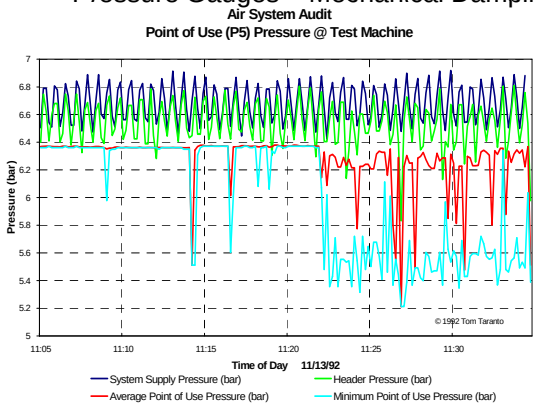
5. Understanding Systems

- Perceived High Pressure Demands
  - Often Dictate the System Pressure
  - Validate Pressure Requirements
  - Rule Out Excessive Pressure Drop
  - Measure Flow & Pressure (Data Logging)
  - Evaluate
    - Connection Practice – Modify Equipment – Storage – Pressure Boosters

5. Understanding Systems

Validate Perceived High Pressure

Pressure Gauges – Mechanical Damping



5. Understanding Systems

Test Machine Flow Dynamic Demand

What's Wrong With This Picture?

5. Understanding Systems

- High Volume Intermittent Demand
  - Consume Large Airflow for Short Periods
  - High Peak Airflow Rate and Low Average Demand
  - Affects the System Pressure Profile

Control Signals	Supply Pressure
Distribution Gradient	Use Point Pressure

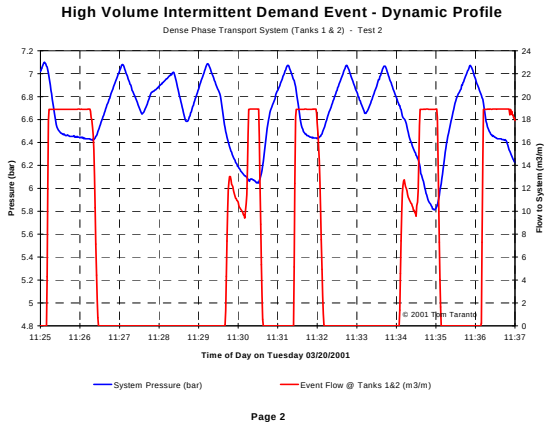
5. Understanding Systems

High Volume Intermittent Demand

- Wastes Energy
  - **Initiates Compressor Start-up**
  - **Operational Remedy – Increased Pressure**
  - **Adds to Artificial Demand**
- Data Logging Airflow & Pressure
  - **Peak Airflow Rate**
  - **Duration of Event & Total Air Consumed**
  - **Dwell Time Between Events – Storage Refill**
  - **Evaluate Control Response & Excess Supply Pressure**

5. Understanding Systems

High Volume Intermittent Demand



5. Understanding Systems

- Pipe Layouts – Point of Use Piping
  - **Delivers Air From Header to – Demand**
  - **Energy = Airflow & Pressure**

- 1 to 2 bar Loss in Point of Use Piping is Common
  - **Poor Unreliable, Inconsistent Applications Performance**
  - **Don't Increase Pressure**
  - **Decrease Piping Resistance**

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5. Understanding Systems

- Which Piping Configuration Performs Best?

5. Understanding Systems

Key Points

- Identify dynamic airflow conditions of average –vs- peak airflow.
- Classify air demands as Flow Static and Flow Dynamic.
- Point of use connection practice has a significant affect on applications performance.

5. Understanding Systems

– Key Points

- Review perceived high pressure air demands to validate their pressure requirements.
- Pressure gauges have slow response to pressure changes. It may be necessary to use pressure transducers and high-speed sampling to capture pressure dynamics.

5. Understanding Systems

Key Points

- Minimize the use of hose for connections. Hose has much smaller ID size (higher pressure drop) than pipe.
- Where hose must be used select the hose size based on the inside diameter and peak airflow rate. Avoid the use of hose barbs and pipe clamps, they are dangerous, very restrictive and frequently develop leaks.

5. Understanding Systems

Key Points

- Do not use redundant point of use dryers, filters, etc. as each component represents additional pressure drop.
- Avoid over filtration, maintain an appropriate compressed air cleanliness class for the application requirements.
- Size all connection equipment to the actual dynamic conditions associated with the application.
- Account for to peak airflow rate that must be supported, do not size equipment based on average airflow rate.

5. Understanding Systems

BALANCING THE SUPPLY TO DEMAND

5. Understanding Systems

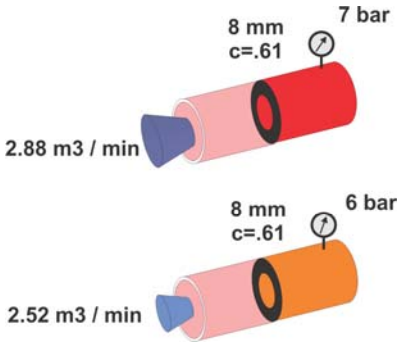
- Supply > Demand ~ Pressure ↑
- Demand > Supply ~ Pressure ↓

5. Understanding Systems

- Air System Minimum Pressure
  - What is the correct pressure?
  - What is the Cost?
- Increased Air Pressure = Waste
  - Artificial Demand
  - Increasing Pressure Increases Airflow

5. Understanding Systems

- Artificial Demand
  - Increasing pressure applied to a hole in the air system, increases the airflow through the air system.
  - Leaks and unregulated air demands all have a potential component of artificial demand.
  - Leak repair without pressure control is not fully effective.



5. Understanding Systems

Discharge of Air Through an Orifice

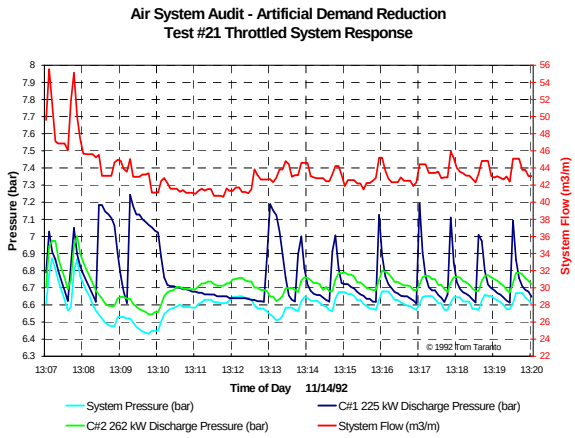
In cubic meters of free air per minute at standard atmospheric pressure 1.013 bar absolute and 21° C

Gauge pressure before orifice, bar	Diameter of Orifice, mm											
	1	2	3	4	5	6	7	8	9	10	15	20
4	0.03	0.11	0.25	0.45	0.70	1.01	1.38	1.80	2.28	2.82	6.34	11.28
4.5	0.03	0.12	0.28	0.50	0.78	1.12	1.52	1.98	2.51	3.10	6.98	12.40
5	0.03	0.14	0.30	0.54	0.85	1.22	1.66	2.16	2.74	3.38	7.61	13.53
5.5	0.04	0.15	0.33	0.59	0.92	1.32	1.79	2.34	2.97	3.66	8.24	14.65
6	0.04	0.16	0.35	0.63	0.99	1.42	1.93	2.52	3.19	3.94	8.87	15.78
6.5	0.04	0.17	0.38	0.68	1.06	1.52	2.07	2.70	3.42	4.23	9.51	16.90
7	0.05	0.18	0.41	0.72	1.13	1.62	2.21	2.88	3.65	4.51	10.14	18.03
7.5	0.05	0.19	0.43	0.77	1.20	1.72	2.35	3.06	3.88	4.79	10.77	19.15
8	0.05	0.20	0.46	0.81	1.27	1.82	2.48	3.24	4.11	5.07	11.40	20.27
8.5	0.05	0.21	0.48	0.86	1.34	1.93	2.62	3.42	4.33	5.35	12.04	21.40
9	0.06	0.23	0.51	0.90	1.41	2.03	2.76	3.60	4.56	5.63	12.67	22.52
9.5	0.06	0.24	0.53	0.95	1.48	2.13	2.90	3.78	4.79	5.91	13.30	23.65
10	0.06	0.25	0.56	0.99	1.55	2.23	3.03	3.96	5.02	6.19	13.94	24.77

Table is based on 0.61 coefficient of flow.

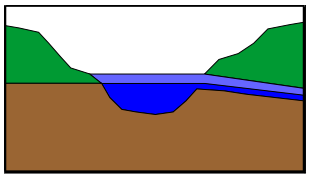
5. Understanding Systems

Engineer Appropriate Storage

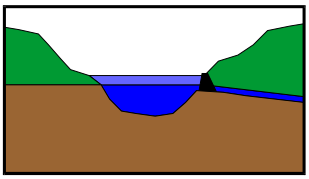


5. Understanding Systems

Storage; A Lake – vs – A Reservoir

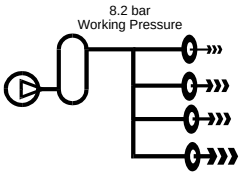


LAKE

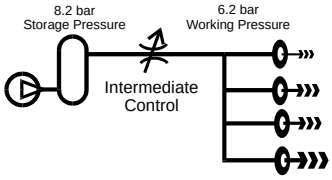


RESERVOIR

AIR RECEIVER



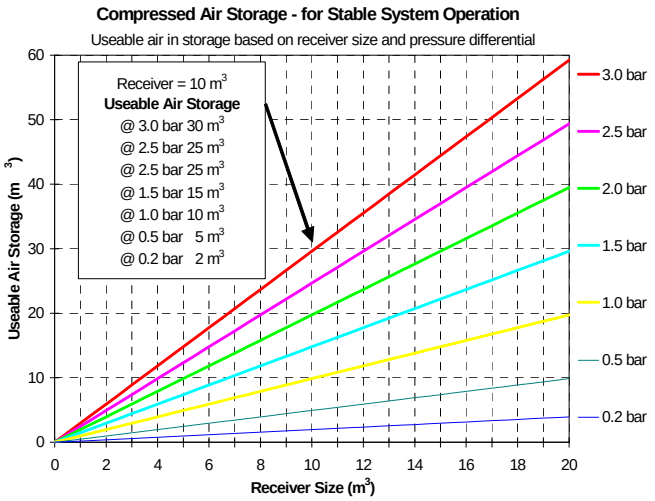
AIR STORAGE



5. Understanding Systems

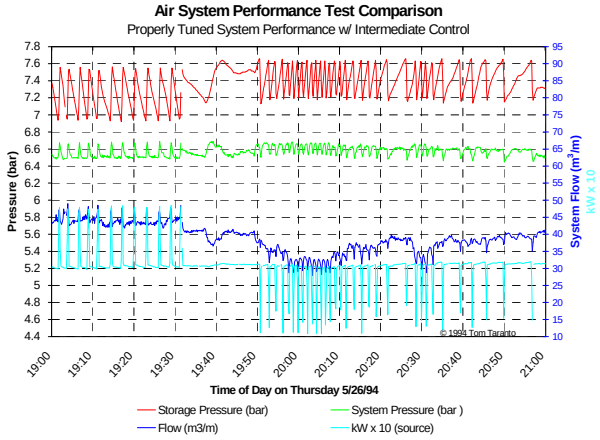
- Stabilize System Operation
  - Minimize the cost of generating compressed air.
  - Control air demand and reduce artificial demand.
  - Create controlled air storage to supply peak demand
- Evaluating Controlled Storage
  - Meet surge demands
  - Satisfy events as defined in the demand profile
  - Improve compressor control response

5. Understanding Systems



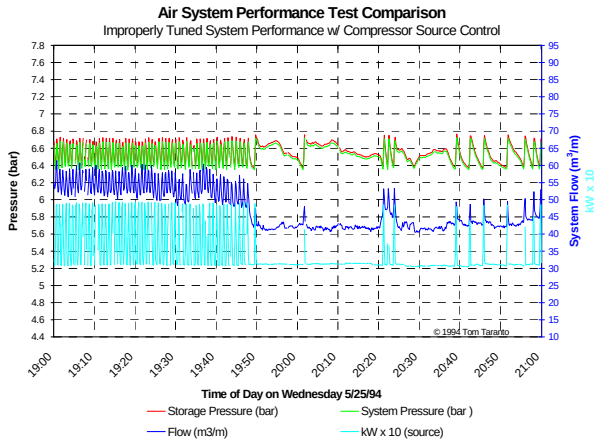
5. Understanding Systems

Tuning Compressor & System Controls



5. Understanding Systems

Tuning Compressor & System Controls



5. Understanding Systems

Key Points

- Stabilize system operating pressure.
- Increased air pressure increases compressed air demand at leaks and unregulated air demands.
- Leakage can be reduced by controlling to a lower system pressure.
- Artificial demand is a component of any unregulated leak or air demand.

5. Understanding Systems

Key Points

- Target pressure should be the lowest optimal pressure to supply productive air demands.
- Air storage should be designed to supply surge demands, satisfy events defined in the demand profile, and improve compressor control response.
- The amount of energy in storage depends on storage volume and controlled pressure differential.

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5. Understanding Systems

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6. Pressure Profile

Graphical description of compressed air pressure as measured throughout the system.

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Typical pressure measurement locations

- Compressor maximum working pressure (MWP)
- Compressor control range
- Treatment equipment pressure drop
- Pressure differential reserved for primary storage
- Supply header pressure to the system
- Distribution header pressure in one or more demand side locations
- Point of use connection pressure
- End use pressure

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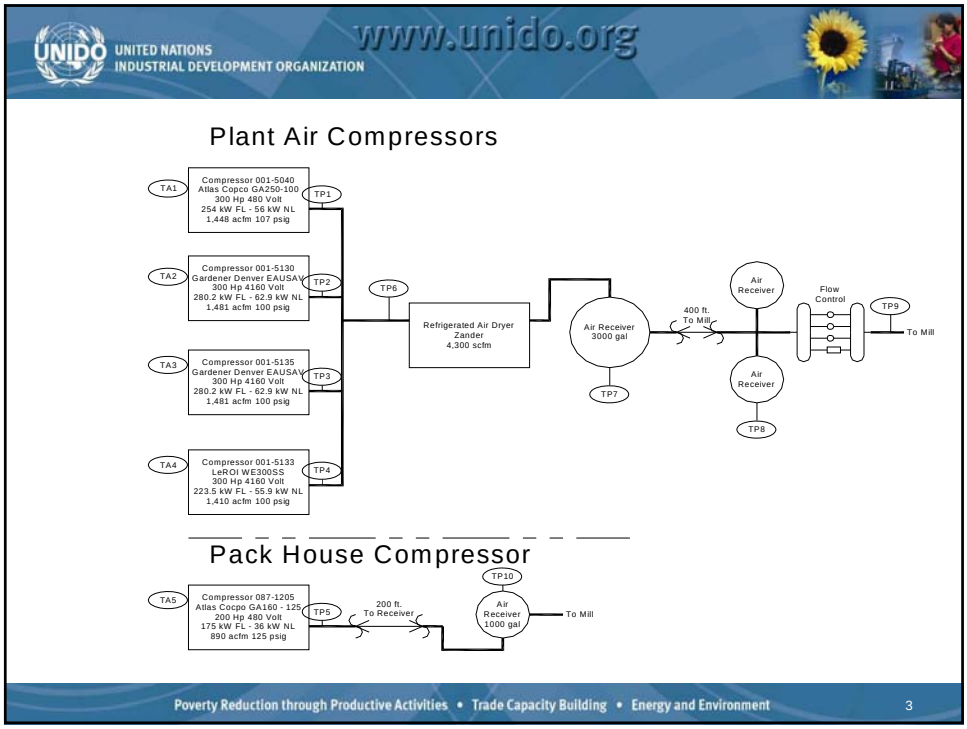

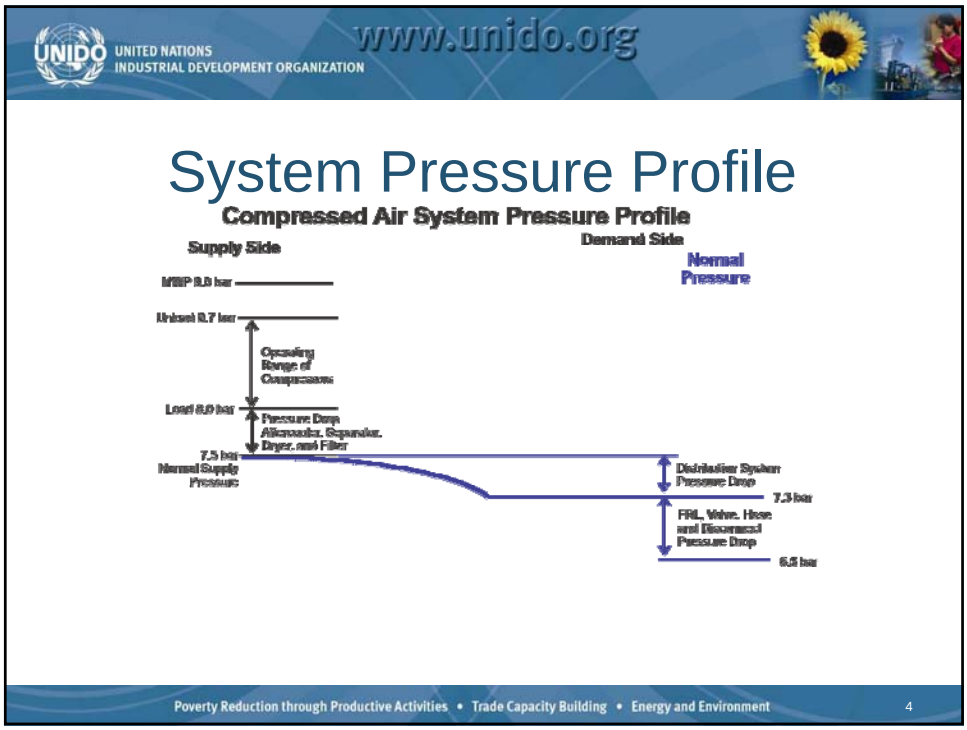

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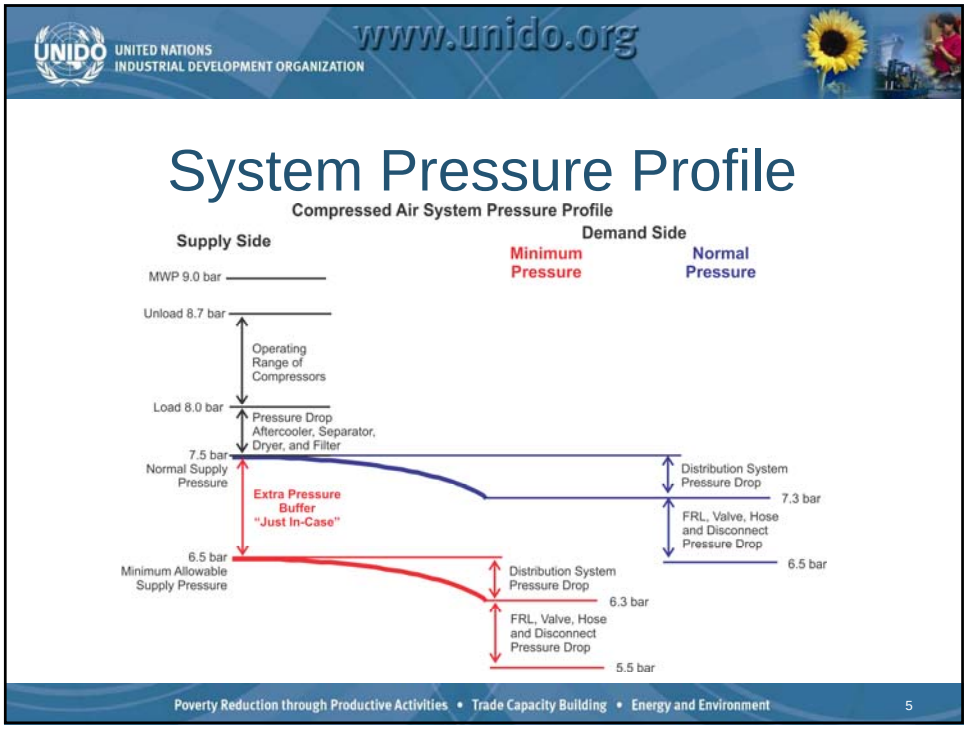

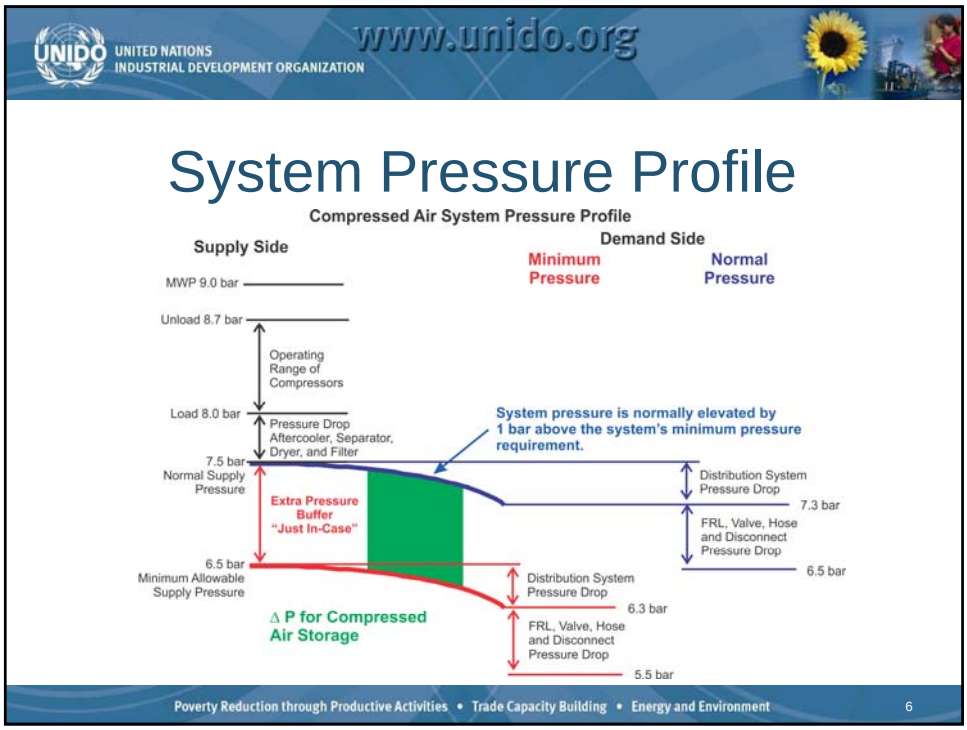

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Measuring Pressure Profile

- Multiple Data Loggers w/ synchronized time
- Dynamic Performance pressure changes with time.
- Dynamic pressure changes affect
  - Compressor control response
  - Compressed air storage
  - End use pressure / reliability

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Practical Application of Pressure Profiles

- Target Pressure
  - The lowest optimum pressure necessary to support production requirements.
- Reducing System Pressure Decreases Energy Use
  - Power at the air compressor drops by 6% per bar of pressure reduction (for positive displacement compressors).
  - Air demand in the system drops by 6 % to 12% per bar of pressure reduction (assuming 50% to 75% of air use is unregulated).

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Pressure Profile
Two types of pressure differentials

- Irrecoverable Pressure Loss
  an energy loss to the system.
  - Pressure drop through a filter, pipe restriction, hose, quick disconnect fitting, etc.
- Recoverable Pressure Differential
  an energy cost to the system
  - Increased pressure of an air storage receiver which creates compressed air energy storage

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Pressure Profile
component pressure loss

- Pressure Regulator
  - Recoverable
    - adjust the regulator to higher pressure
  - Irrecoverable
    - offset pressure required to open the regulator
    - pressure loss at a given air flow rate
- Pressure Flow Control
  - Recoverable
    - differential between storage pressure and target pressure
  - Irrecoverable
    - control pressure differential
    - pressure loss at a given air flow rate with valve(s) wide open.

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Pressure Profile Design Criteria

- Operate compressor controls in as narrow a pressure band as possible while allowing:
  - Unneeded compressors to automatically shutdown.
  - All compressors, except one, to operate at full load capacity.
  - Only one compressor to provide trim capacity, selecting the most efficient part load capacity control available.
- Operate compressor discharge pressure at the lowest possible pressure

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Pressure Profile Design Criteria

- Establish the delivered use point pressure at the lowest optimum pressure necessary to support productive air demand.
- Create pressure differential (P final minus P initial) to create the necessary compressed air energy storage. Energy storage should serve normal demand events and cover permissive start-up time of reserve compressor capacity.
- Use energy storage to prevent additional air compressors from starting in response to short duration peak demand events.
- Minimize irrecoverable pressure loss throughout the system.

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Pressure Profile Design Criteria

- Control recoverable pressure differential of primary storage to eliminate artificial demand.
- Control supply header target pressure to the lowest optimum pressure while accounting for irrecoverable pressure loss through distribution, and point of use piping.
- Apply pressure regulation at use points where recoverable pressure differential is available. Eliminate pressure regulators that are set at maximum.

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Pressure Profile Design Criteria

- Supply Side – upper pressure limit
- Supply Side – lower pressure limit
- Demand side – upper pressure limit
- Demand side – lower pressure limit

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Pressure Profile
Key Points - Pressure Limits

1. Pressure limits form the operating envelope of the pressure profile
2. Supply maximum working pressure (MWP) is the high limit of the pressure profile
3. Demand side point of use pressure target is the low limit of the pressure profile
4. Consider minimum design pressure (velocity) rating of supply components
5. Protect demand side components from exceeding their MWP

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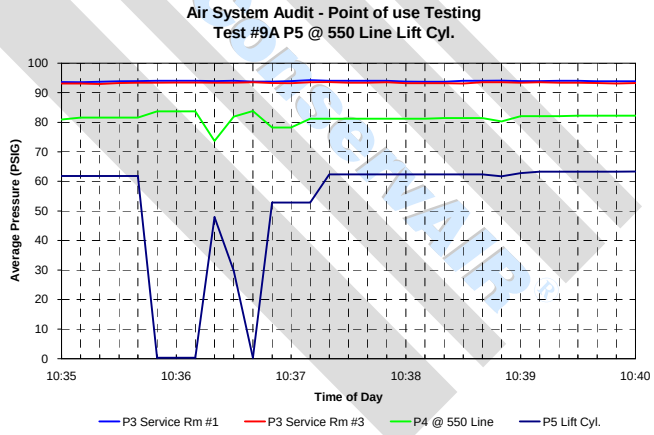
Pressure Profile – point of use
Perceived –vs– actual required pressure



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Pressure Profile – point of use
Flow Static –vs- Flow Dynamic Demand

- Flow Static Demand
  - applications are characterized when peak airflow does not occur simultaneously with the minimum pressure required.
- Flow Dynamic Demand
  - applications where-in the peak airflow and minimum pressure must occur simultaneously.

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Pressure Profile
Key Points – Point of Use Pressure

1. Evaluate use points that require high system pressure.
2. Validate perceived high pressure requirements.
3. Eliminate poor point of use piping causing excessive pressure loss.
4. Check dynamic supply pressure to end use pneumatic devices.
5. Review OEM designs to identify excessive pressure loss within machines.
6. Establish an appropriate target pressure for point of use supply connection.

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Pressure Profile
Distribution Pressure Gradient

- Pressure Gradient, the rate of change of pressure with respect to distance in the direction of maximum change.
  - In fluid mechanics the change in pressure P, along the length and distance X of a fluid conduit. It is represented by dP / dX.
- NOTE 1: The air velocity in a pipeline depends on the magnitude of the gradient and the resistance of the pipeline.
- NOTE 2: With out gradient there is no airflow. In a compressed air system air moves from high-pressure toward low-pressure areas.

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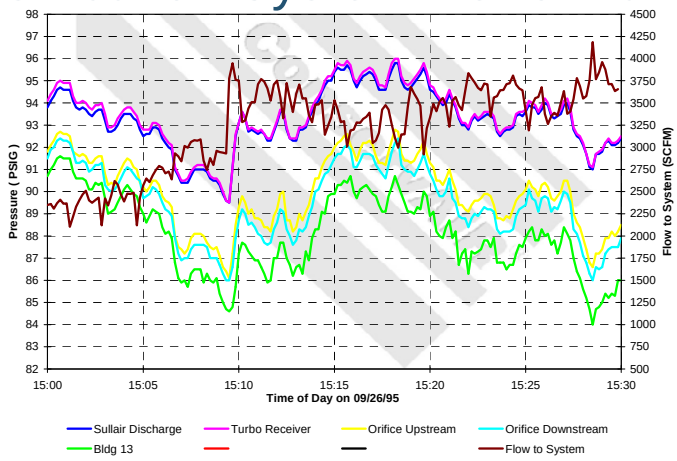
Pressure Profile
Distribution System Performance



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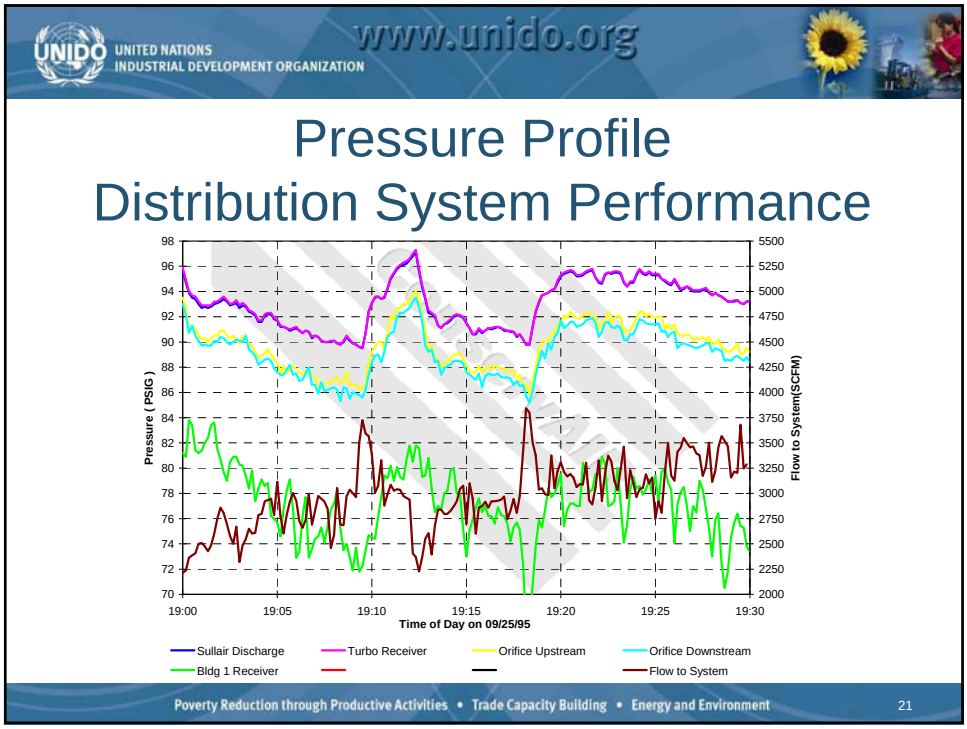

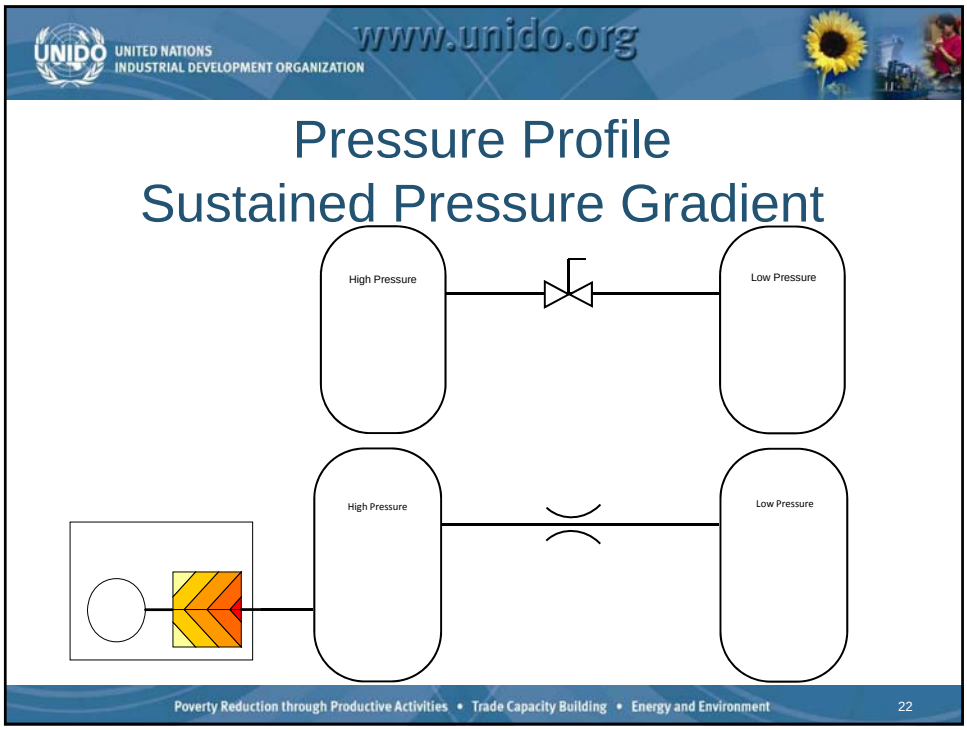

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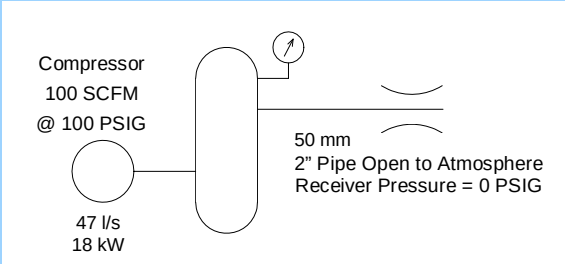
Pressure Profile
System Resistance Creates Pressure

Flow, Pressure & System Resistance
Compressors Pump Flow
Resistance Creates Pressure



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Pressure Profile
Key Points - Distribution

- Distribution pressure gradient requires measurements throughout the system.
- Check pressure gradient at peak airflow rate.
- Normally pressure should track supply at < 0.15 bar (2 psig) pressure differential.
- High pressure gradient leads to unstable performance.
- High pressure gradients in distribution piping must be corrected.
- Sustained pressure gradient will drive inefficient compressor load cycles.
- Compressors create airflow, system resistance creates pressure.
- Pressure drop increases as a function of airflow change squared.
- Pipeline design velocity should be less than 30 ft/sec.

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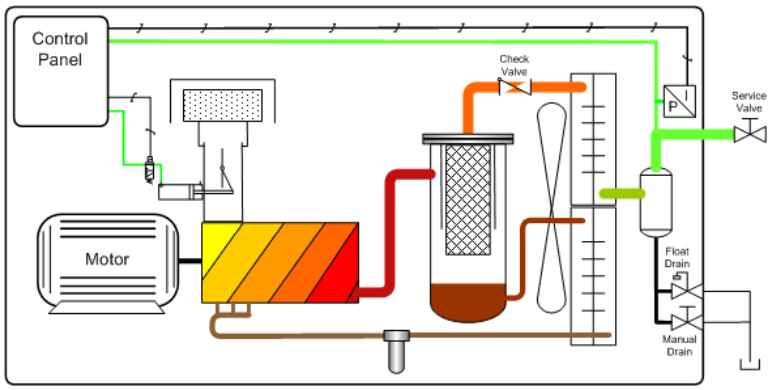
Pressure Profile
Air Compressor Control Signal



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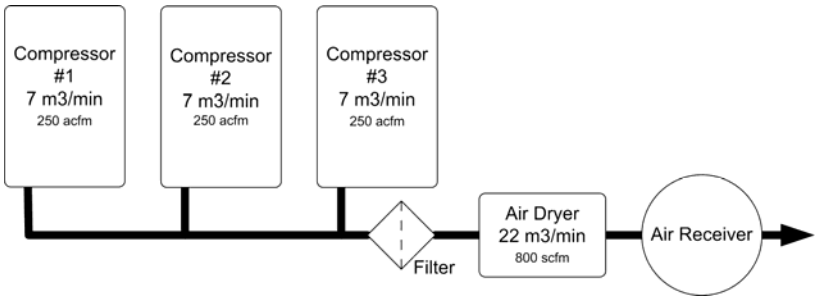
Pressure Profile
Control Shift as Flow Changes



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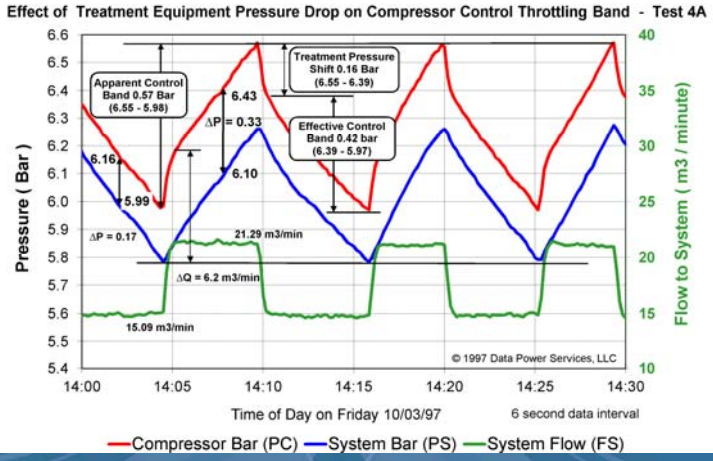
Pressure Profile
Control Shift as Flow Changes



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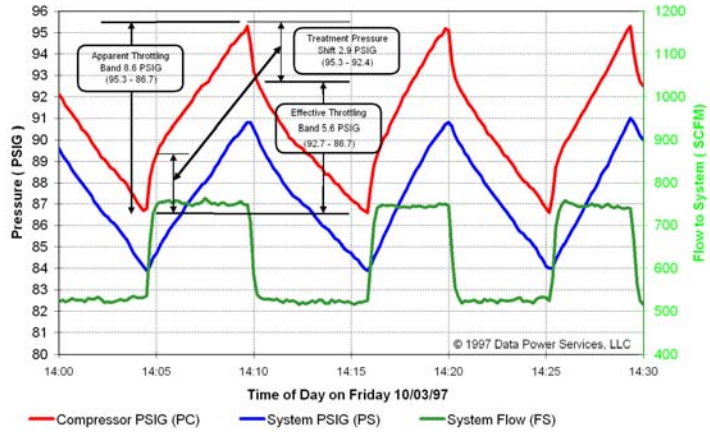
Pressure Profile
Control Shift as Flow Changes



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Pressure Profile
Pressure Drop Changes w/ Flow

- In a Fluid System, pressure drop changes as the square of the change in velocity.

$$\Delta P_2 = \left(\frac{Q_2}{Q_1}\right)^2 \times \Delta P_1$$

$$\Delta P_2 = \left(\frac{21.29\ m3/\min}{15.09\ m3/\min}\right)^2 \times 0.5\ bar = 0.995\ bar$$

The resultant control pressure shift would be $\Delta P_2 - \Delta P_1$, or 0.495 bar

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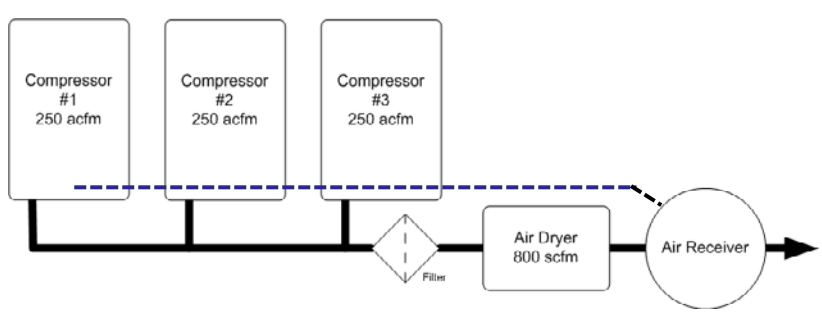
Pressure Profile
Remote Control Pressure Sensing



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Pressure Profile
Key Point – Control Signals

1. Air compressor capacity controls react to pressure sensed by its control system.
2. As pressure decreases compressor air delivery will increase until its maximum output is being produced.
3. As pressure increases compressor air delivery is reduced.
4. Restrictions in the system such as air dryers and filters can impact compressor control.
5. Remote sensing or external sequencing of compressor controls can improve control response.
6. Over pressure protection should sense pressure within the compressor package.

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Air Storage and System Energy Balance

Air Storage and System Energy Balance

- DYNAMICS
  - Dynamics is the study of the affect of time variant parameters on system performance.
- AVERAGE AIR DEMAND
  - For an individual compressed air use point, Average Air Demand is the compressed airflow rate (Nm3 / min) consumed by the use as considered during the time duration of one or more full cycles of operation.

Air Storage and System Energy Balance

- Peak Air Demand
  - The highest compressed airflow rate (Nm^3 / min) of the system's combined air demand which is a detectable airflow rate greater than the continuous steady demand. Peak demand duration may be a few seconds or minutes of time.
- Demand Event
  - A peak air demand along with duration of time during which that airflow rate must be sustained.

Air Storage and System Energy Balance

- Demand Event
  - A peak air demand along with duration of time during which that airflow rate must be sustained.
- Demand Shift
  - Similar to a demand event where-by air demand quickly increases or decreases. However, a demand shift will operate at the new airflow rate for several minutes, an hour, or more.

Maintaining an Efficient Supply / Demand Balance

- Compressed air system controls must maintain a real time energy balance between supply and demand.
  - **Rotating Capacity** – Compressed air energy generated by operating air compressors.
  - **Rotating Reserve Capacity** – Potential compressed air energy in operating air compressors which are operating a less than their full load capacity.
  - **Storage Capacity** – Potential compressed air energy stored in an air receiver tank.
  - **Stand-by Capacity** – Potential compressed air energy in air compressors that are shutdown.

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Maintaining an Efficient Supply / Demand Balance

- System Supply / Demand Control Strategy
  - Operate rotating capacity equal to or slightly greater than the system's average air demand. Shutdown any rotating capacity that is not needed.
  - Operate all compressors at full load with only one compressor operating at part load to provide trim capacity.
  - Serve demand events from storage capacity. Eliminate the use of rotating reserve capacity and prevent stand-by capacity from coming on-line in response to short duration demand events.

Where:

Storage Capacity Calculation

$$V_a = V_s \times \left(\frac{(P_{\max} - P_{\min})}{P_{amb}} \right)$$

Where:

V_a	=	Useable compressed air storage capacity
V_s	=	Storage Volume = total volume of storage system
P_{max}	=	Maximum storage or receiver pressure (cut-out pressure)
P_{min}	=	Minimum storage or receiver pressure required (cut-in pressure)
P_{amb}	=	Absolute ambient air pressure

Storage Volume Calculation

$$V_s = \frac{T \times C \times P_{amb}}{P_{\max} - P_{\min}}$$

Where:

T	=	Time duration of the event (minutes)
C	=	Air demand of the event
V_s	=	Total volume of storage system
P_{max}	=	Maximum storage or receiver pressure (cut-out pressure)
P_{min}	=	Minimum storage or receiver pressure required (cut-in pressure)
P_{amb}	=	Absolute ambient air pressure

Air Storage
Controlled and Uncontrolled

- Controlled Storage
  - pressure / flow controls separate the demand side of the system from the supply side.
  - pressure in the distribution system is maintained at a low pressure in order to minimize artificial demand
  - provide a stable pressure regardless of air use or compressor control response.

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Air Storage
Controlled and Uncontrolled

- Uncontrolled Storage
  - pressure throughout the plant rises and falls over the full control range of the compressors.
  - plant air pressure can fall significantly below the lowest desired pressure because the compressor controls cannot react to changes in demand as quickly as they occur.
  - artificial demand is introduced whenever the demand side pressure is above the lowest optimum pressure for the system.

Air Storage and System Energy Balance

- Ideal Supply / Demand Balance
  - only if pressure is constant

$$Q_{gen} = Q_{dmnd}$$

- Practical Supply / Demand Balance
  - accounts for changing system pressure

$$Q_{sys} = Q_{dmnd}$$

$$Q_{sys} = Q_{gen} \pm Q_{sto} = Q_{dmnd}$$

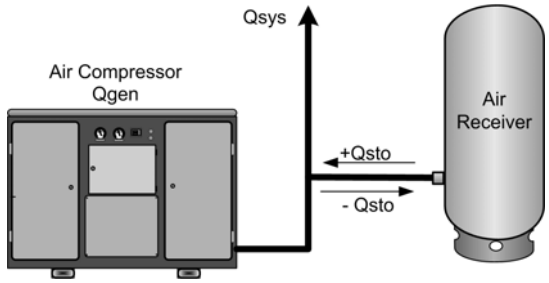
Air Storage and System Energy Balance

$$Q_{sys} = Q_{dmnd}$$

$$Q_{sys} = Q_{gen} \pm Q_{sto} = Q_{dmnd}$$

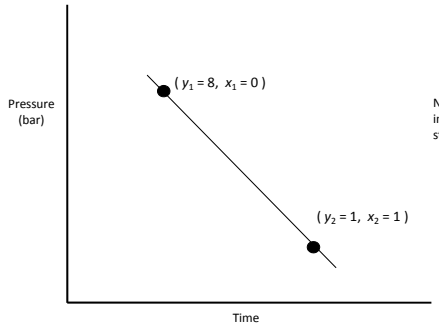
($-Q_{sto}$) for increasing pressure

($+Q_{sto}$) for decreasing pressure



Air Storage and System Energy Balance

Air Receiver Pressure Change



Slope of a Line

Negative slope, decreasing pressure implies that air is released from storage to the system.

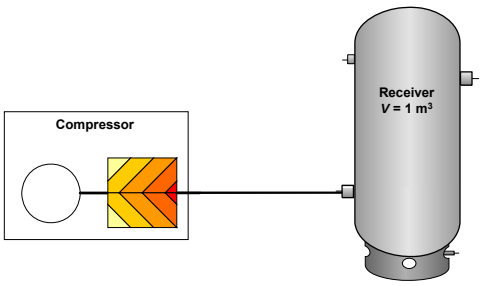
$$V_{gas} = V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}$$

$$V_{gas} = 1\,m^3 \times \frac{(1\,bar - 8\,bar)}{1\,bar} = V_{gas} = -7\,m^3$$

Negative Slope = Energy is Released from Storage to the System

Positive Slope = Energy is Absorbed to Storage from the System

Gas Volume – Receiver Volume Relationship



$$V_{gas} = V_{rec} \times \frac{(\Delta P_{rec})}{P_{atm}}$$

$$V_{gas} = \frac{V_{rec} \times (P_f - P_i)}{P_{atm}}$$

$$V_{gas} = \frac{1\,m^3 \times (1\,bar - 8\,bar)}{1\,bar} = -7\,m^3$$

Introducing Time into Air Receiver Storage Calculations

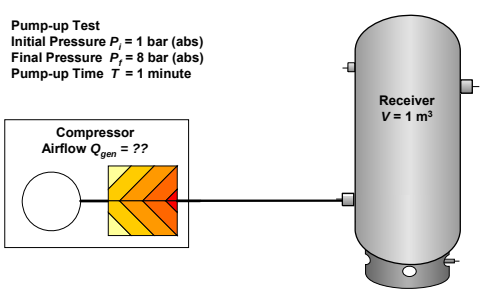
- Adding time to the air storage calculation results in airflow rate Q_{gas} being calculated.
- The flow rate of gas is volume per unit of time.

$$V_{gas} = V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}$$

$$\frac{V_{gas}}{T} = \frac{V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}}{T}$$

$$Q_{gas} = \frac{V_{rec} \times (P_f - P_i)}{T \times P_{atm}}$$

Air Receiver Pump-up Test

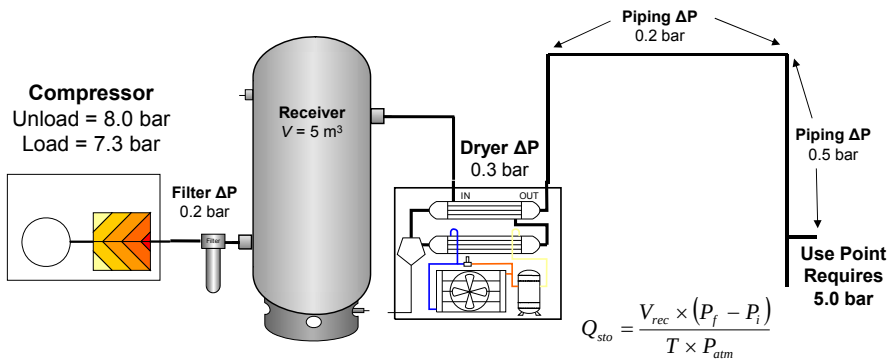


$$Q_{gen} = \frac{V_{rec} \times (P_f - P_i)}{T \times P_{atm}}$$

$$Q_{gen} = \frac{1m^3 \times (8\,bar - 1bar)}{1\text{minute} \times 1bar}$$

$$Q_{gen} = +7\,m^3 / \text{minute}$$

Useable Air in an Air Receiver



$$Q_{sto} = \frac{V_{rec} \times (P_f - P_i)}{T \times P_{atm}}$$

$$Q_{sto} = \frac{5\,m^3 \times (6.0\,bar - 7.3\,bar)}{1\,\text{minute} \times 1.013\,bar}$$

$$Q_{sto} = -6.42\,Nm^3/\text{minute}$$

The useable compressed air energy depends on the receiver volume V*rec* and the available storage pressure differential (ΔP = P*f* – P*i*).

Pneumatic Capacitance of Compressed Air Systems

- Volume of gas calculation

$$V_{gas} = V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}$$

$$V_{gas} = 1\,m^3 \times \frac{(1\,bar - 8\,bar)}{1\,bar} = V_{gas} = -7\,m^3$$

- Volume of gas using Pneumatic Capacitance

$$V_{gas} = \frac{V_{rec}}{P_{atm}} \times (P_f - P_i)$$

$$V_{gas} = C_{PN} \times (P_f - P_i)$$

$$V_{gas} = 1\frac{m^3}{bar} \times (1\,bar - 8\,bar) = V_{gas} = -7\,m^3$$

Pneumatic Capacitance & Dynamic Time Based Calculations

- Flow rate of gas calculation

$$Q_{gas} = \frac{V_{rec} \times (P_f - P_i)}{T \times P_{atm}}$$

- Flow rate of gas using Pneumatic Capacitance

$$Q_{gas} = \frac{V_{rec}}{P_{atm}} \; x \; \frac{(P_f - P_i)}{T}$$

$$Q_{gas} = C_{pn} \; x \; \frac{dP}{dT}$$

Air Storage & System Energy Balance – Key Points

1. Consistent, Stable, & Efficient Operation – Balance Supply & Demand.
2. System dynamics determine the nature of the compressed air demand profile.
3. Average air demand (compressors) – Peaks & valleys in demand (system).
4. Sources of supply – rotating capacity – rotating reserve – energy storage & stand-by compressors.
5. Rotating online capacity must be greater than average air demand.
6. Peak demand from storage – don't forget that refill of storage is an air demand.

Air Storage & System Energy Balance – Key Points

7. Control Strategy – turn off unneeded compressors – run compressors at full load
8. Pick one machine for trim capacity (efficient at part load operating point).
9. Engineer storage to system applications avoid using rules of thumb.
10. Energy available from storage depends on volume and available pressure differential.
11. The unanticipated shutdown of an operating air compressor is often the largest event that will occur in a system.

8. Compressed Air System Assessment

8. Compressed Air System Assessment

- The Systems Approach
  - A comprehensive system assessment examines the entire compressed air system, including:
    - Generation
    - Treatment
    - Storage
    - Distribution
    - Use and waste of compressed air

8. Compressed Air System Assessment

- The systems approach evaluates overall system performance rather than individual component efficiency.
- The system boundary includes energy input to the compressed air supply and treatment through the production equipment and work performed as a result of the energy input.

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8. Compressed Air System Assessment

- The information gathered should allow the assessment team to:
  - Understand point of use applications
  - Correct poor performing applications and those that upset system operation
  - Eliminate wasteful practices
  - Create and maintain an energy balance
  - Optimize storage and compressor controls

8. Compressed Air System Assessment

- **Brake horsepower calculation for annual energy cost.**

$$\frac{bhp \times 0.746 \; x \; hours \; x \; energy \text{ cost}}{mtr \; eff} = annual \; energy \text{ cost}$$

Where:

bhp = full load brake horsepower of the motor
0.746 = conversion of bhp to kW
hours = annual running hours
energy cost = $ / kWh
mtr eff = full load motor efficiency

8. Compressed Air System Assessment

- **Measured Volts - Amps calculation for annual energy cost.**

$$\frac{volts \times amps \times 1.732 \; x \; pf \; \times hours \times energy \text{ cost}}{1000} = annual \; energy \text{ cost}$$

Where:

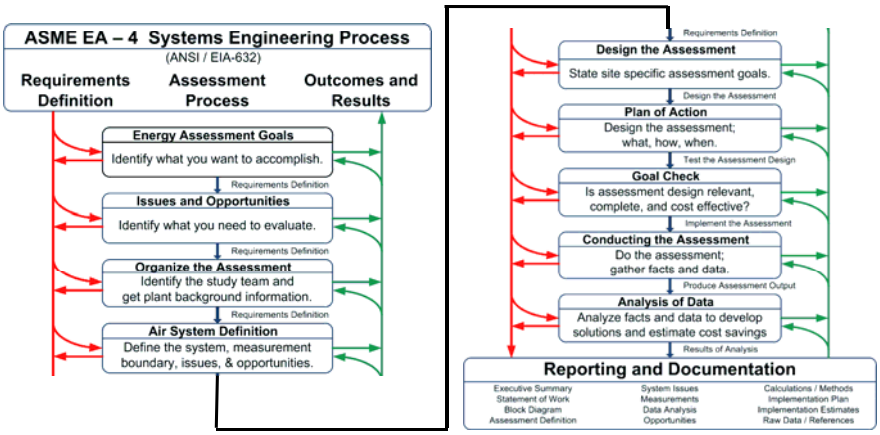
volts = average line to line 3 phase voltage
amps = full load amperage of the motor
1.732 = square root of 3 for phase to neutral voltage from line to line voltage
pf = power factor of the motor (0.80 to 0.85 typical)
hours = annual running hours
energy cost = $ / kWh
mtr eff = full load motor efficiency

8. Compressed Air System Assessment

- Systems Engineering Process
  - Establish requirements definitions
  - Evaluate assessment process
  - Evaluate outcomes and results

(see chart in the workbook Figure 4 – 8.1)

8. Compressed Air System Assessment



8. Compressed Air System Assessment

- Common goals in all compressed air system assessments:
  - Baseline airflow and energy use
  - Capture system pressure trends during baseline period
  - Establish pressure profile through system to key applications
  - Characterize system performance and operation of poor performing end use applications that cause productions issues
  - Identify waste and inappropriate use and evaluate alternatives
  - Understand system dynamics and measures to create balance between supply and demand
  - Implement control strategy to maintain balance.

8. Compressed Air System Assessment

- **Reality is**, the supply of compressed air does not drive system performance or cost. If you never take any air out of a system, performance would be stable and cost would be minimal. The determination of both performance, and cost is how the compressed air gets out of the system, not how it gets in.

8. Compressed Air System Assessment

- Issues and Opportunities –
- Organize the Assessment –
- Air System Definition –
- Design the Assessment –

8. Compressed Air System Assessment

- **The table below is an example of how various measurement points should be identified.**

Measurement	ID	Description
Test Flow	TF1	Air flow in 6” header leaving the Compressor Room
Test Pressure	TP1	Air pressure in 6” header leaving the Compressor Room
Test Dew Point	TD1	Air pressure dew point in 6” header leaving the Compressor Room
Test Amperage	TA1	Compressor #1 Package Amperage taken at Disconnect Box
Test Power kW	TK1	Compressor #1 Package Power taken in the Compressor Panel

8. Compressed Air System Assessment

- Goal Check – review and compare plan to original assessment goals for:
  - Relevance
  - Completeness
  - Timeliness
  - Simplicity
  - Cost effectiveness
  - Repeatability
  - Accuracy

8. Compressed Air System Assessment

- Analysis of Data –
  - Is it reasonable and correct?
  - Consistent with established assessment goals?
  - Create various profiles
  - Estimate energy savings
  - Suggest multiple measures to improve reliability and produce sustainable savings

8. Compressed Air System Assessment

- Reporting and documentation
  - Executive summary
  - Detailed report
  - Appendices
  - Attachments
  - Data files

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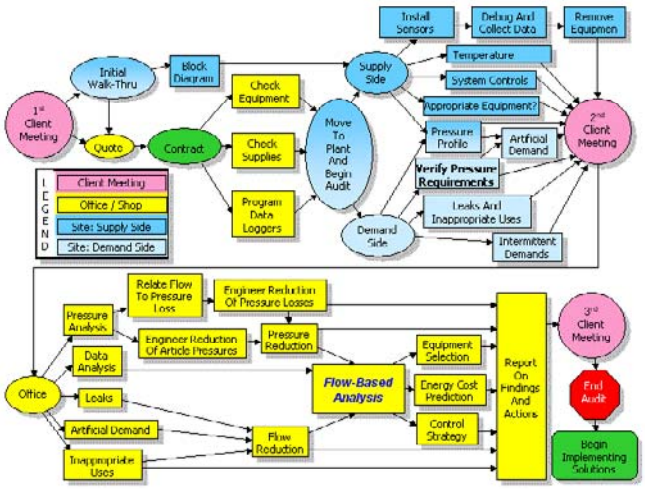
8. Compressed Air System Assessment

- Common Assessment Mistakes
  - An air compressor power study is not an air system assessment
  - An air system assessment designed to prove a point usually will
  - Controlling leaks is not controlling the system
  - Drawing the distribution piping does not define performance.


Install Sensors
Debug And Collect Data
Remove Equipmen
Temperature
System Controls
Appropriate Equipment?
Supply Side
Block Diagram
Initial Walk-Thru
Check Equipment
1st Client Meeting
Quote
Contract
Check Supplies
Move To Plant And Begin Audit
Pressure Profile
Artificial Demand
2nd Client Meeting
Verify Pressure Requirements
Leaks And Inappropriate Uses
Program Data Loggers
Demand Side
Intermittent Demands
LEGEND
Client Meeting
Office / Shop
Site: Supply Side
Site: Demand Side
Relate Flow To Pressure Loss
Engineer Reduction Of Pressure Losses
Pressure Analysis
Engineer Reduction Of Article Pressures
Pressure Reduction
Equipment Selection
Data Analysis
Flow-Based Analysis
Energy Cost Prediction
Report On Findings And Actions
3rd Client Meeting
Office
Leaks
End Audit
Control Strategy
Artificial Demand
Flow Reduction
Inappropriate Uses
Begin Implementing Solutions

9. Data Collection & Analysis

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9. Data Collection & Analysis

- Data collection training will consists of several elements:
  - Defining the objectives & information goals
  - Connecting to the system
  - Sensors, transmitters and transducers
  - Data acquisition hardware and software
  - Measurement techniques
  - Analysis
  - Recommendations

9. Data Collection & Analysis

- Informational goals:
  - Demand profile
  - Pressure profile
  - High volume intermittent demand events
  - Perceived high pressure demands
  - Power consumption
  - Production levels

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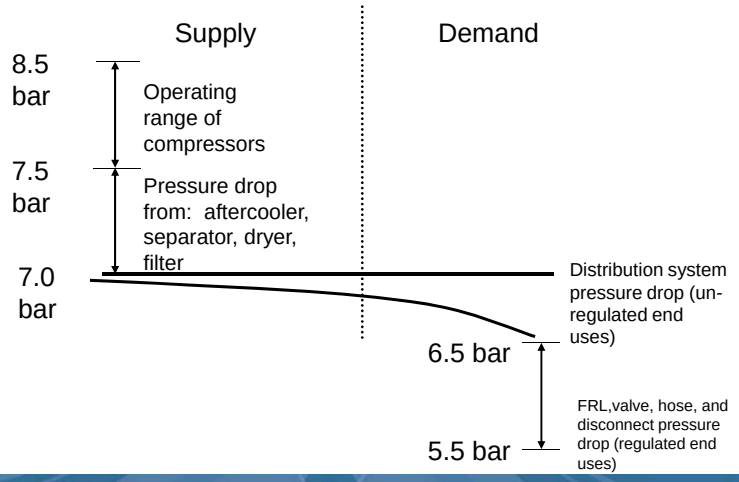
9. Data Collection & Analysis

- Collect demand data to establish the dynamics of the system.
- Identify events and their impact on the system.
- Identify cycle times and duration of these events.
- Identify periods of system draw-down.

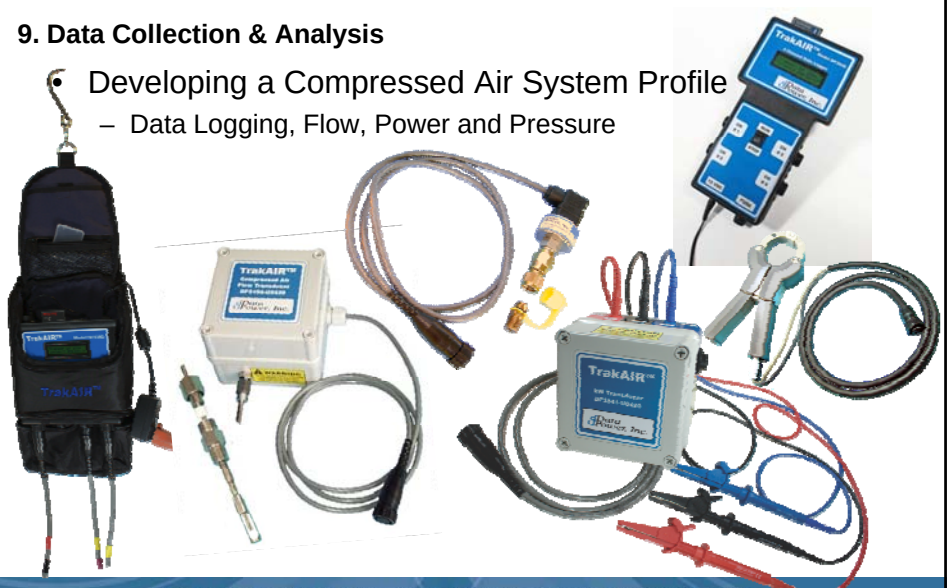
9. Data Collection & Analysis

System Pressure Profile (typical)



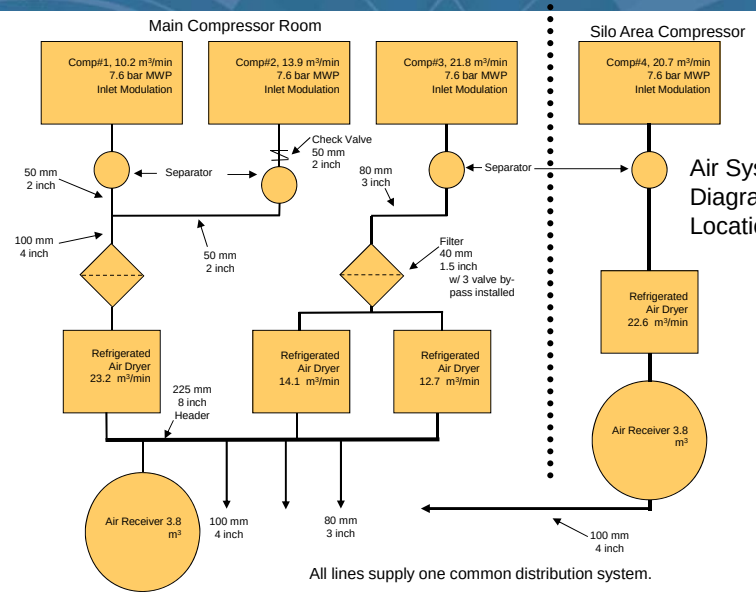
9. Data Collection & Analysis

- Developing a Compressed Air System Profile
  - Data Logging, Flow, Power and Pressure



9. Data Collection & Analysis

- Supply Side Operational Baseline
  - Energy Consumption of Compressors for Typical Operating Days
  - Airflow, Average Demand, Peak Demand
  - Pressure, Part Load Compressor Response

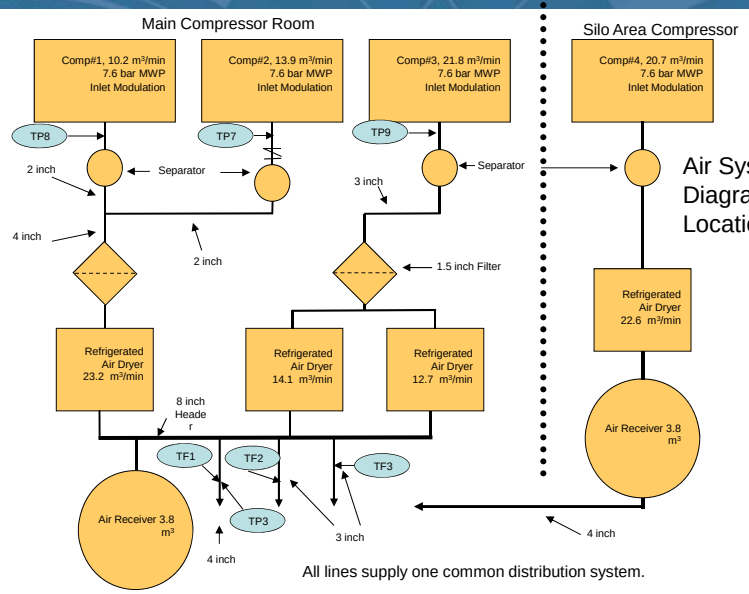


Air System Block Diagram with Test Locations

All lines supply one common distribution system.

9. Data Collection & Analysis

- Pressure & Flow Dynamic Profiles
  - Identify Characteristic Signatures
  - Characterize Drawdown Rates, magnitude and duration of events
  - Quantify Transient Supply Deficits, evaluate benefits of increased storage
  - Correlate Known Demand Events with demand side performance upsets and supply side control response

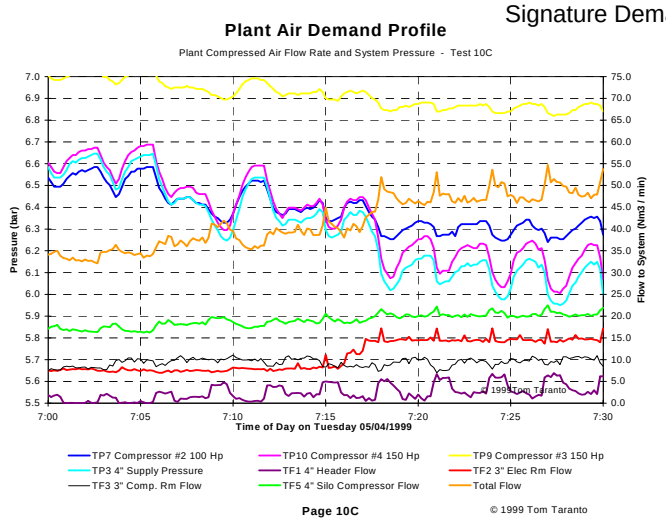


Air System Block Diagram with Test Locations

All lines supply one common distribution system.

9. Data Collection & Analysis

Demand Profile & Characteristic Signature Demand Events



Page 10C

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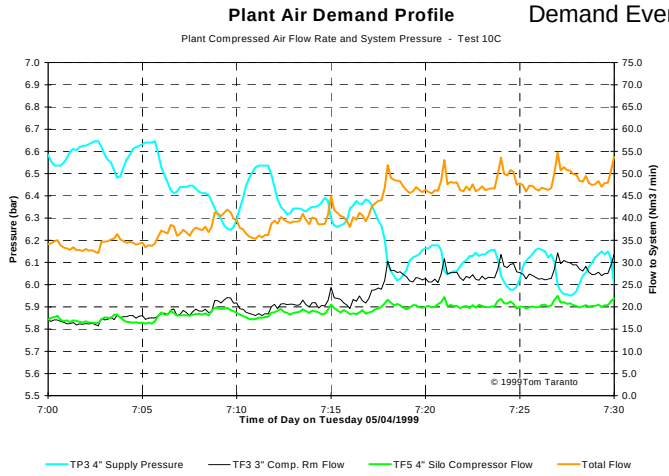
9. Data Collection & Analysis

Supply Side Response to the Demand Events



Page 10C

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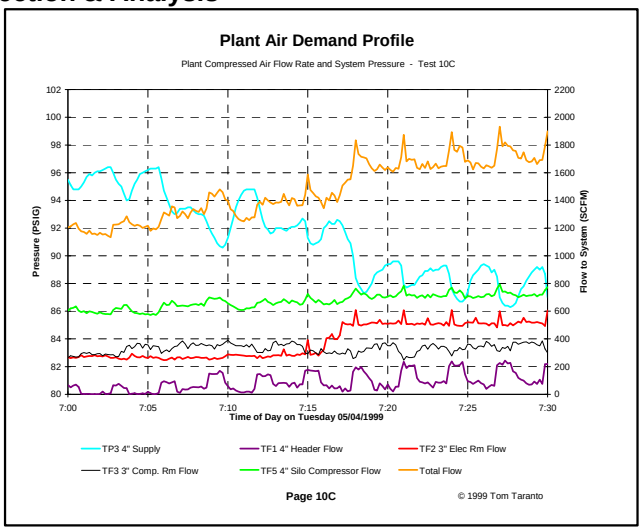
9. Data Collection & Analysis



9. Data Collection & Analysis

- Key Points
  - Compressed air energy is a significant investment including capital, energy, maintenance, and productivity costs.
  - In today's highly competitive global economy, timely compressed air system management information is essential.
  - Multiple compressor systems can be very inefficient if not properly controlled.
  - Compressed air demand and pressure profile data can help identify potential areas for improvement.

9. Data Collection & Analysis

- Key Points
  - Compressed air system assessment defines performance and current method operating costs.
  - Balancing system operation provides stable performance and reduces energy cost.
  - Inappropriate compressed air demands must be identified and replaced with more energy efficient alternatives.
  - Leak management, correctly sized distribution piping, and good point of use piping practice improves air application performance.

9. Data Collection & Analysis

- Key Points
  - Reducing system operating pressure to the lowest optimum pressure necessary to supply productive air demands, will reduce energy cost.
  - Training and education must raise awareness of compressed air cost, opportunities to lower air pressure, and improve system performance.
  - Monitoring compressed air system performance provides necessary management information to keep the air system operating efficiently, and reliably.

9. Data Collection & Analysis

- Data Acquisition sample rate, data averaging, and data storage interval
  - Analysis of compressed air system performance is only as good as the data that the analysis is based on.
  - What is worse than having no information about system performance?

9. Data Collection & Analysis

- What is worse than having no information about system performance?
- **Having bad information about system performance.**
- Many factors impact the accuracy of measured performance data.
  - Sample Rate
  - Data Interval
  - Accuracy
  - Repeatability
  - Electrical signals
  - Interference and errors
  - Equipment set –up
  - Scaling of engineering units

9. Data Collection & Analysis

Data Acquisition

Sample Rate – The time interval (in seconds) at which data inputs are read from the attached sensor or transducer.

Data Averaging – A data reduction method that reduces multiple samples to a single data point.

$$S_{AVG} = \left(S_1 + S_2 + \ldots S_n\right) / n$$

Data Interval – The frequency with which an averaged sensor reading is recorded as a measured data point.

$$Data\ Interval = T \times n$$

9. Data Collection & Analysis

Hourly Trend Data – Hourly trend data can be used to develop the profile of compressor power, or flow data to calculate operating cost. Trend data will not, however, define dynamic performance.

	Method #1	**Method #2**
Sample Rate	T = 5 minutes	T = 1 second
Samples to Average	n = 12 samples	n = 3600 samples
Data Interval	60 minutes (1 hour)	3600 seconds (1 hour)

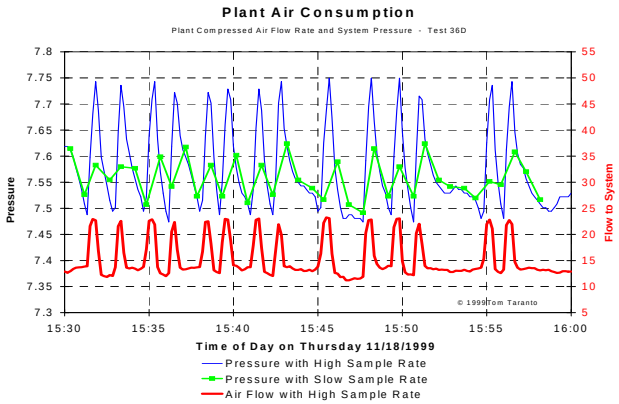
9. Data Collection & Analysis

Dynamic Response – When system events are of short duration, the data interval must decrease to properly characterize performance.

	High Rate	Slow Rate
Sample Rate	1 sample per 1 second	1 sample per 3 seconds
Data Averaging	10 samples	15 samples
Data Interval	10 seconds	45 seconds

9. Data Collection & Analysis

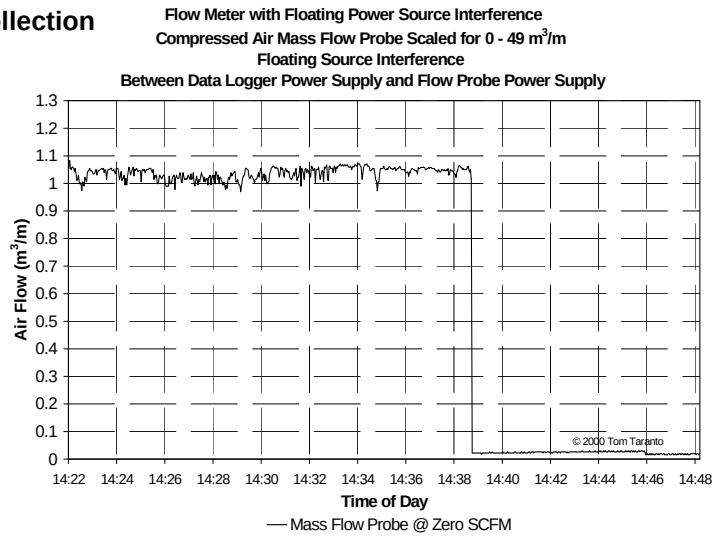
Data shown for the high sample rate is reading pressure once per second and averaging 10 samples. The low sample rate is reading pressure every 3 seconds and averaging 15 samples.



9. Data Collection & Analysis

- Selecting Sensors to Support Informational Goals and the Measurement Plan
  - Physical parameters to be measured
    - pressure, power, energy, airflow, and others.
  - Sensor detects a physical parameter
    - Mechanical movement sensed by a strain gauge & output is changing resistance
  - Transmitter electrical resistance is modified to a output signal for example 4-20 ma
  - Sensor + Transmitter = Transducer

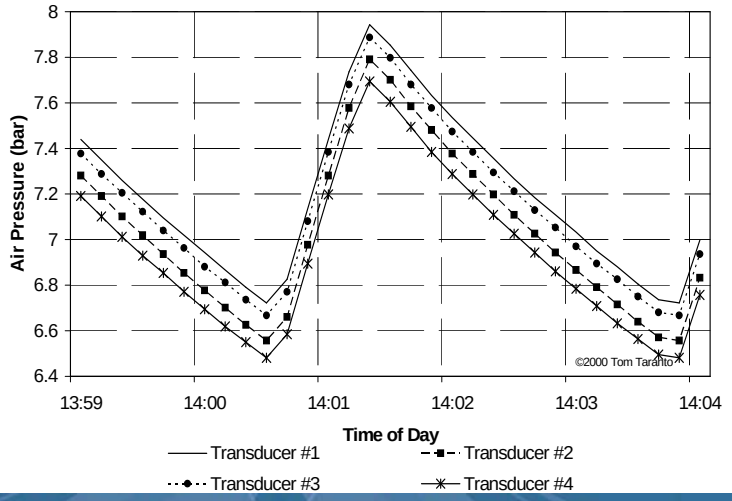
9. Data Collection



9. Data Collection

Pressure Transducer Comparison

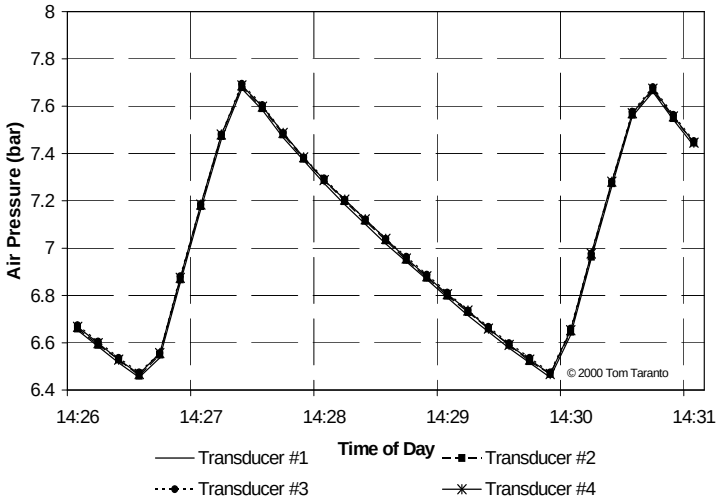
Four General Purpose 0 - 14 bar Pressure Transducers Connected to a Common Pressure Signal



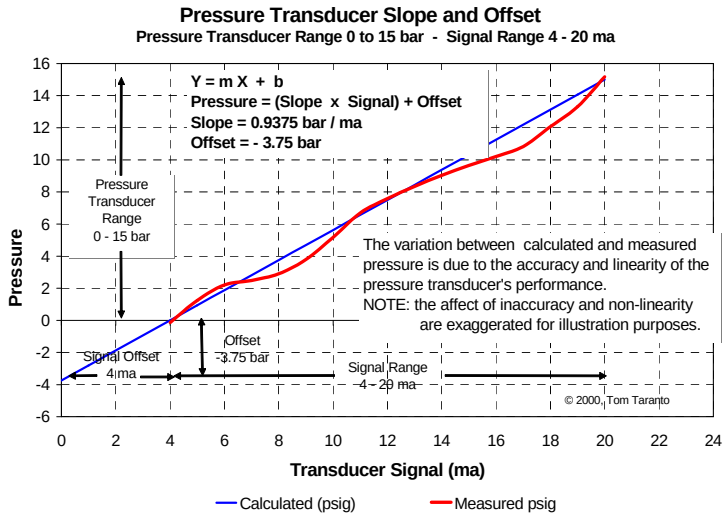
9. Data Collection

Pressure Transducer Comparison

Four High Accuracy 0 - 14 bar Pressure Transducers Connected to a Common Pressure Signal



9. Data Collection & Analysis



9. Data Collection & Analysis

- Key Points
  - Measurement system accuracy depends on human factors; connections to the system, transducers; wiring, cables, electrical connections; data acquisition hardware and software; along with measurement techniques.
  - Sample rate, data averaging, and data intervals depend on system characteristics.
  - Use appropriate sensors, transducers, and measurement system accuracy.
  - Transducers output various signals in proportion to the physical parameter being measured.
  - Signals must be properly scaled to correctly record the measurement.