1. Introduction to Compressed Air Systems

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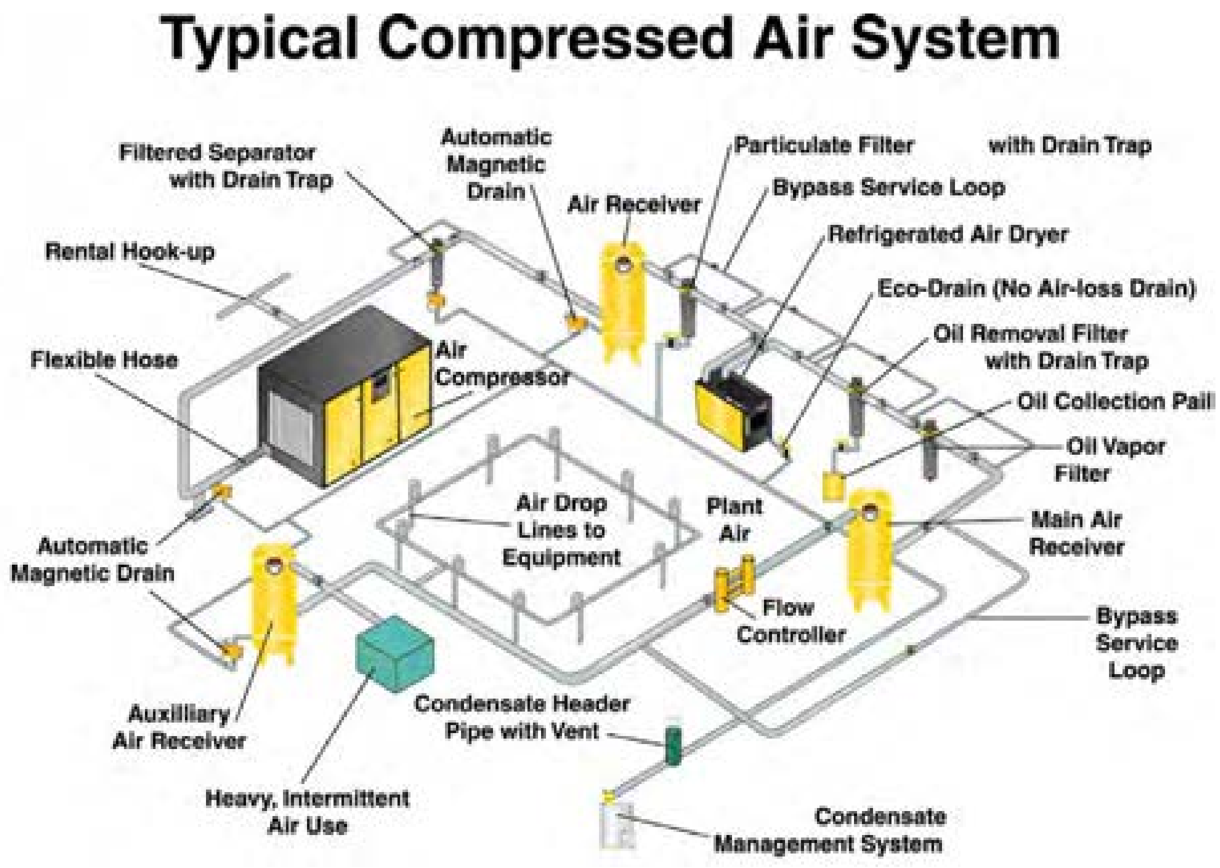
- **Compressed air has 3 primary uses**
  - **Power**
    - **As an energy source to perform work**
  - **Process**
    - **Air becomes part of a process**
  - **Control**
    - **To stop, start or regulate the operation of a machine**

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

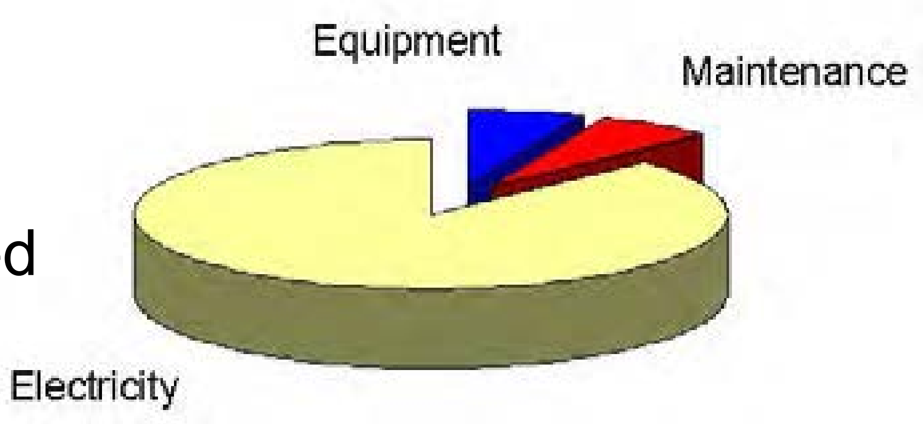
- **Old Management Technique**
  - **Plant production is #1 priority**
  - **Plant compressed air system must always be maintained**
  - **Over supply of compressed air is acceptable, under supply is not acceptable**
  - **Minimum pressure must be maintained. Higher pressure is acceptable**
- **New Management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

Systems Approach

- Understand compressed air use as it supports critical plant production functions.
- Correct existing poor performing applications, and those that cause upset to system operation.
- Eliminate wasteful practices.
- Maintain an energy balance between the compressed air supply and productive compressed air demands.
- Optimize energy efficiency with application of compressed air energy storage and air compressor control.

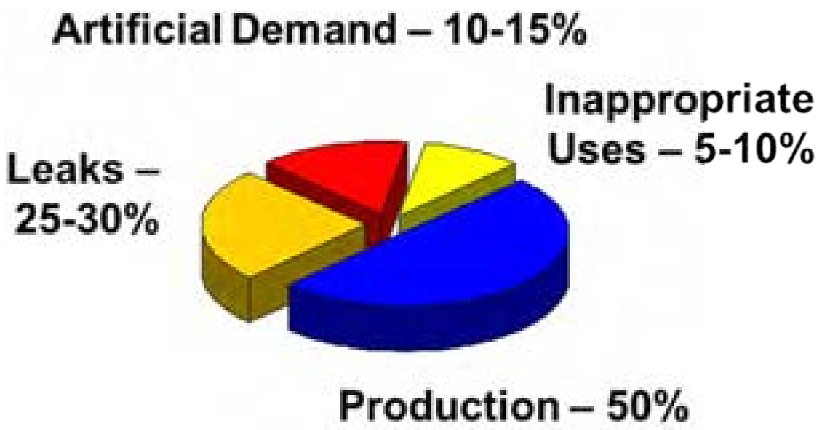
1. Introduction to Compressed Air Systems

- Equipment cost and maintenance cost represent only a small part of the total cost of operating a compressed air system.
- Electrical cost usually exceeds 75% of the total operating expense.

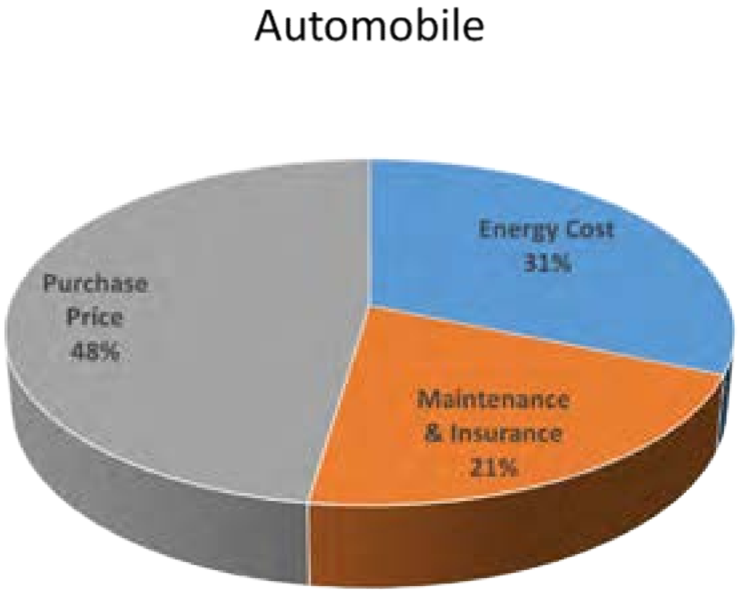


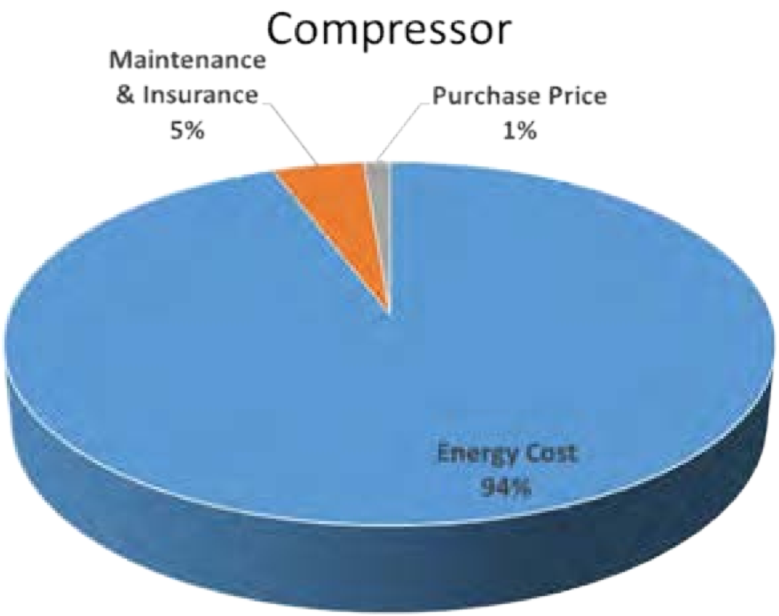
Identify & Eliminate Compressed Air Waste

- Of the total power used to generate compressed air, as little as 50% may actually be used for production.
- Leaks, artificial demand and inappropriate uses can use as much as 50% of the air supply.
- Identifying and reducing this waste will result in a significant drop in energy use.

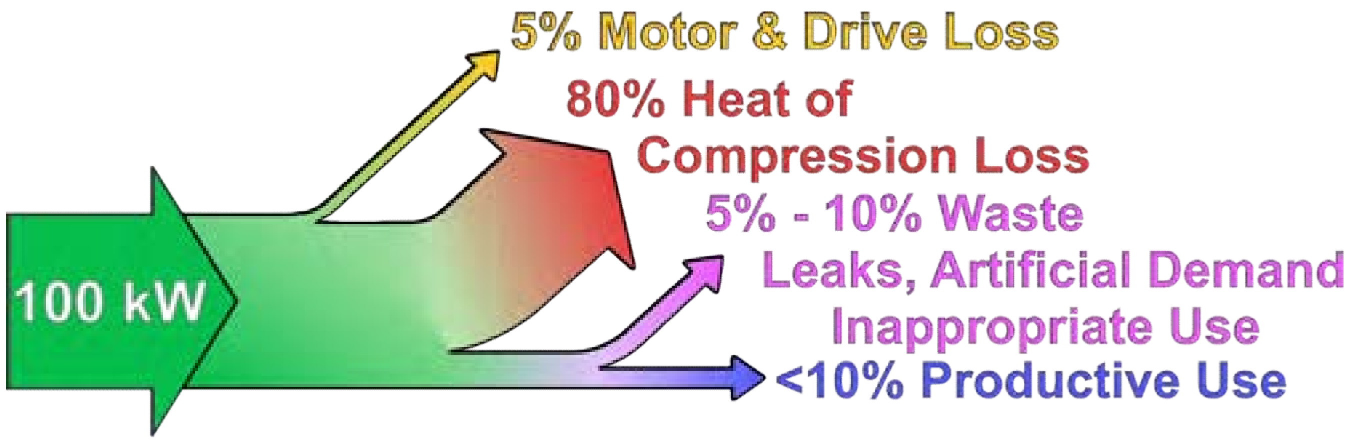


Compressed Air Economics – Reducing Life Cycle Costs



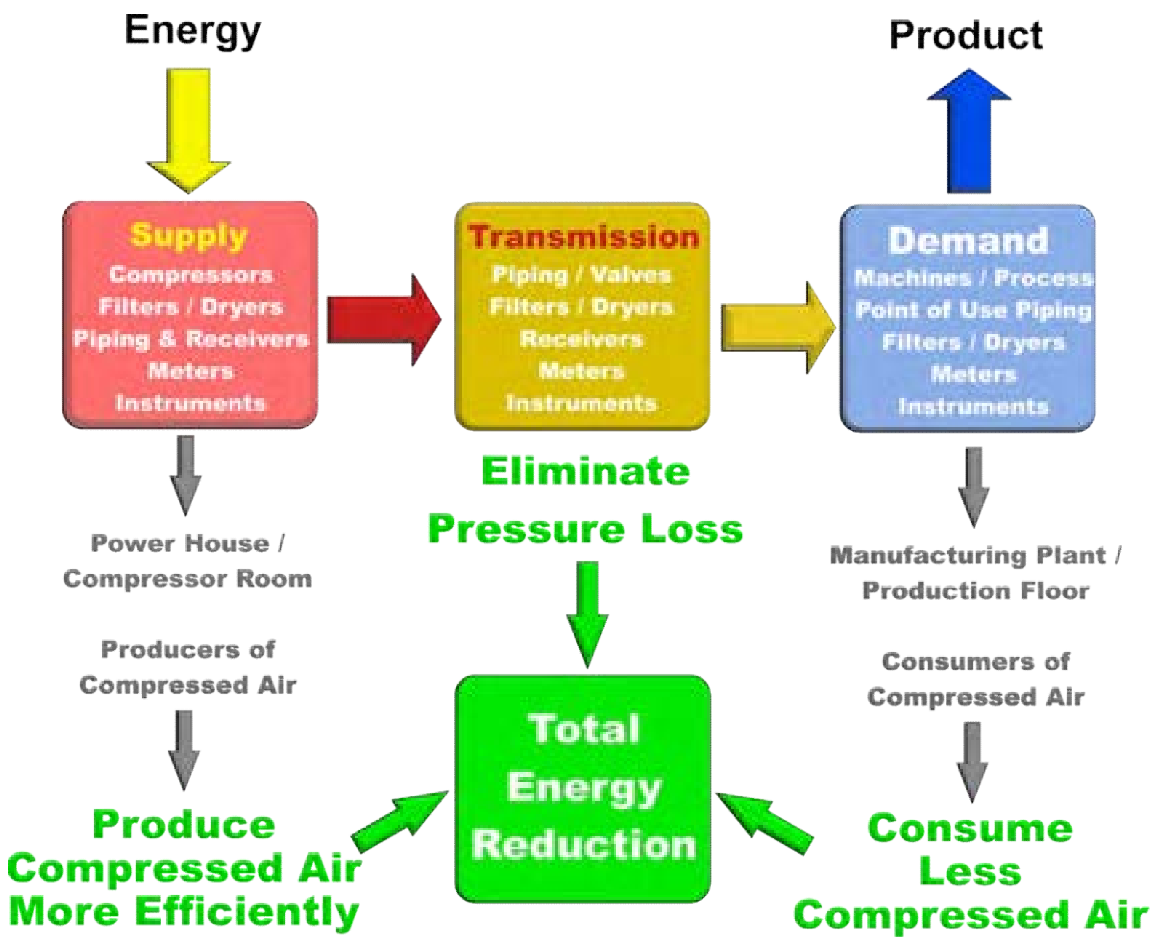


Compressed Air Energy Flow

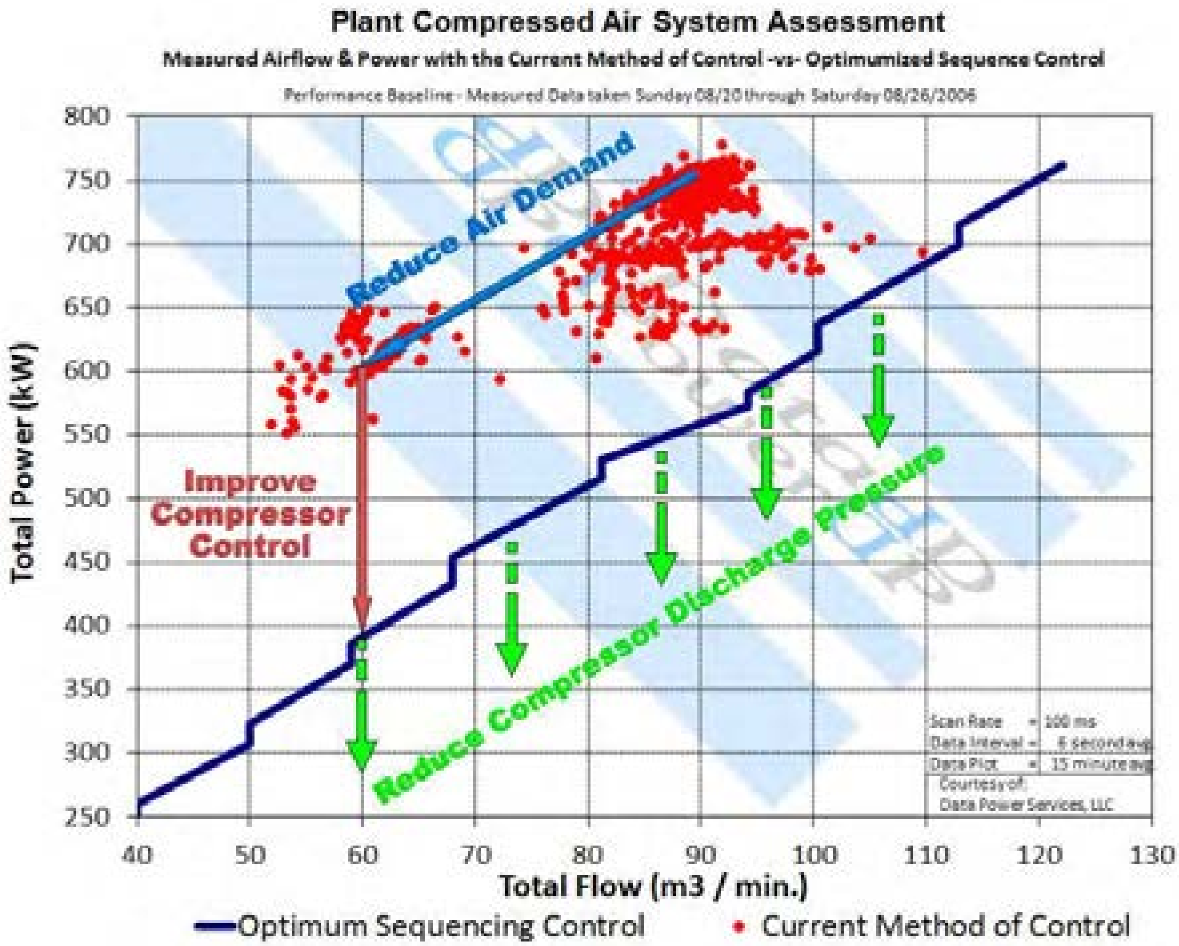


- Compressed air electrical energy conversion to pneumatic energy is very inefficient ~ 15%
- Typically 50% of the pneumatic energy is wasted
- The overall conversion efficiency < 10%

The Systems Approach and Reducing Energy Consumption



Optimizing Compressed Air System Efficiency



Business Case for Compressed Air System Management

- Why do factories have compressed air systems?

Business Case for Compressed Air System Management

- Why do factories have compressed air systems?
- To make a profit
  - Compressed air cost is frequently overlooked
  - If production is interrupted there is little concern for cost
- System reliability is the primary concern; Energy Efficiency and Cost are Secondary
- Using the Systems Approach, well managed systems are more reliable AND achieve energy savings.

Key Learning Points

1. Compressed air is a necessary utility for industrial plants.
2. When compressed air is integral to the production process, it is a process variable.
3. System management must focus on productivity (controlling cost) rather than traditional goals.
4. The Systems Approach is an integrated approach, not component efficiency.

Key Energy Points

5. Energy cost is over 75% of the total life cycle cost to own and operate a compressed air system.

6. Generating compressed air is an inefficient energy conversion.

7. Avoiding the compression of air provides the greatest energy savings. Eliminate compressed air waste.

8. Many systems waste 50% or more of the compressed air that is consumed.

9. Including waste most compressed air systems have overall efficiency of < 10%.

Key Energy Points

10. Three basic opportunities to save energy include:
    - Generate compressed air more efficiently
    - Minimize pressure loss in the system
    - Reduce compressed air demand

For more information:

Wayne Perry
Technical Director
Kaeser Compressors
P.O Box 946
Fredericksburg, VA 22404
USA
540 898 5500
wayne.perry@kaeser.com

Tom Taranto
President
Data Power Services
8417 Oswego Road PMB-236
Baldwinsville, NY 13027
USA
315 635 1895
tom@datapowerservices.com

2. Understanding Compressed Air

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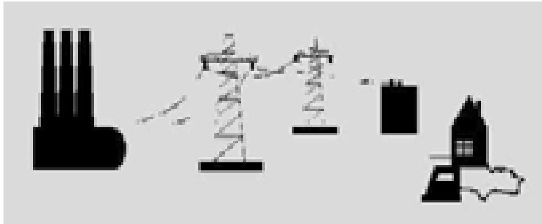
What is compressed air?

grid system user
Power station transformer



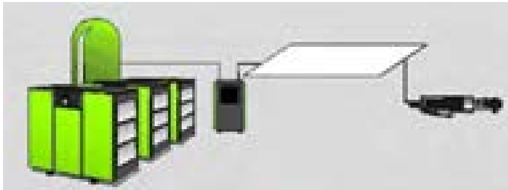
Compressed air is ...

... compressed atmospheric air

... a mixture of gases

... compressible

... an energy carrier



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

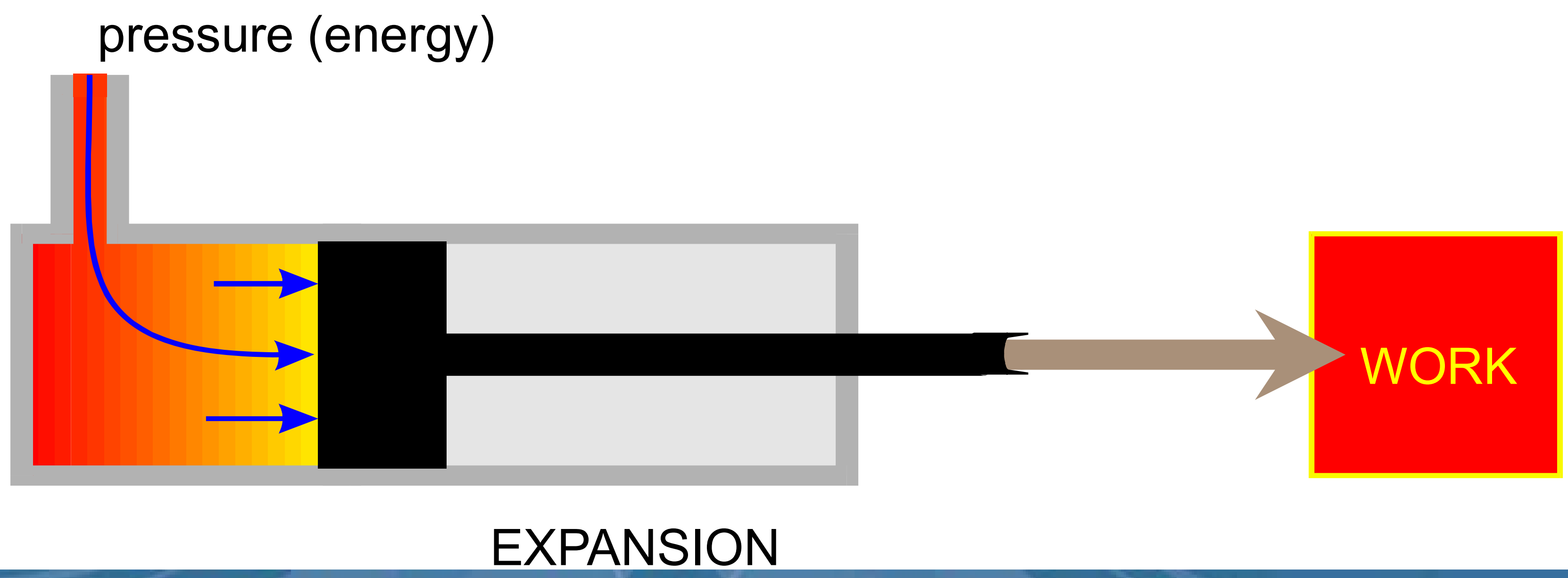
N = Newton	Pa = Pascal
bar = Bar	Ω = Ohm
J = Joule	W = Watt
C = Celsius	Hz = Hertz

2. Understanding Compressed Air

Physical laws

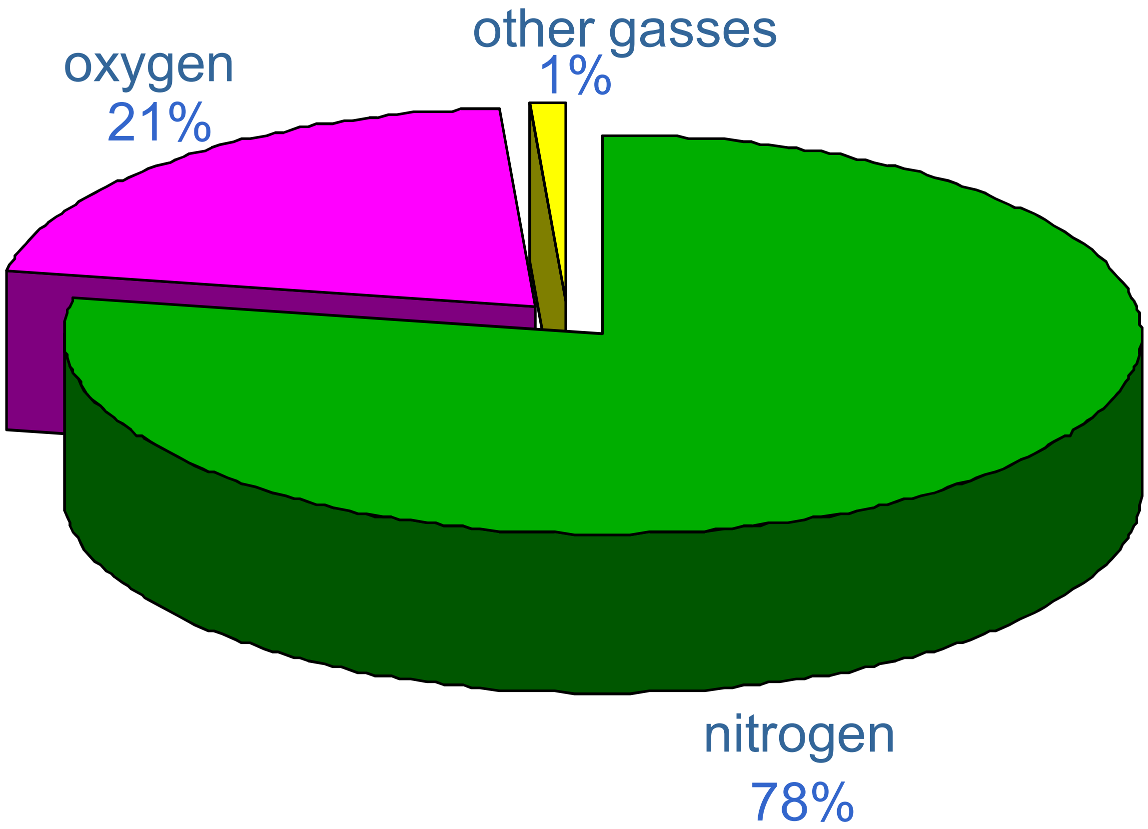
COMPRESSED AIR is atmospheric air under pressure.
That means energy is stored in the air.

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



2. Understanding Compressed Air

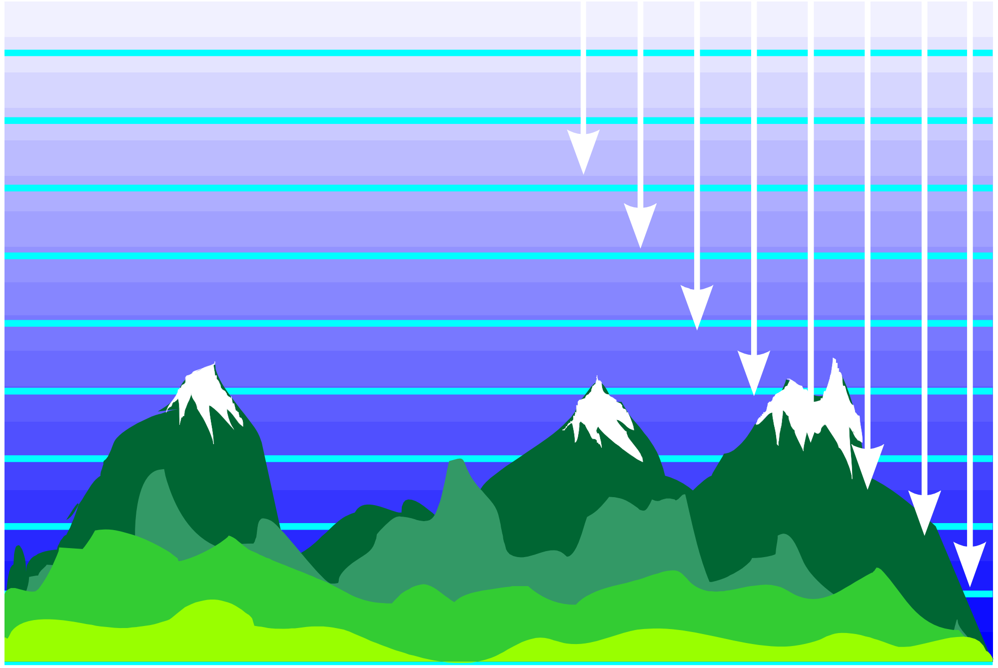
Components of air



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))

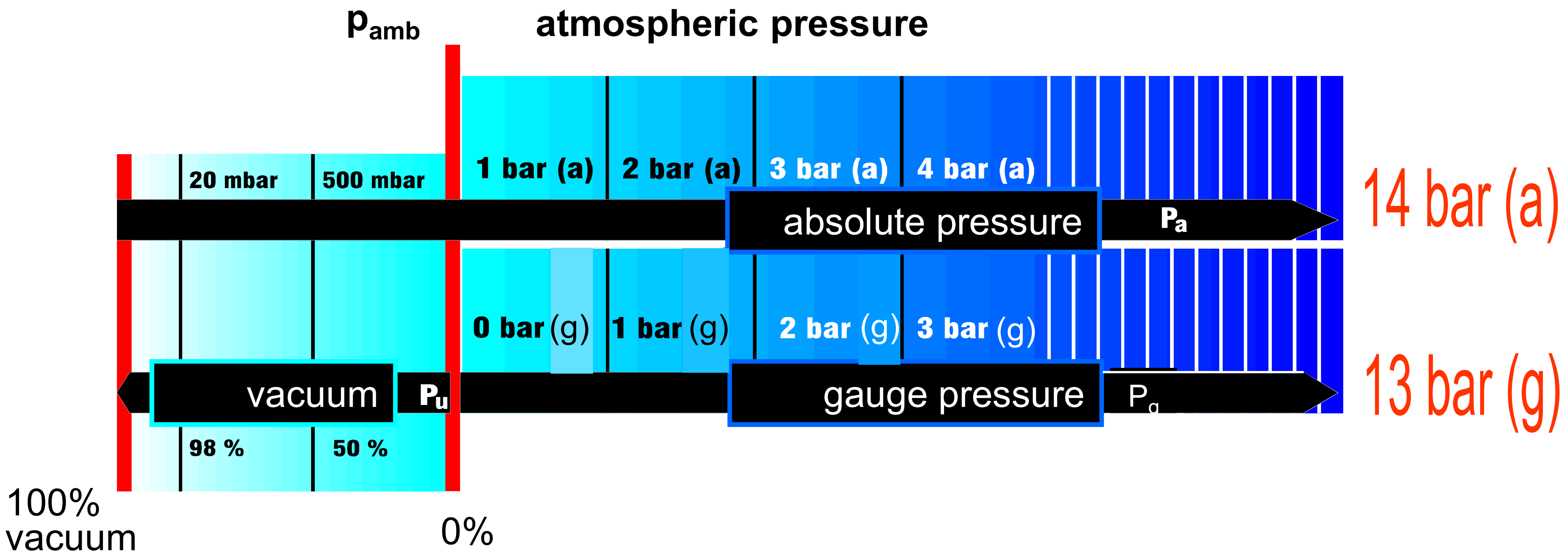
2. Understanding Compressed Air

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

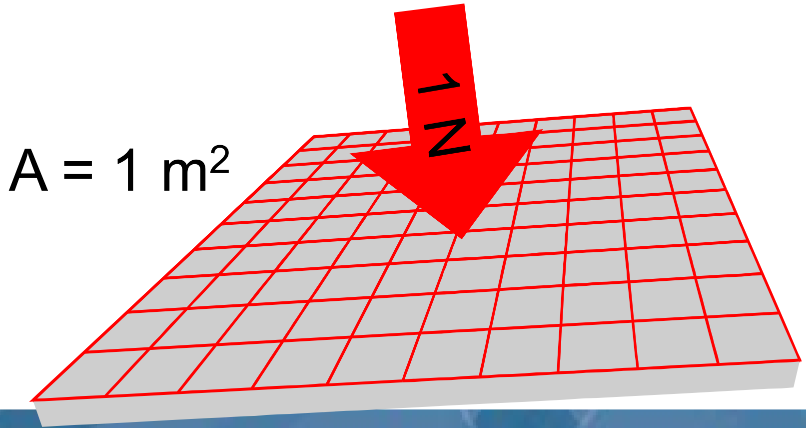
Generally:

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

Dimensions:

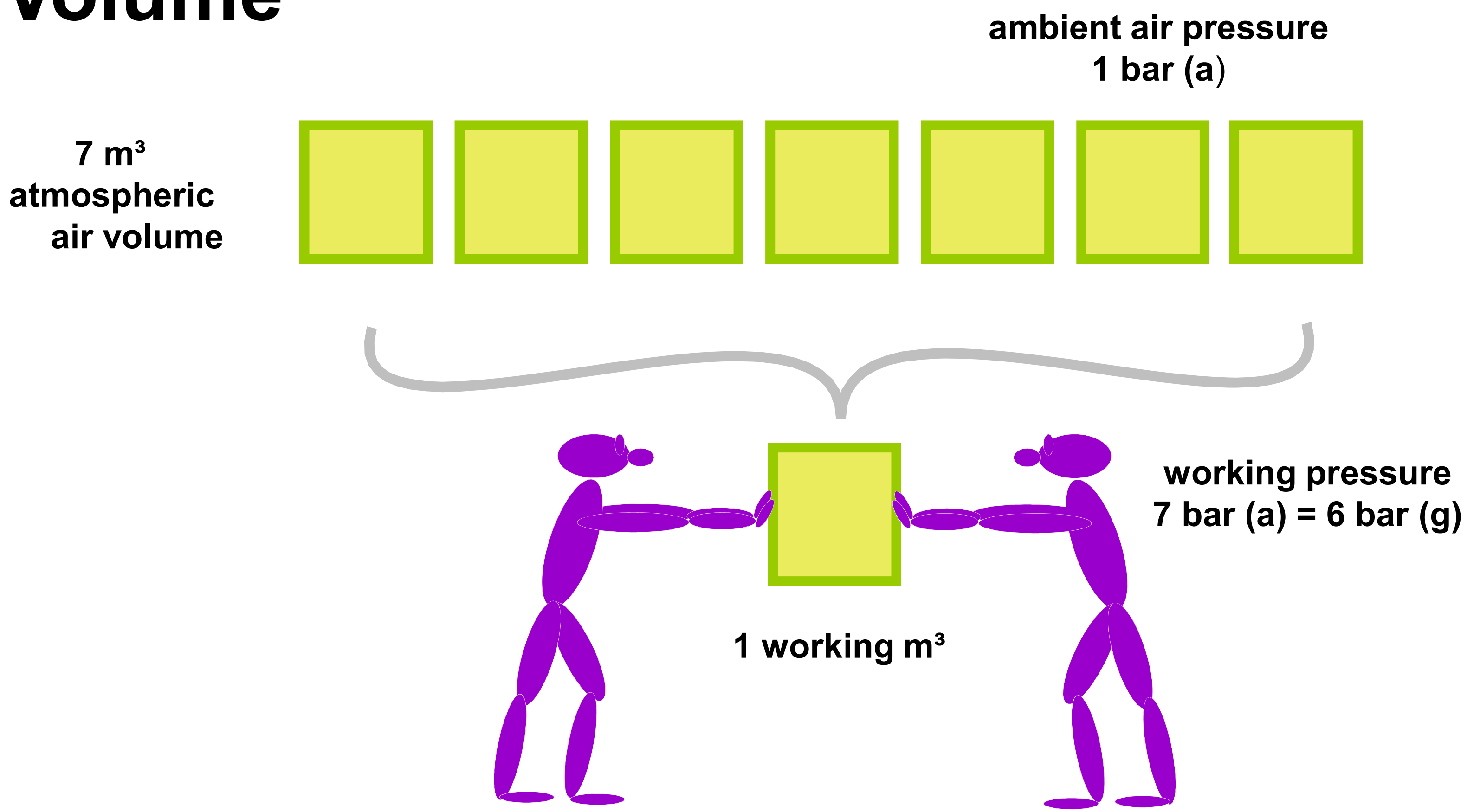
$$1 \text{ Pascal (Pa)} = \frac{1 \text{ Newton (N)}}{1 \text{ m}^2 \text{ (A)}}$$

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



2. Understanding Compressed Air

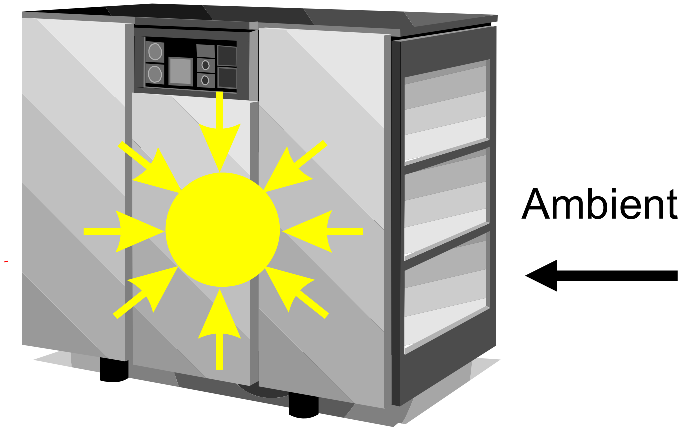
Volume



2. Understanding Compressed Air

Volume

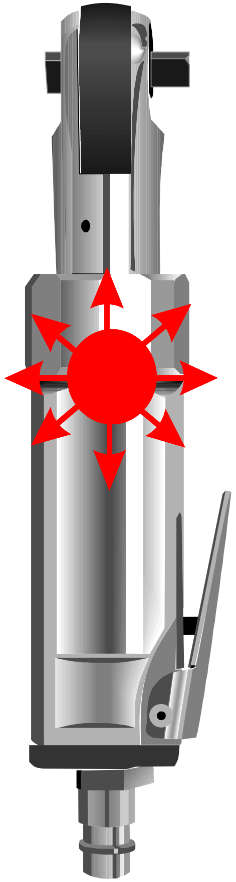
Working pressure p_1, V_1



Ambient air pressure p_0, V_0

Expansion:

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



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

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

FAD (Free Air Delivered) volume flow rate
FAD is the volume of air delivered at the discharge of an air compressor package. The volume flow rate is expressed at the prevailing ambient conditions of temperature, pressure, and relative humidity as they exist at the compressor intake.

Nm^3/min (Normal cubic meters / minute)
Normal cubic meters / minute (Nm^3/min) is a weight or mass flow rate measurement. Although Nm^3/min and m^3/min sound similar, they are as different as liters and kilograms. Nm^3/min refers to the weight (or mass) of air that occupies one cubic meter of space under a defined (normal or standard) condition of temperature, pressure and humidity conditions.

Volumetric and Mass Flow
Why two different measures?

- Compressor manufacturers use volumetric flow
- Mass flow is the actual measure of work done
- Why rate in volumetric terms?
- Mass flow depends on the air pressure, temperature and relative humidity
- Job site conditions determine the air's pressure temperature, and relative humidity

Sample Calculation
correcting volume rating to mass flow

- An old air compressor with 4 m3/min FAD rating is being replaced.
- The old compressor is operating a maximum capacity and barely keeps up with the present plant air demand.
- Two new production lines requiring 2.0 Nm3/min (DIN1343) are being added.
- The new compressor is rated for 8.26 m3/min FAD.
- Job site design condition is 600m elevation, 35 deg C, and 70% RH
- Can compressor capacity of 4.26 m3/min supply air demand of 4 Nm3/min (DIN 1343) at the job site design condition?

2. Understanding Compressed Air

Definition of volumes

	Temperature	Pressure	Relative humidity	Density
Volume according to **ISO 1217:2009**	20°C = 273.15K	1.0 bar	0%	1.188 kg/m³
Volume according to **DIN 1343**	0°C = 293.15K	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	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

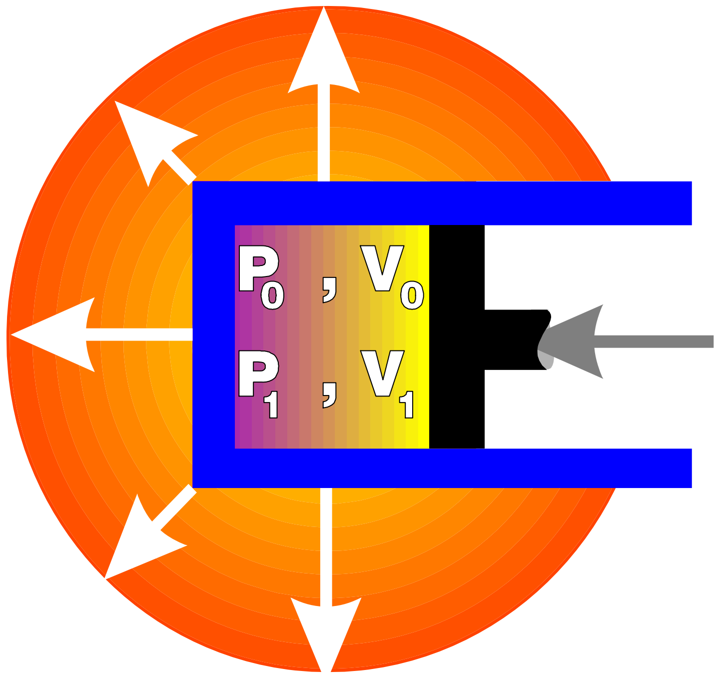
2. Understanding Compressed Air

Gas laws – Boyle's Law

Isotherms (constant temperature)

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

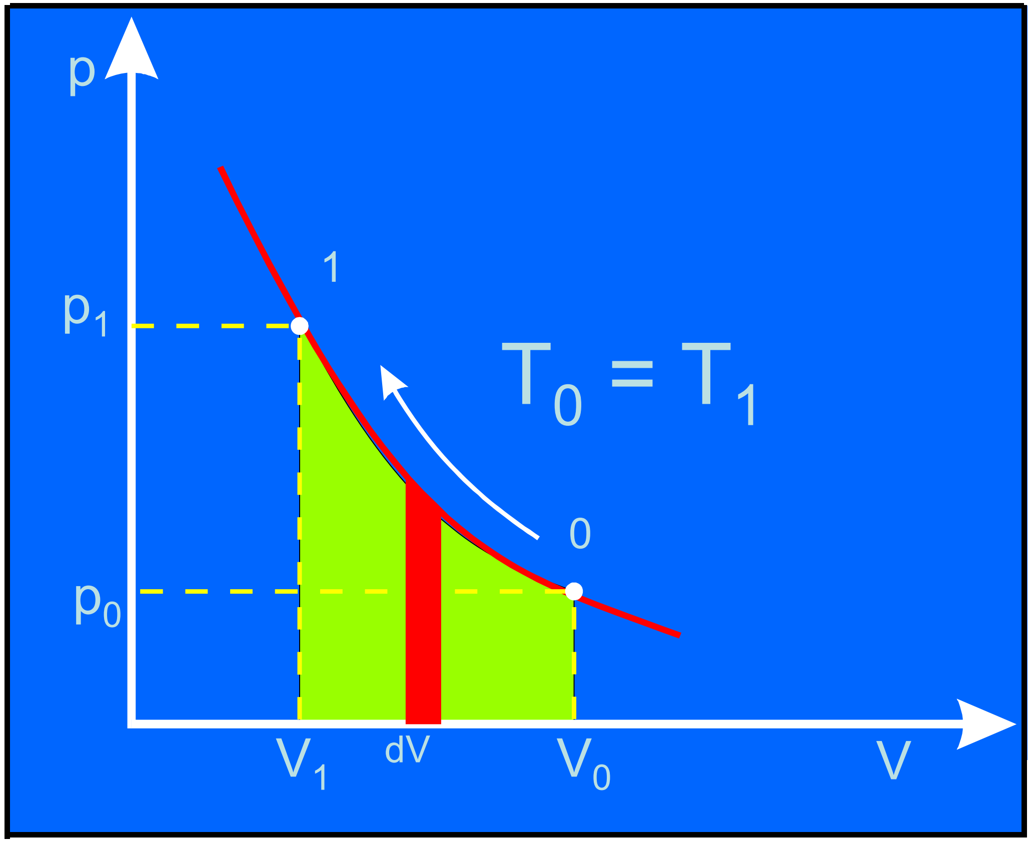
$$P_0 \times V_0 = P_1 \times V_1$$



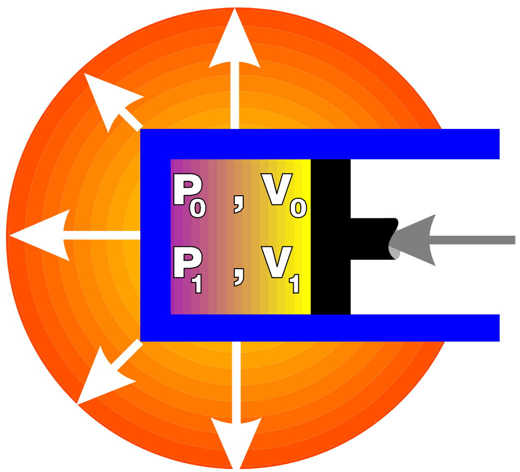
Heat dissipation

2. Understanding Compressed Air

Isotherms (constant temperature)



Heat dissipation



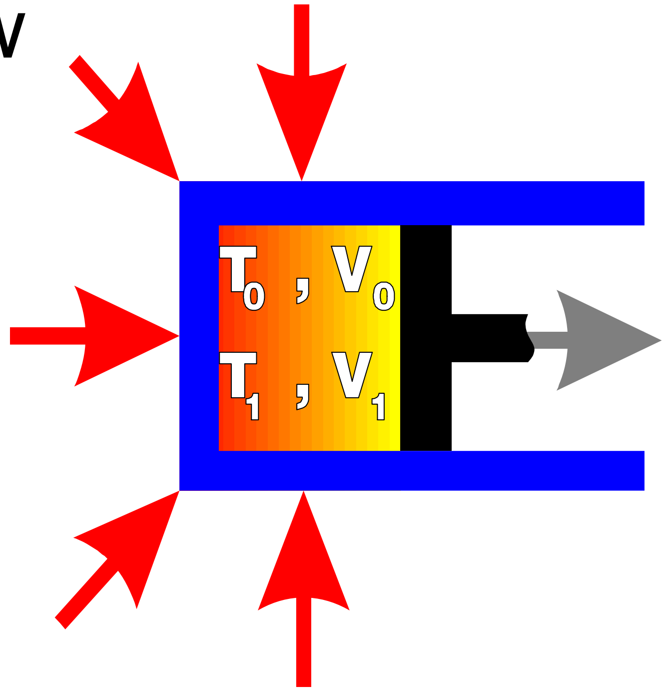
2. Understanding Compressed Air

Gas laws – Charles' Law

Isobars (constant pressure)

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

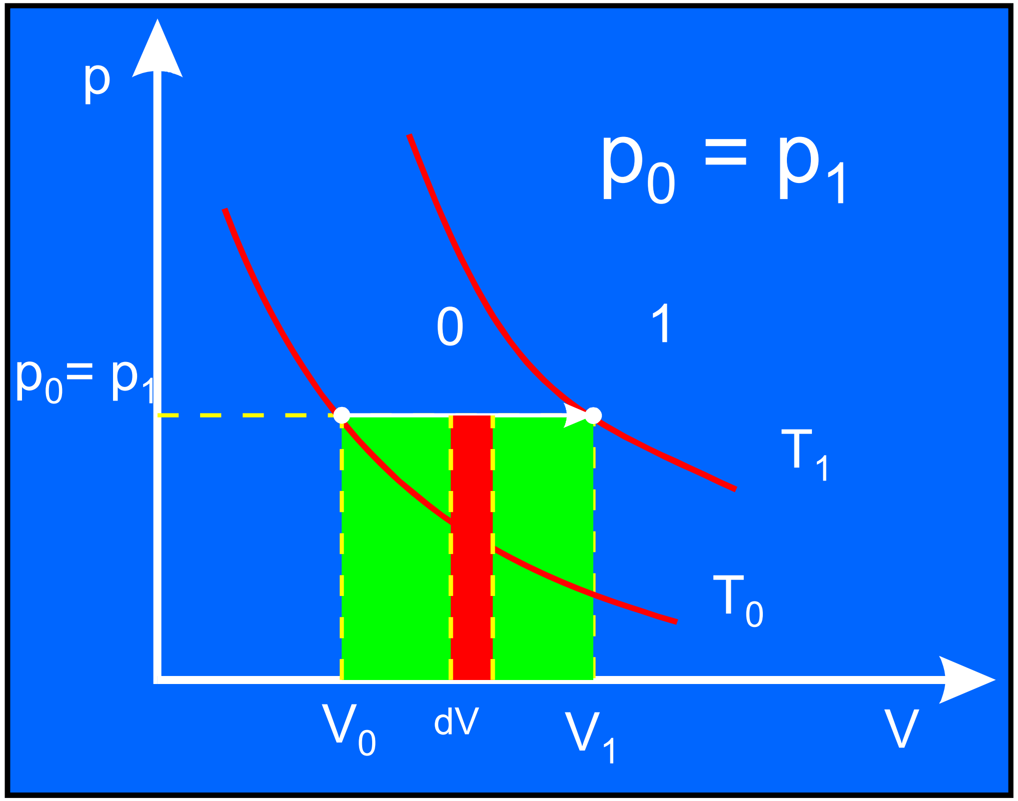
$$\frac{V_0}{V_1} = \frac{T_0}{T_1}$$



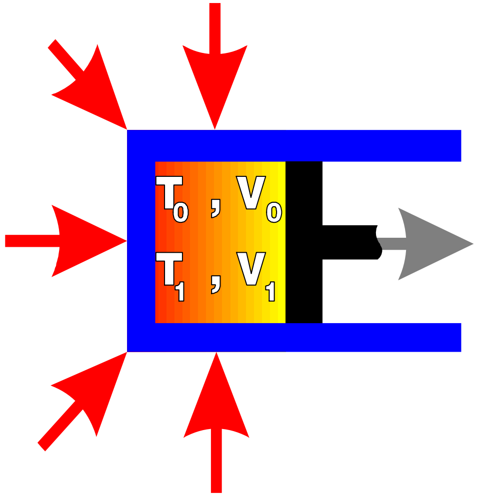
Application of heat

2. Understanding Compressed Air

Isobars (constant pressure)



Application of heat



2. Understanding Compressed Air

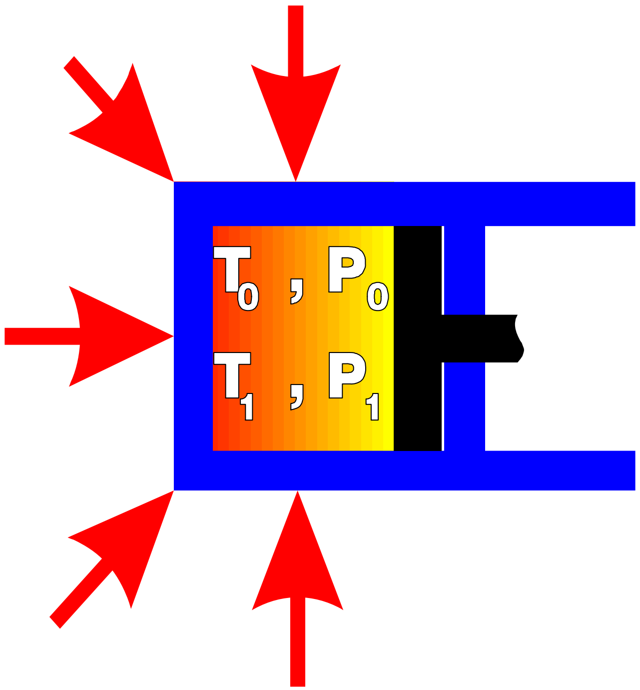
Gas laws – Amonton's Law

Isochors (constant volume)

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

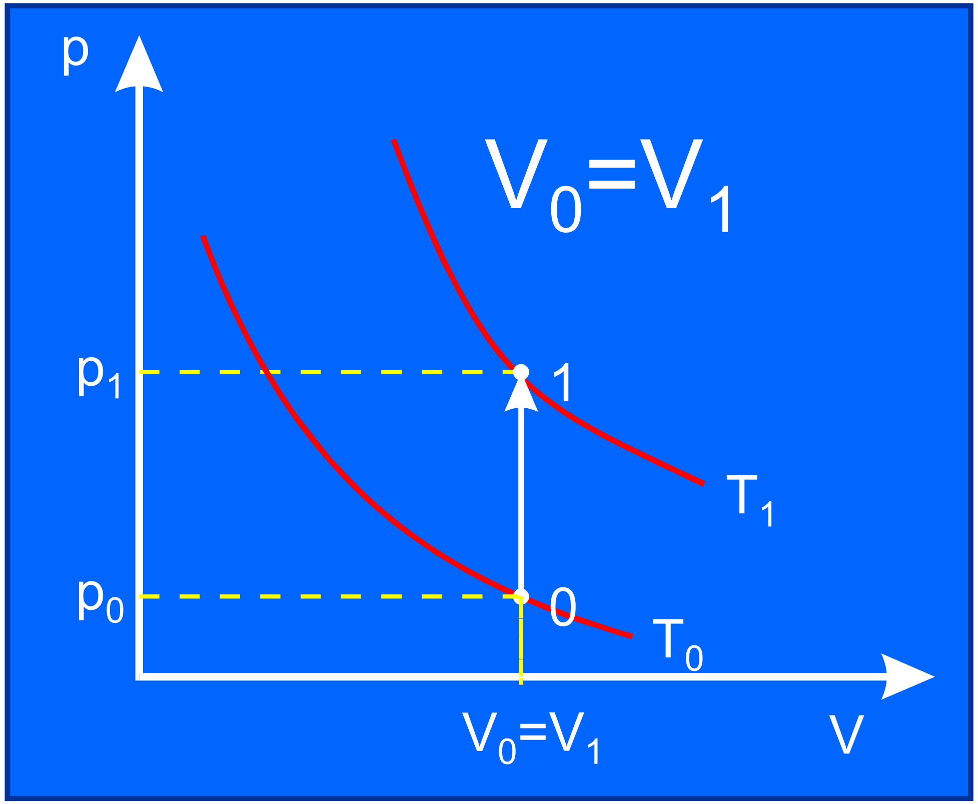
$$\frac{P_0}{P_1} = \frac{T_0}{T_1}$$

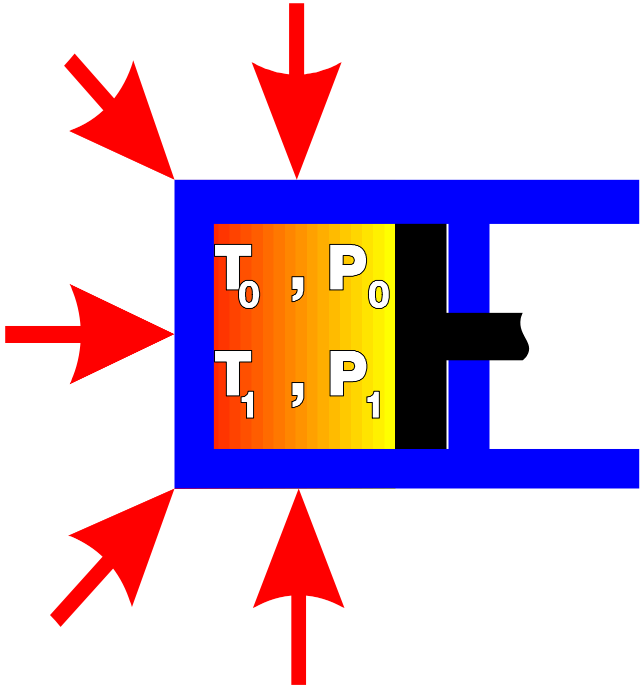
Application of heat



2. Understanding Compressed Air

Isochors (constant volume)





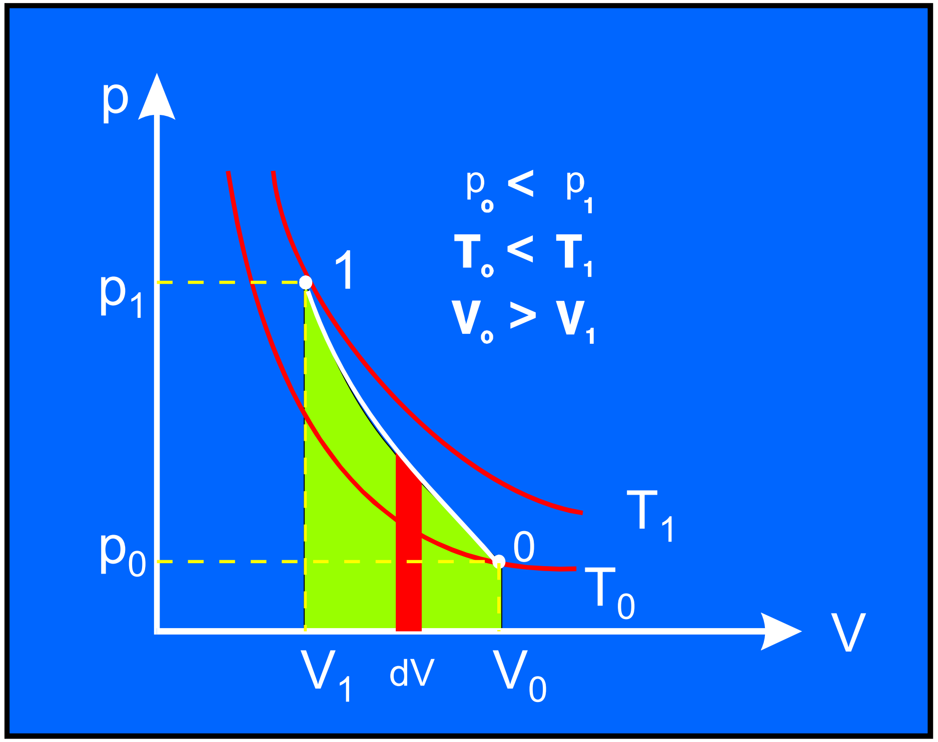
Application of heat

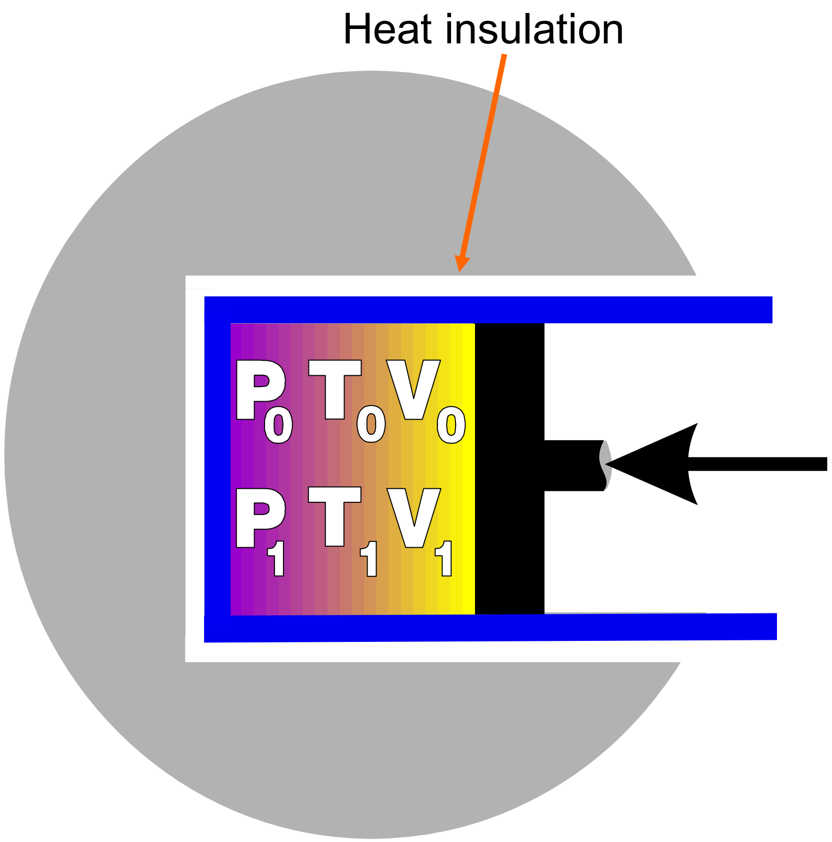
2. Understanding Compressed Air

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)

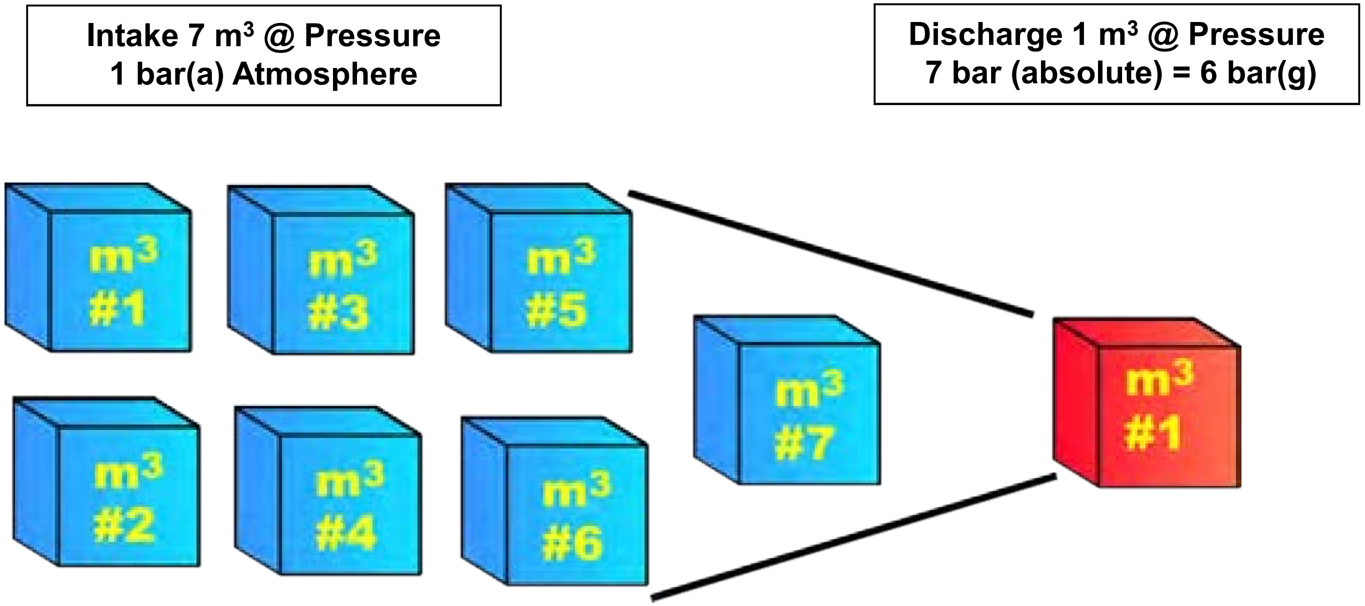
T = temperature (K)

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

Volumetric Flow Rate
Compression Ratio



Key Learning Points

1. Compressed air is a common method of transmitting energy to pneumatic tools and devices.

2. The work accomplished by compressed air is dependent on the weight of air delivered to the end use equipment.

3. The weight of air is dependent on the conditions of pressure, temperature, and relative humidity.

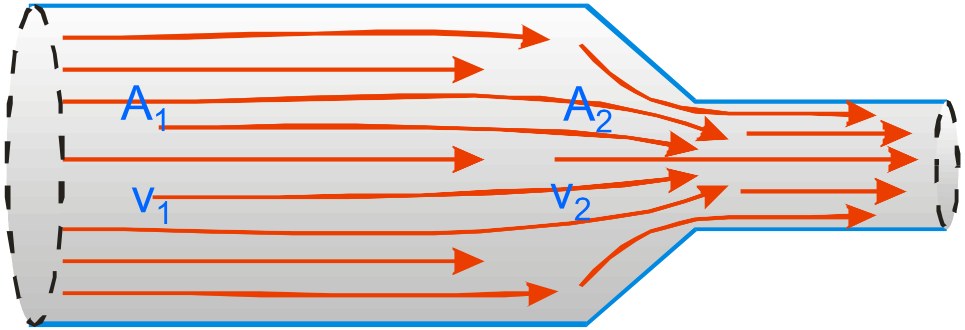
4. Pressure, volume, and temperature are interrelated, in this relationship air is treated as an ideal gas.

2. Understanding Compressed Air

Introduction to Pneumatic Energy Transmission

2. Understanding Compressed Air

Flow velocity in air lines



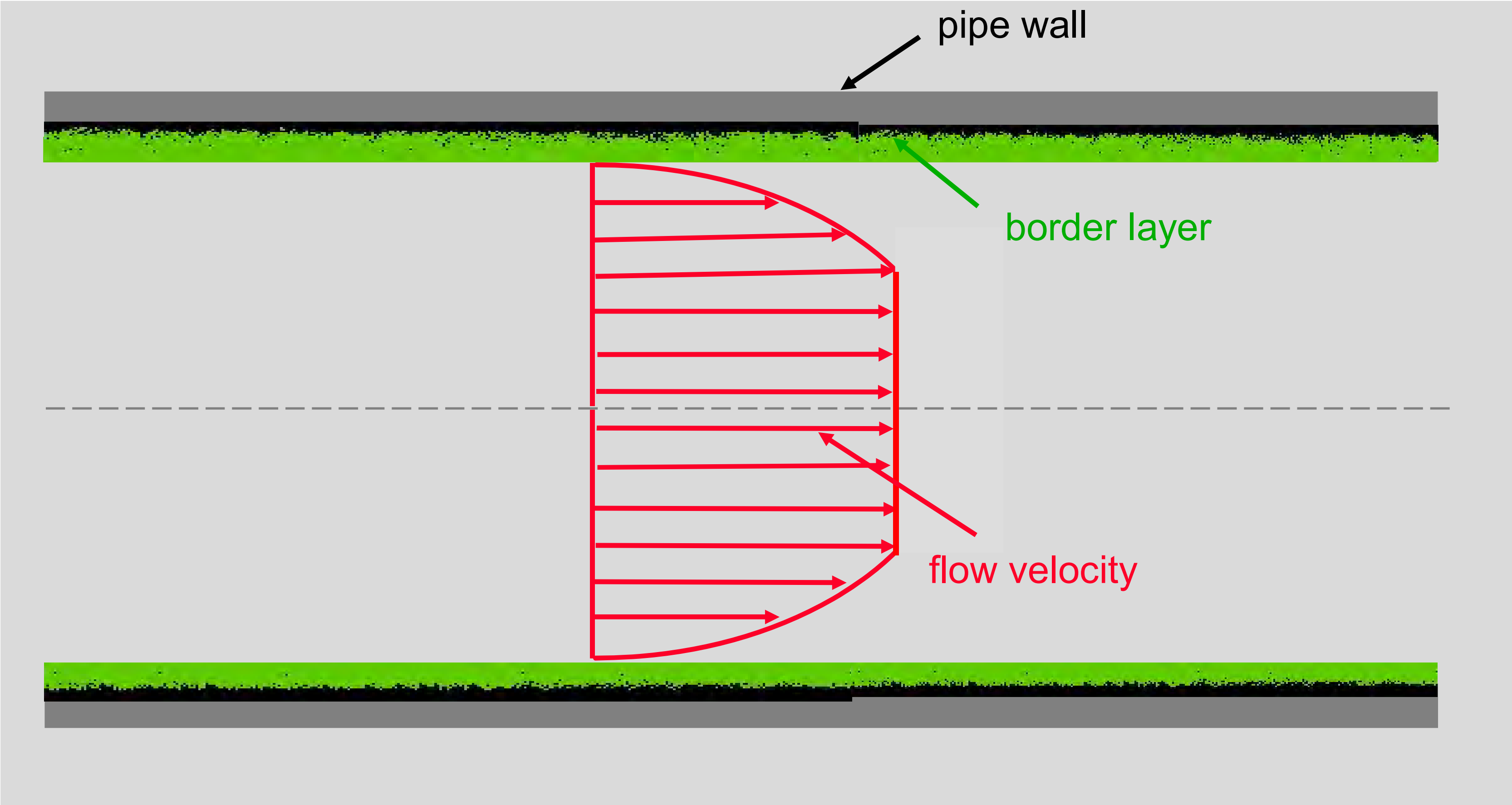
valid is:

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

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

2. Understanding Compressed Air

Flow profile

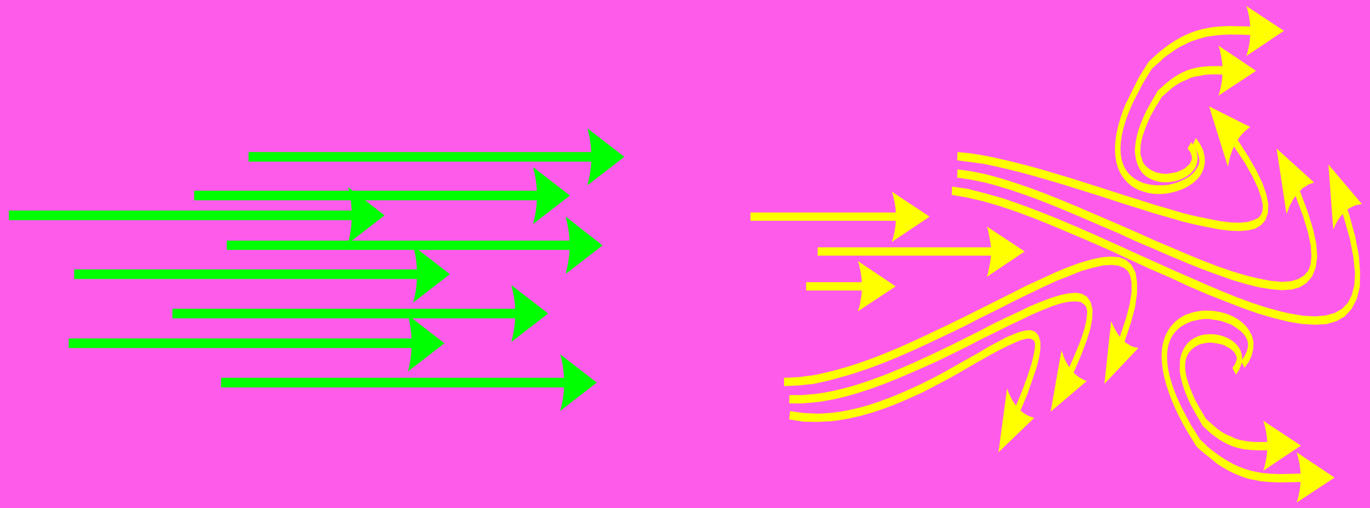


2. Understanding Compressed Air

Flow types

We differentiate between:

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



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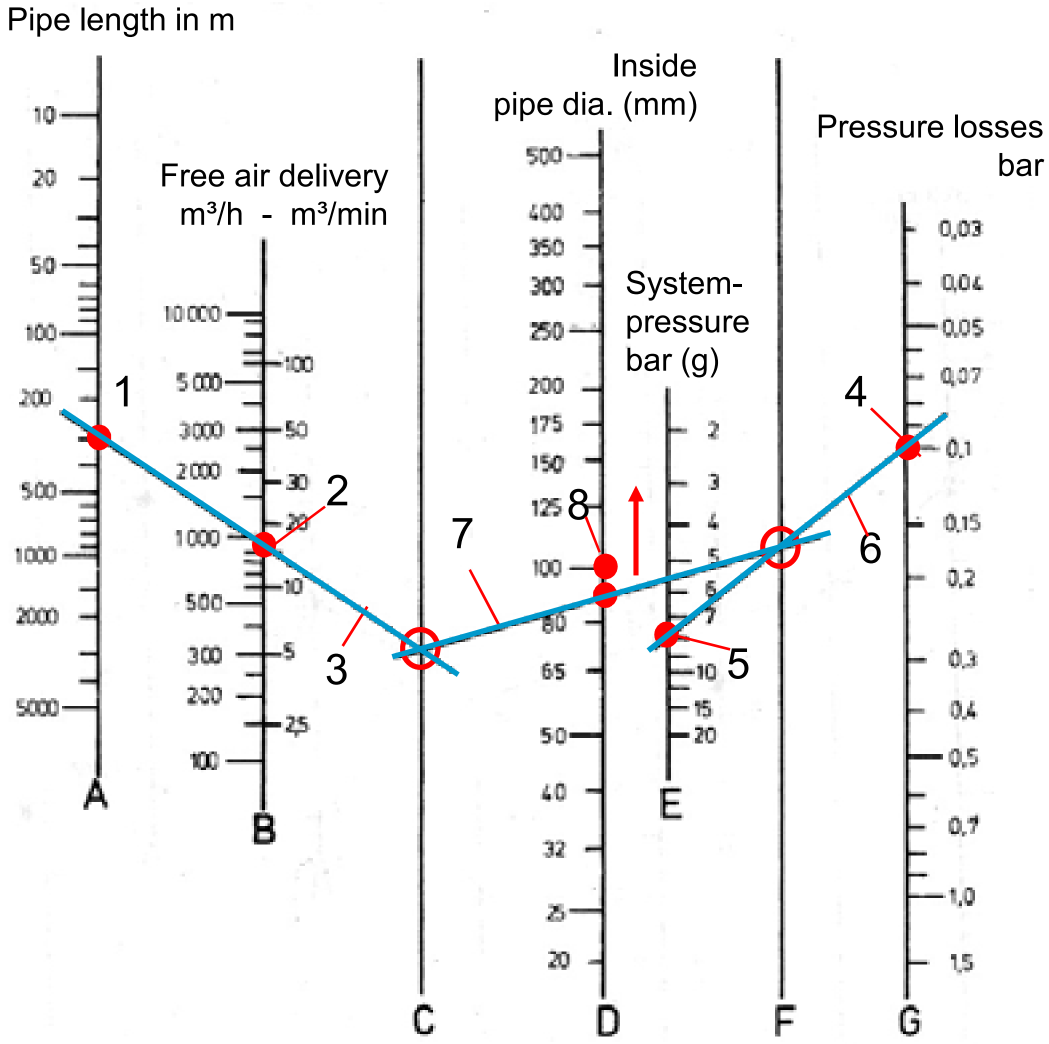
Straight-line graph

for determining inside

pipe diameter (steps 1 to 8)



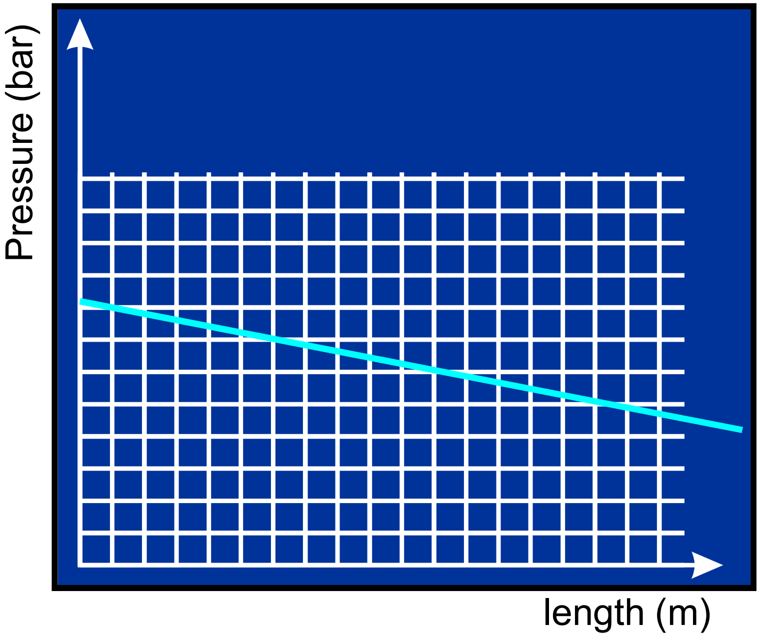
2. Understanding Compressed Air

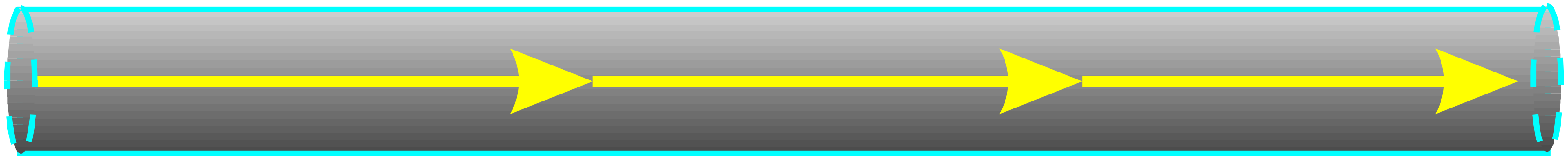
Compressed air in motion

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

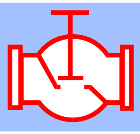
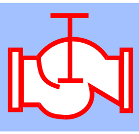
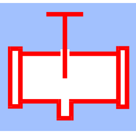
Minimum diameters of pipes

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

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 m^3/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.

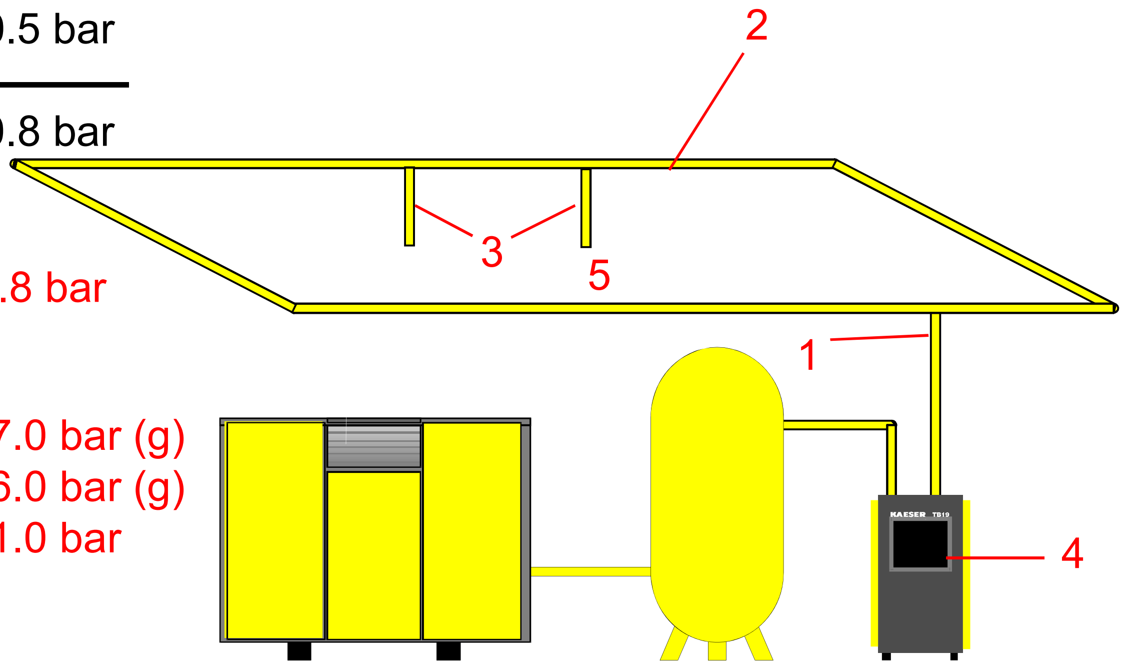
The maximum pressure drop in the air piping system should be no more than 1.5 % of the working pressure

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

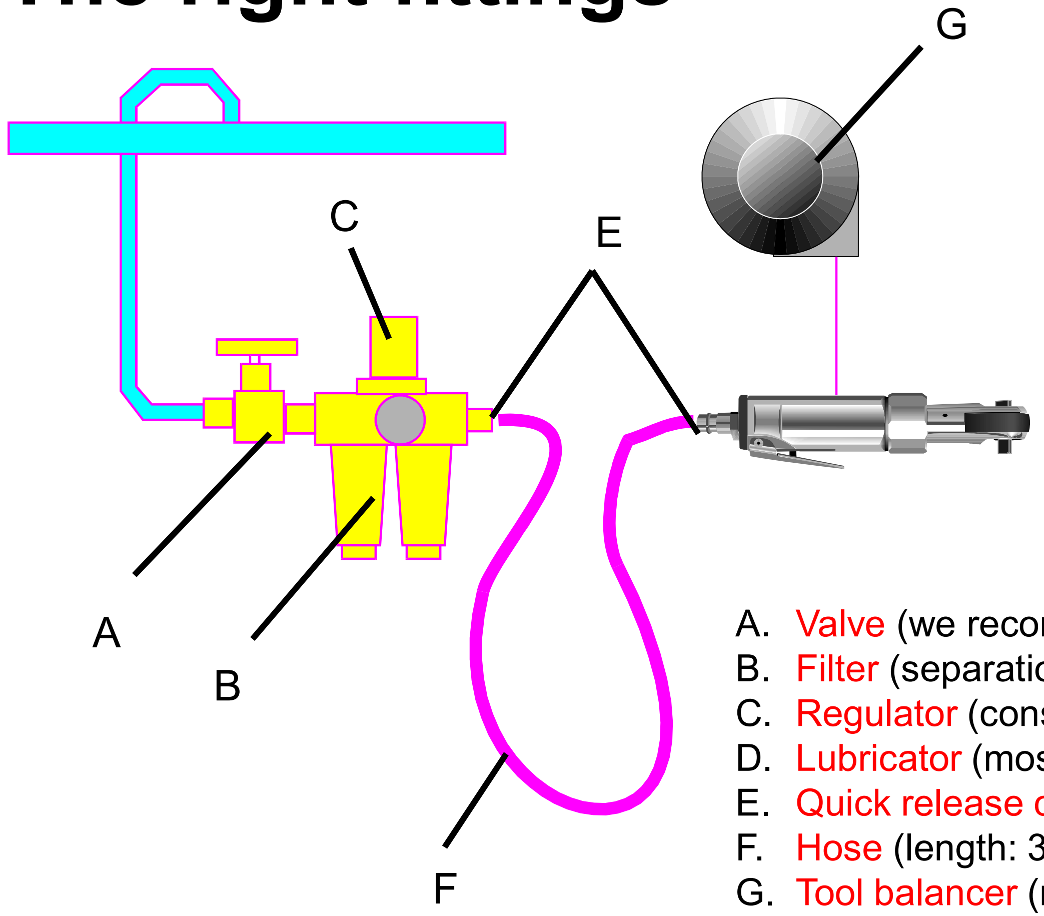
Overall pressure drop 0.8 bar



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)

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

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

Pipe layout

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

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

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

Key Energy Points

1. As compressed air energy is transmitted from one location to another, pressure loss is an irrecoverable loss of energy.

2. The amount of pressure loss is related to the velocity in the compressed air pipeline.

3. Compressed air energy can be stored.

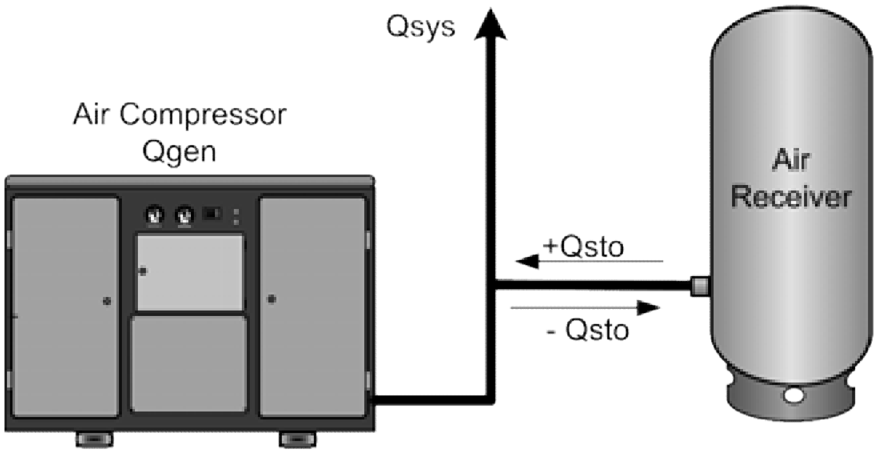
4. The amount of useable compressed air energy in storage depends on the storage tank's volume and pressure differential between the storage pressure and minimum system pressure requirement.

2. Understanding Compressed Air

Introduction to Compressed Air Energy Storage

Introduction to Compressed Air Storage

- Flow generated by the compressor *Qgen* seldom exactly matches the system air demand Qsys
- To create a supply / demand balance air flows in and out of storage.
- As system pressure increases air enters storage (-Qsto)
- As system pressure decreases air leaves storage (+Qsto)



Calculating usable compressed air available in storage

- Useable compressed air available from storage is the product of pressure differential and available storage volume.

Equation 4 - 2.11 Usable air volume V_a available from Storge

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

Where:

Va = Useable compressed air in storage

Vs = Total volume of storage system

Pmax = Maximum storage or receiver pressure (cut-out pressure)

Pmin = Minimum storage or receiver pressure required (cut-in pressure)

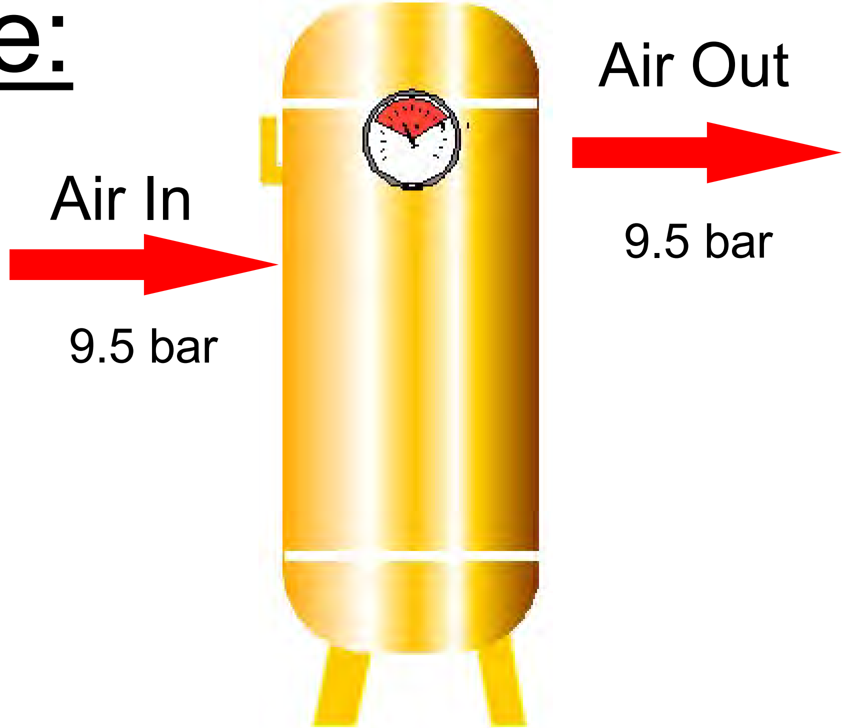
Pamb = Absolute ambient air pressure

2. Understanding Compressed Air

Uncontrolled Storage:

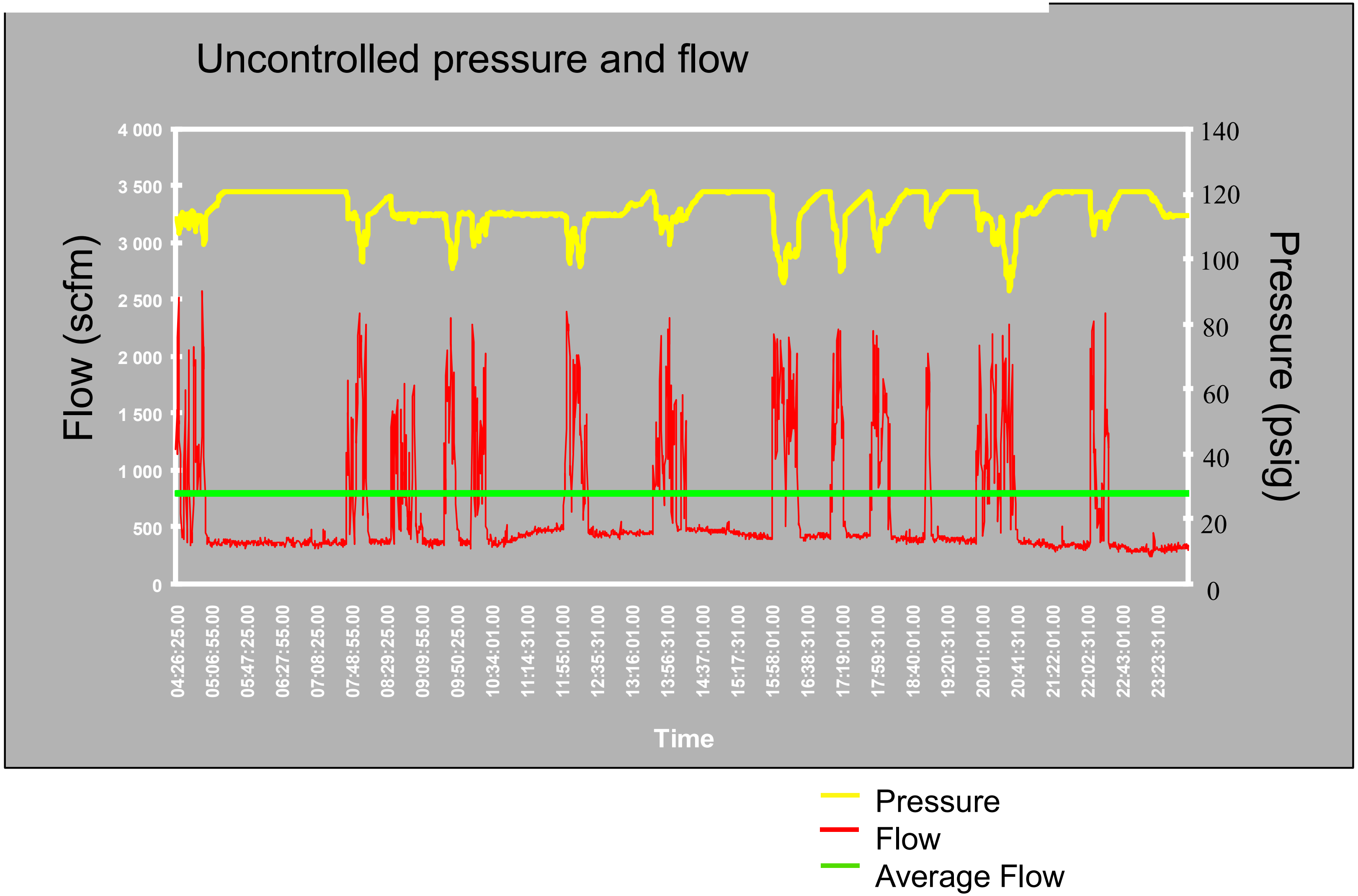
Without Pressure Differential

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



No " Real" Storage

2. Understanding Compressed Air

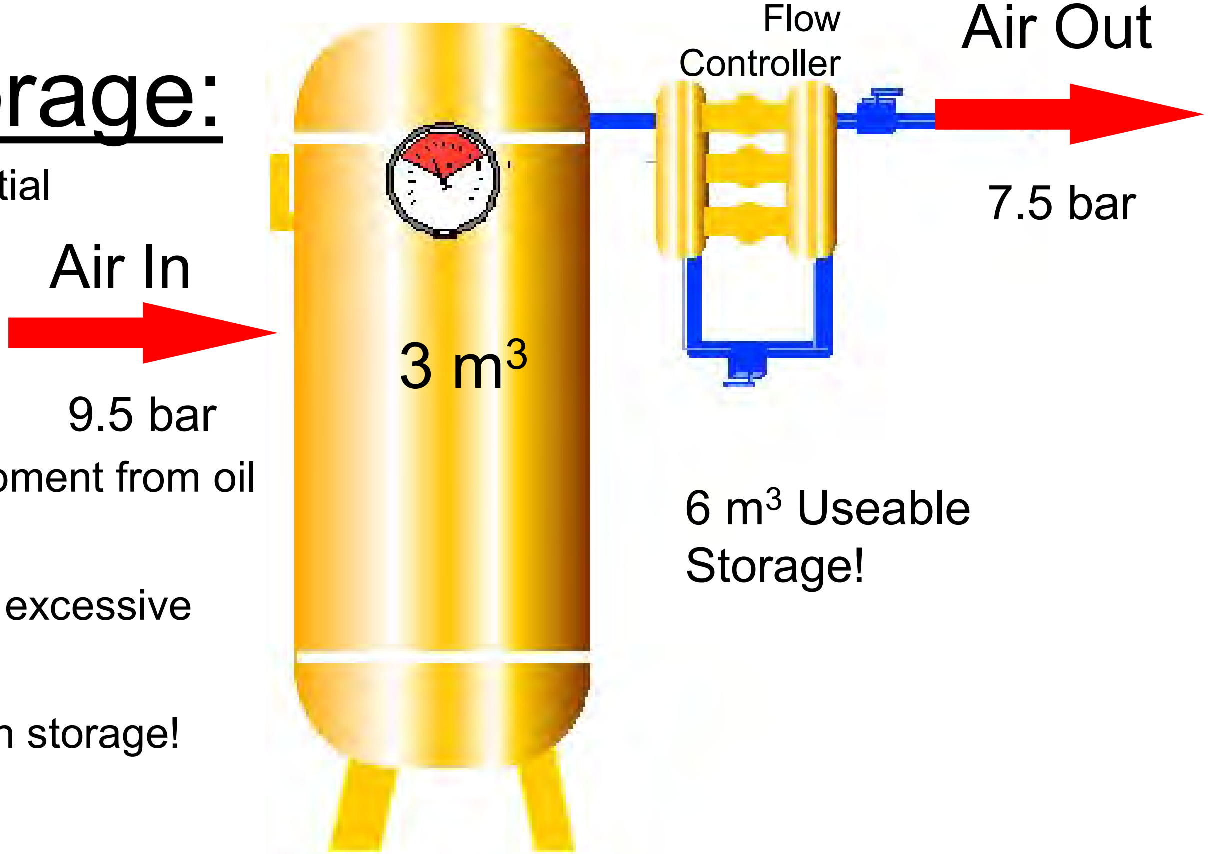


2. Understanding Compressed Air

Controlled Storage:

With Pressure Differential

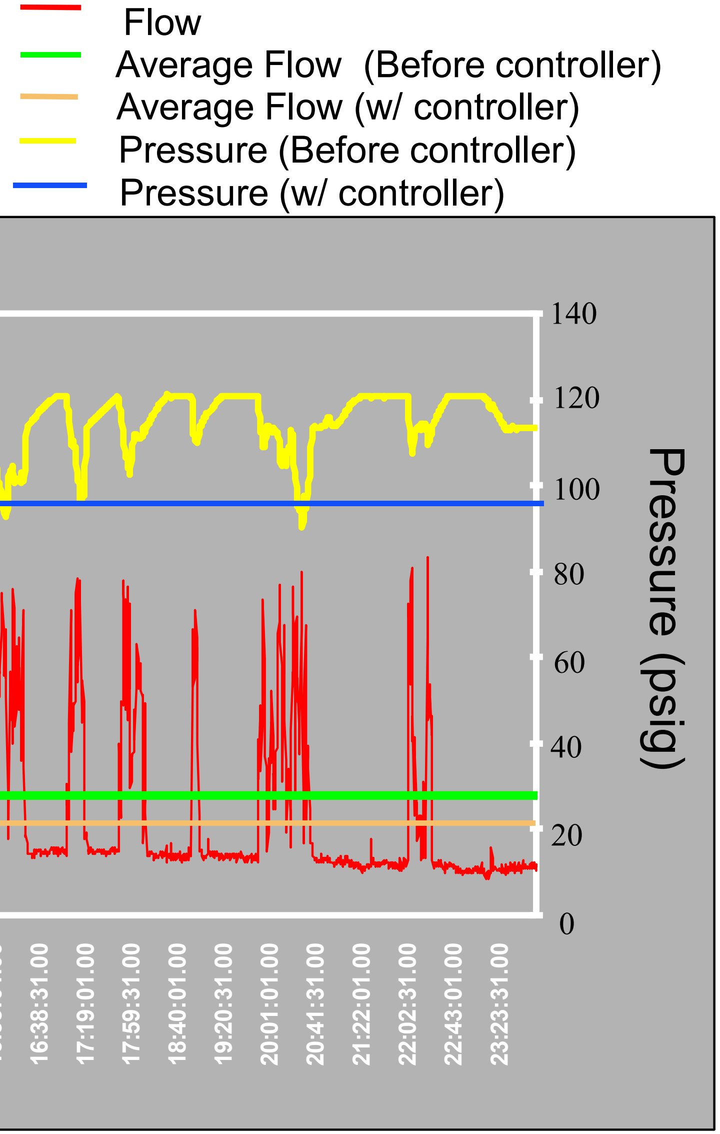
- Quiet zone
- Moisture separator
- Protects downstream equipment from oil slugs
- Prevents compressor from excessive cycling
- PLUS 6 m^3 of useable air in storage!



Pressure Differential Creates Stored Energy!

2. Understanding Compressed Air

Controlled pressure and flow

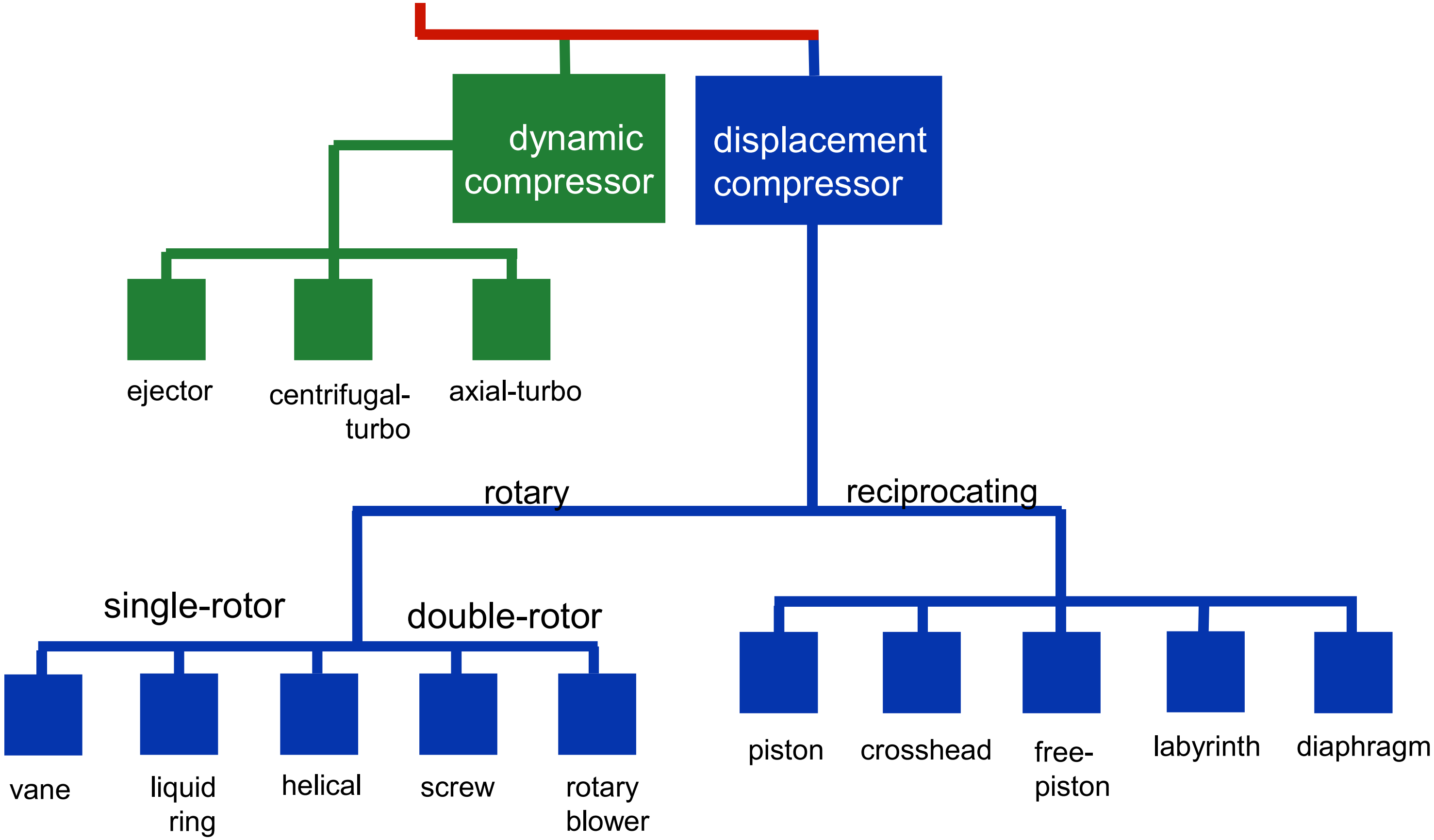


3. Supply Side - Compressors and Their Application

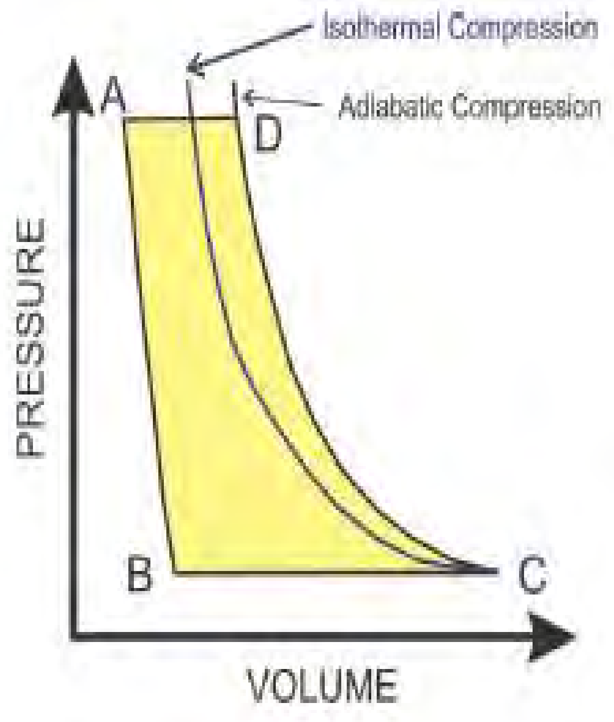
Courtesy of Kaeser Compressors

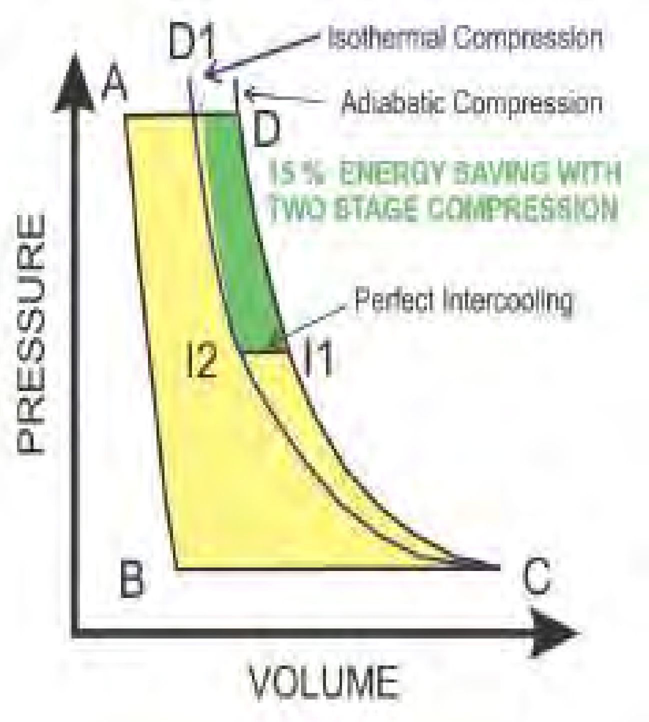
Types of Compressors

Compressor types



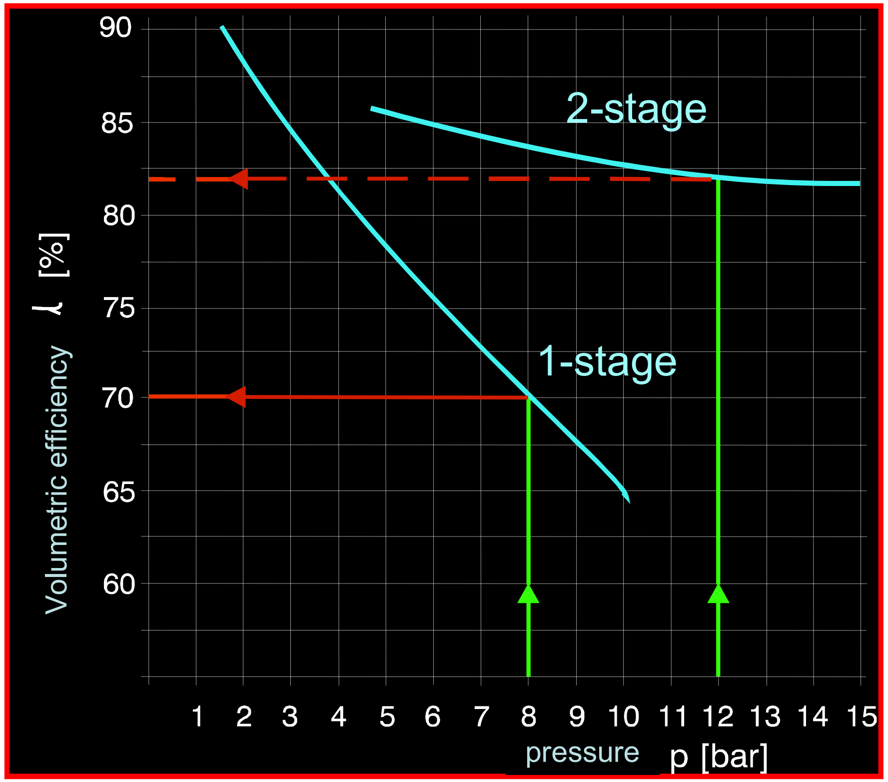
Stages of Compression: Single-stage, Two-stage, Multi-Stage





Reciprocating compressors

Volumetric efficiency of single and two stage compressors

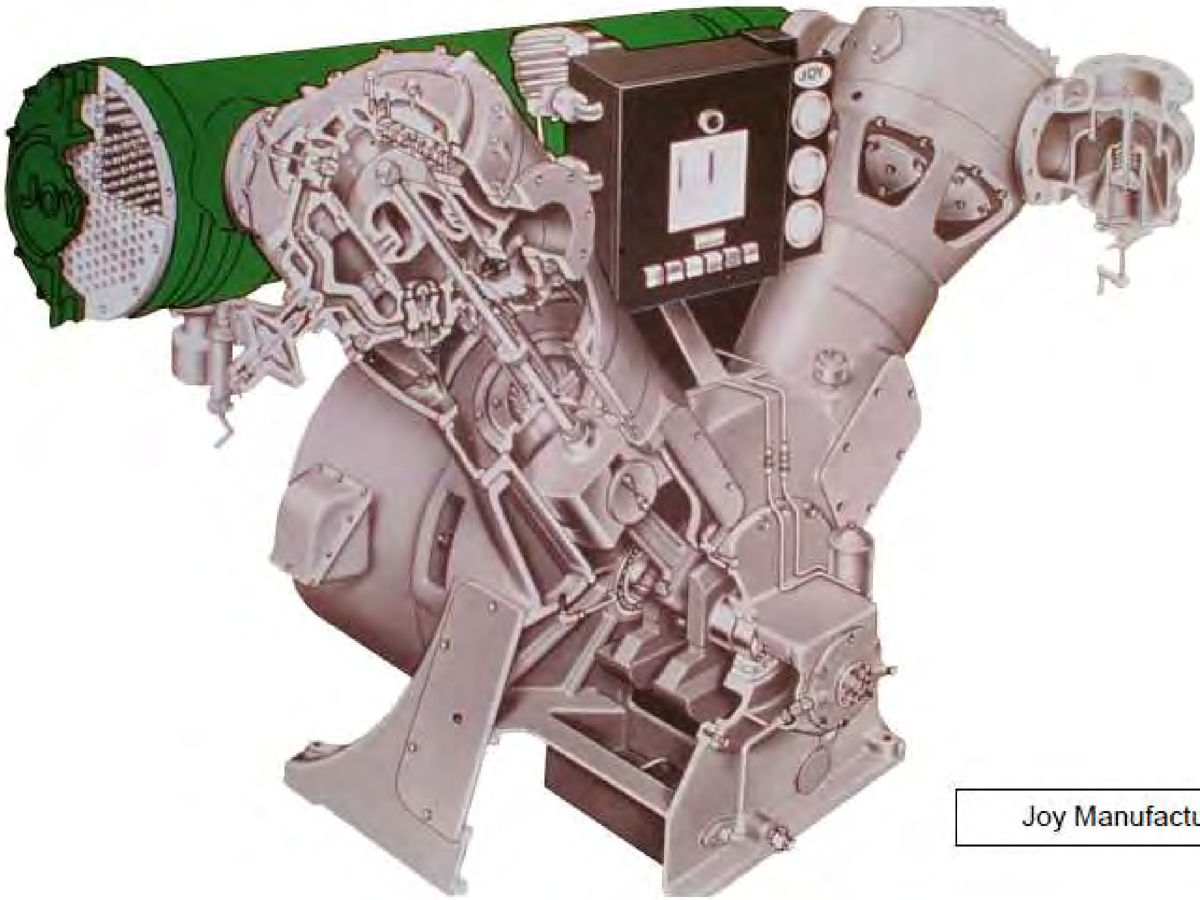


$$\text{Volumetric efficiency} = \frac{\text{free air delivery}}{\text{theoretical displacement}}$$

Specific Power for Various Compressor Types

Specific Power for Various Compressor Types (typical range)			
Volumetric flow rate (free air delivery)	kW / m^3/ min	kW / 100 l/sec	kW / 100 cfm
Recip. Single Acting (sgl stage)	7.8 - 8.5	47 - 51	22 - 24
Recip. Single Acting (2 stage)	6.4 - 8.1	38 - 49	18 - 23
Recip. Double Acting (sgl stage)	8.5 - 10.2	51 - 61	24 - 29
Recip. Double Acting (2 stage)	5.3 - 5.7	32 - 34	15 - 16
Lubricated Screw (sgl stage)	6.0 - 7.8	36 - 47	17 - 22
Lubricated Screw (2 stage)	5.7 - 6.7	34 - 40	16 - 19
Lubricant Free Screw (2 stage)	6.4 - 7.8	38 - 47	18 - 22
Centrifugal (3 stage)	5.7 - 7.1	34 - 42	16 - 20

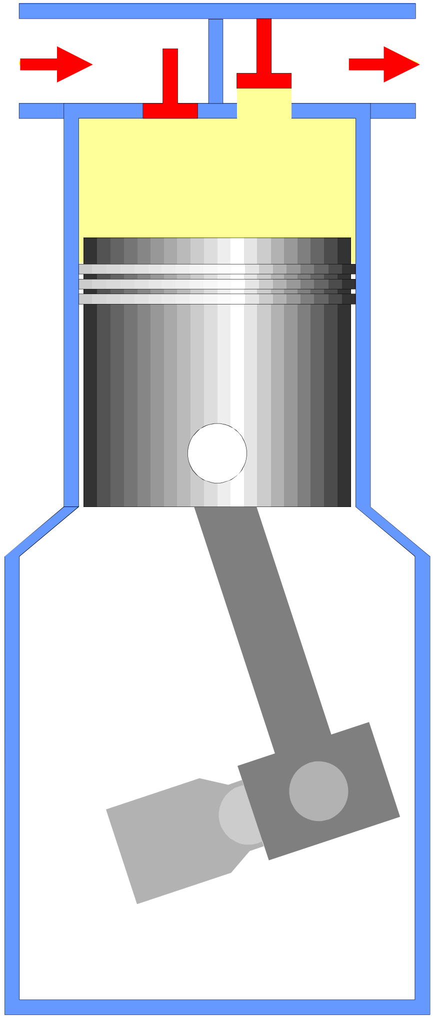
Reciprocating Compressors



Joy Manufacturing

Reciprocating compressors

single / two stage

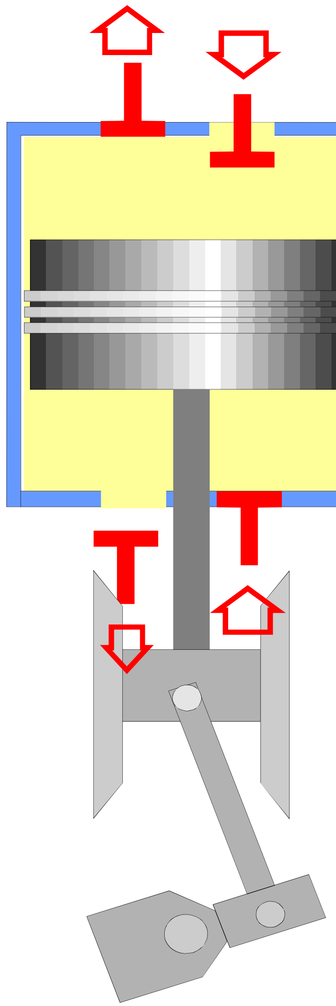


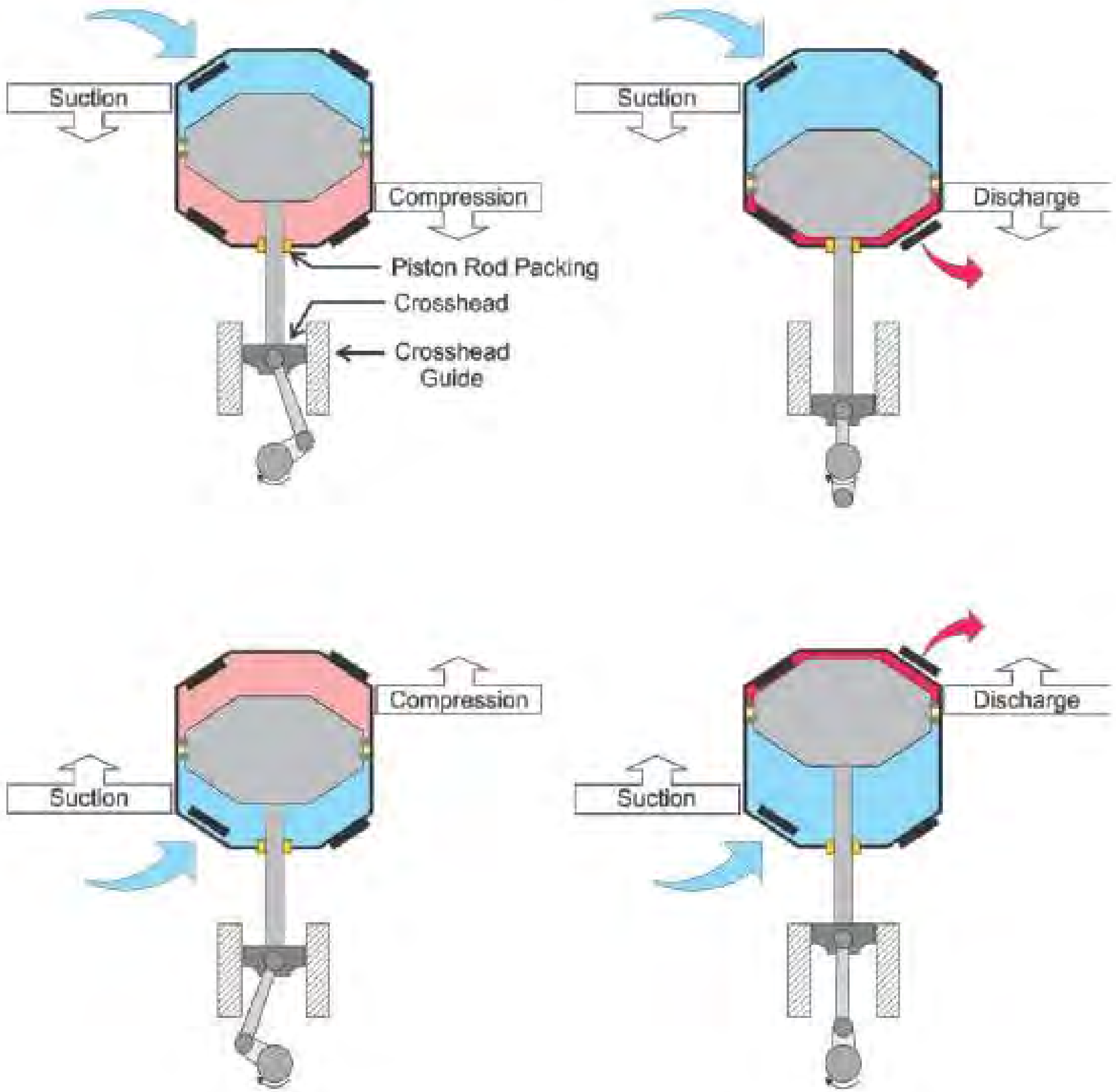
Note the difference:	- single / two stage - single acting / double acting
Installation:	- portable - stationary
Application: (single stage)	- common 10 bar - boosters 35 bar

Double-acting

with crosshead

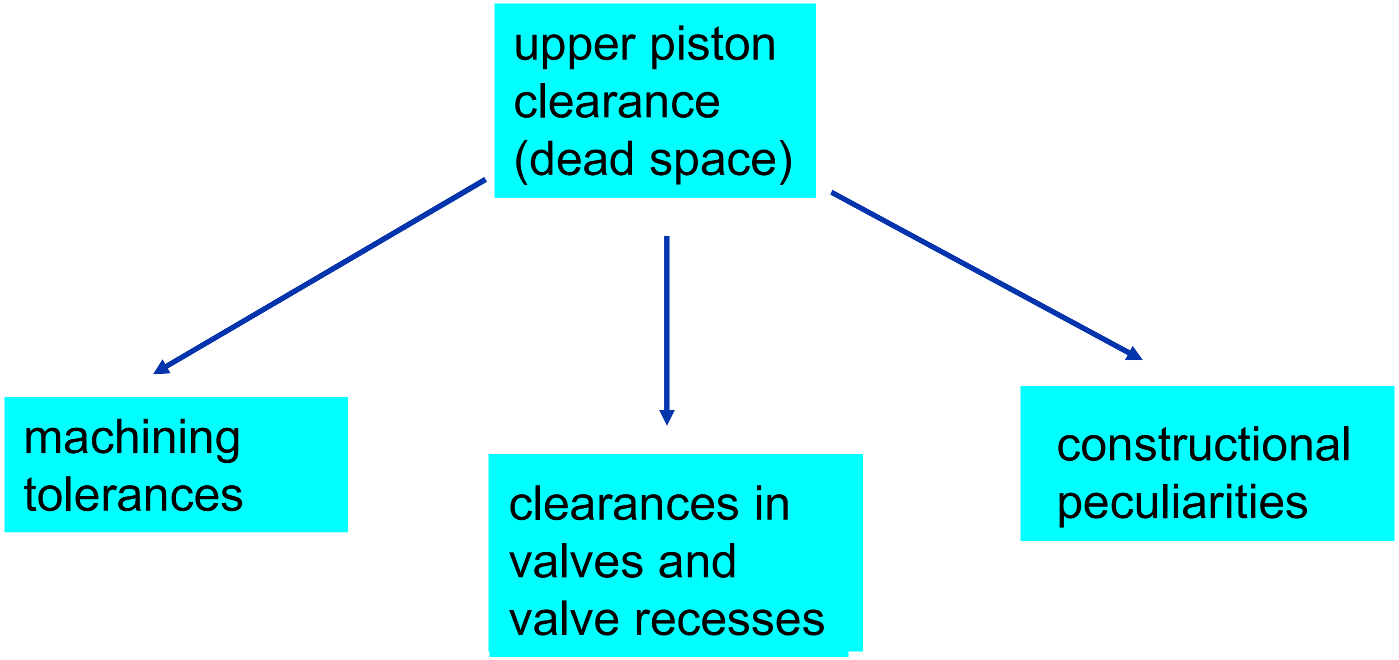
Application:
High pressure, up to 1000 bar
in combination with screw compressors.
Compression of gas



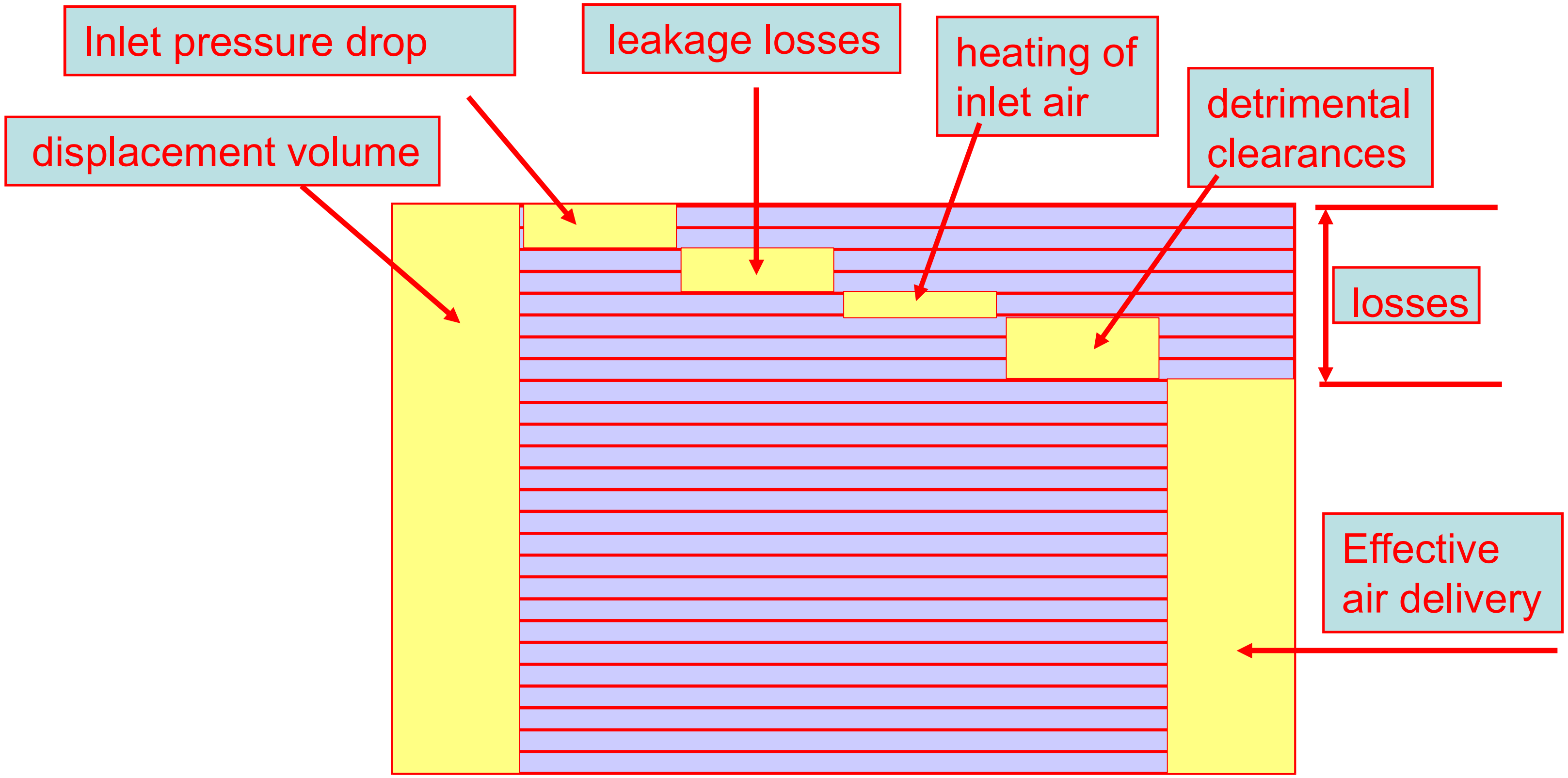

Suction
Compression
Piston Rod Packing
Crosshead
Crosshead Guide
Suction
Discharge
Compression
Suction
Discharge
Suction

Reciprocating compressor

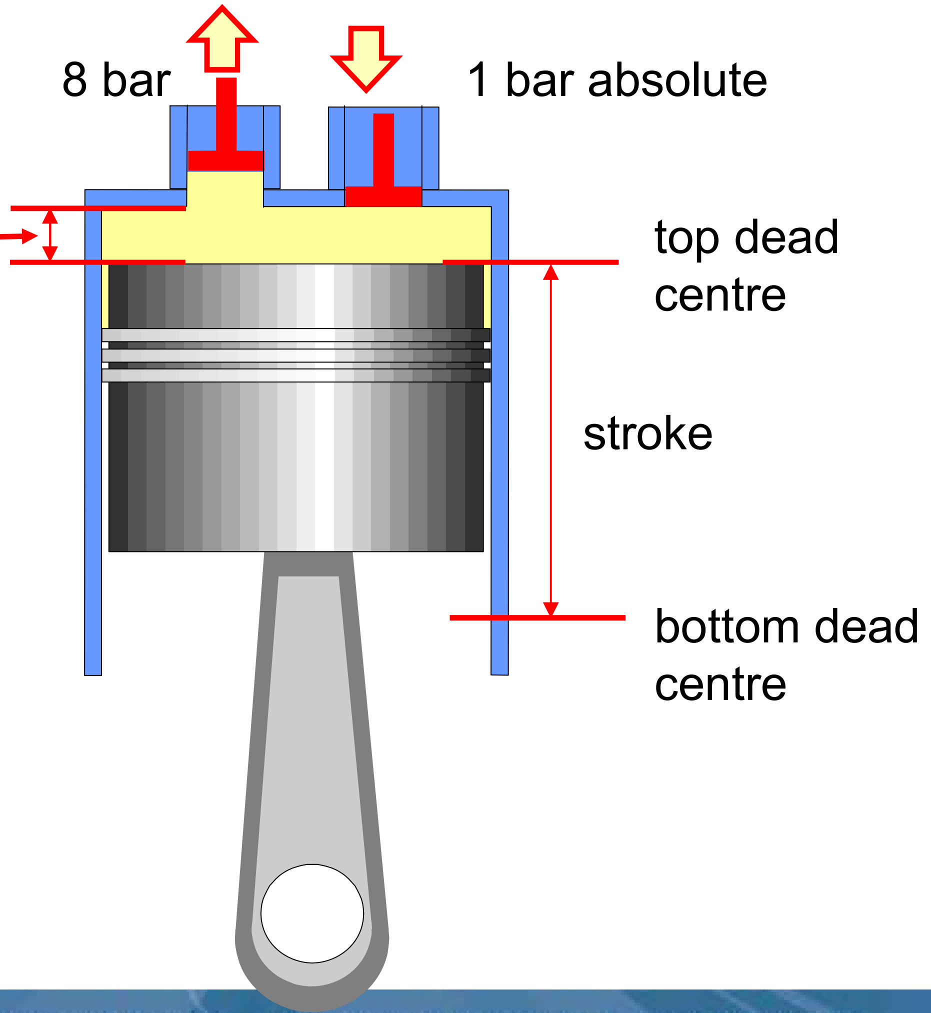
Clearances that affect efficiency



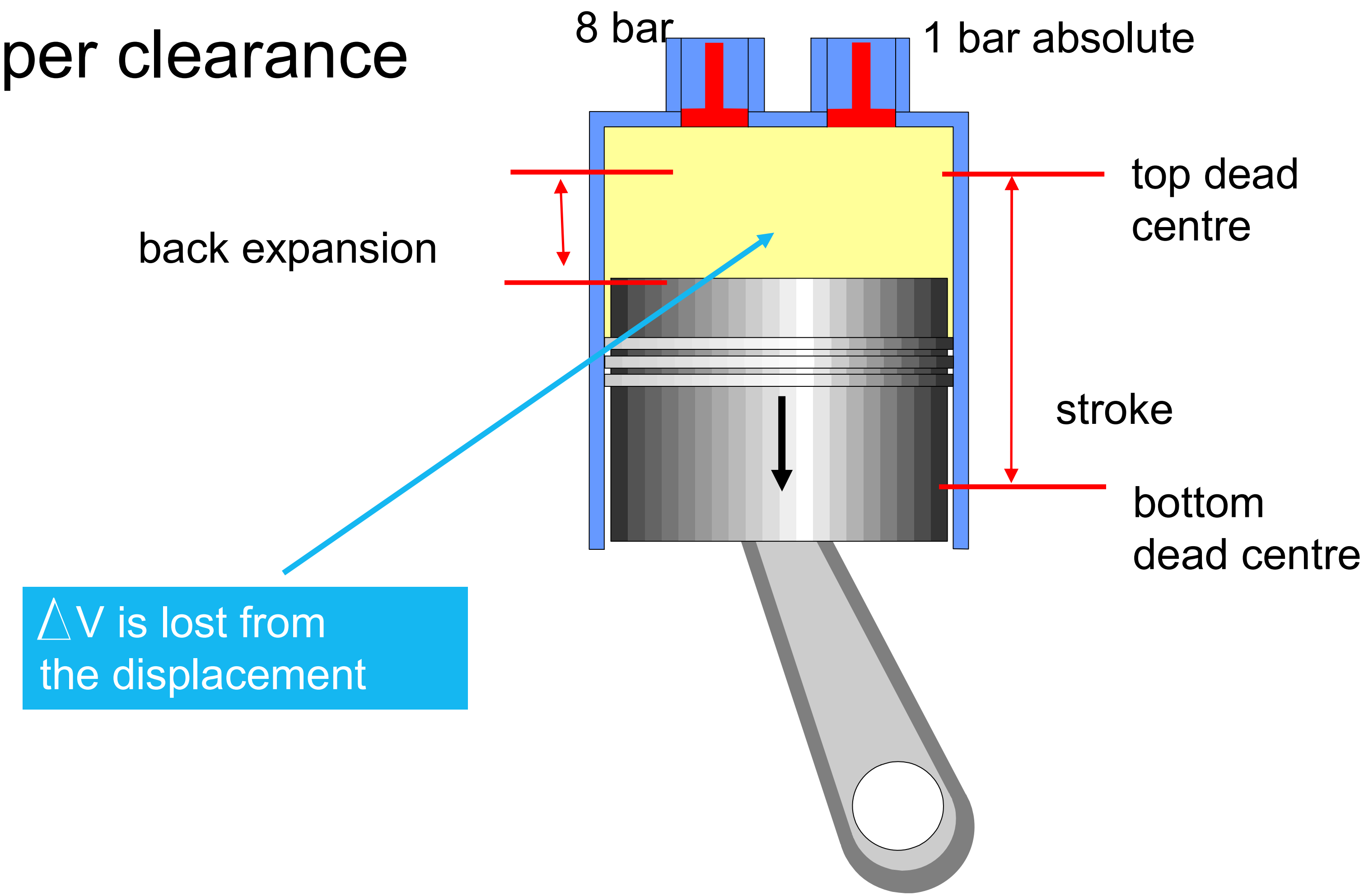
Effective air delivery with reciprocating compressors



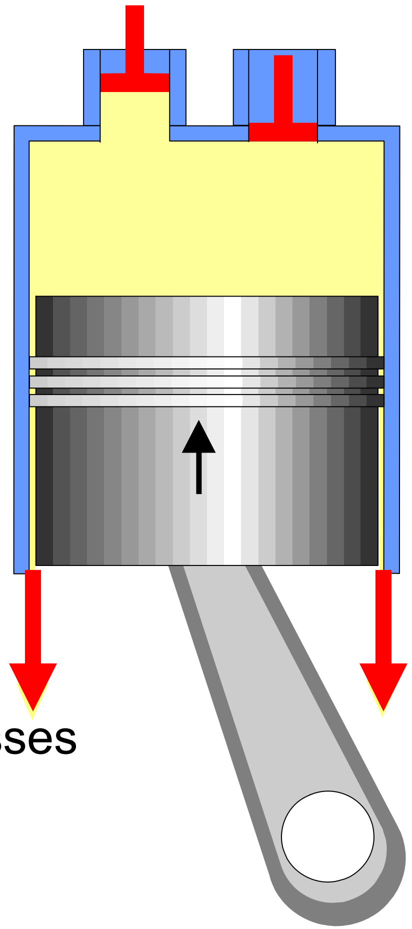
Upper piston clearance (dead space)



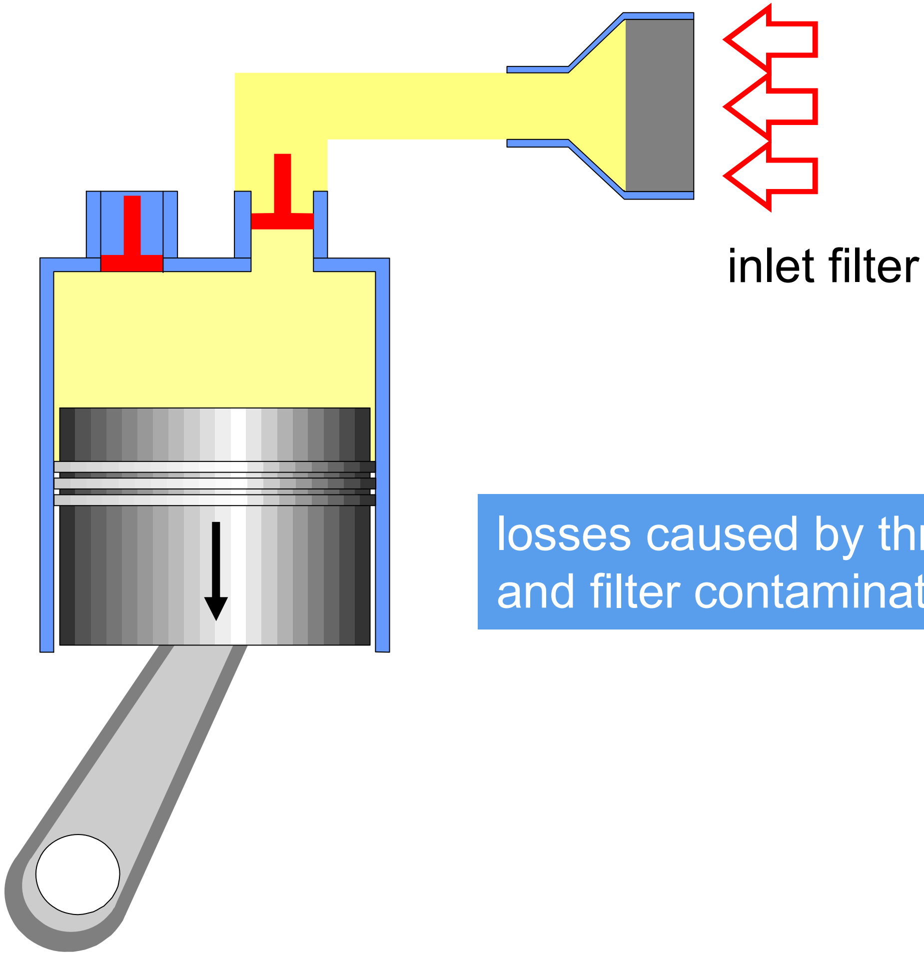
upper clearance



Compression

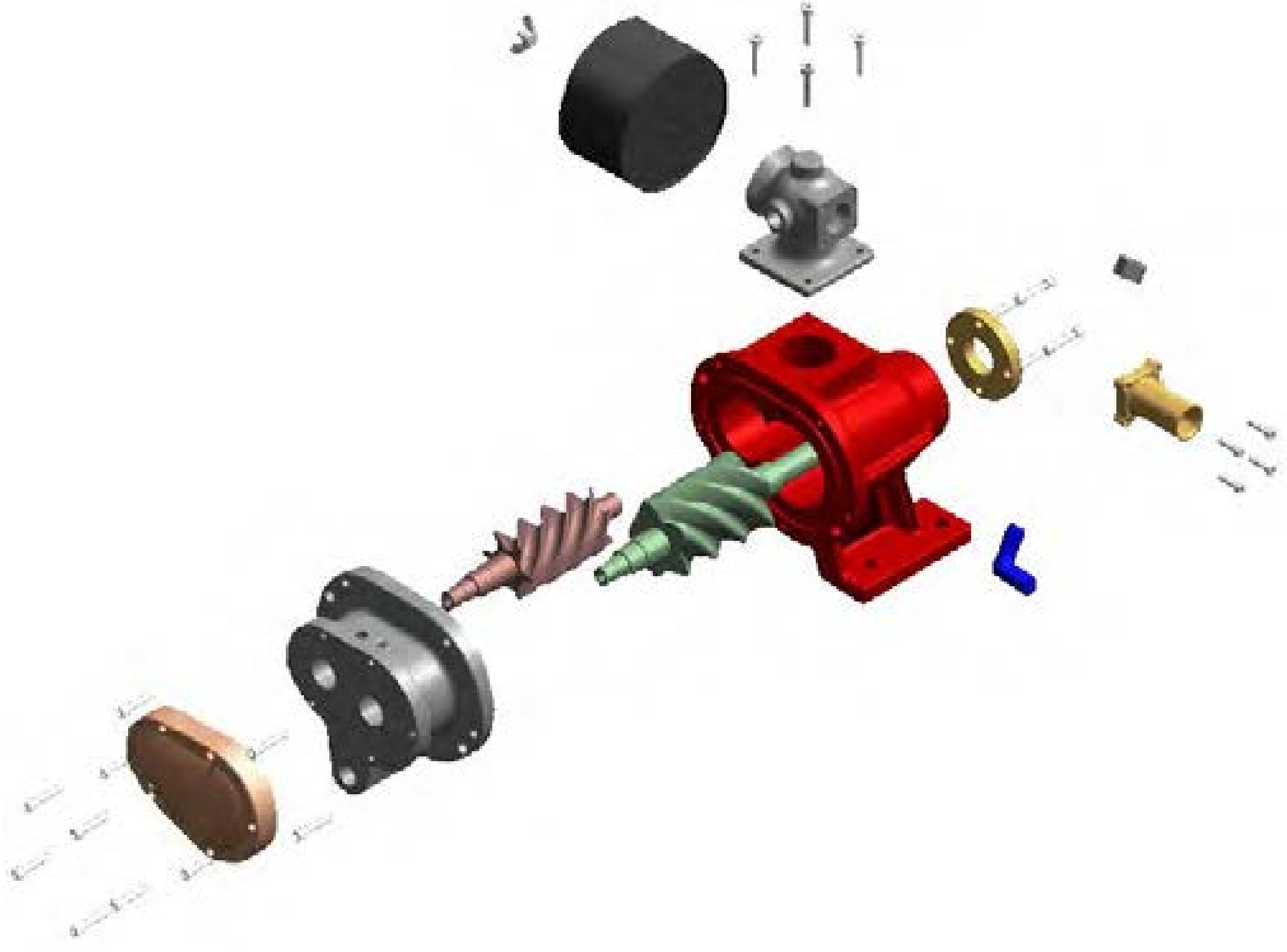


Suction



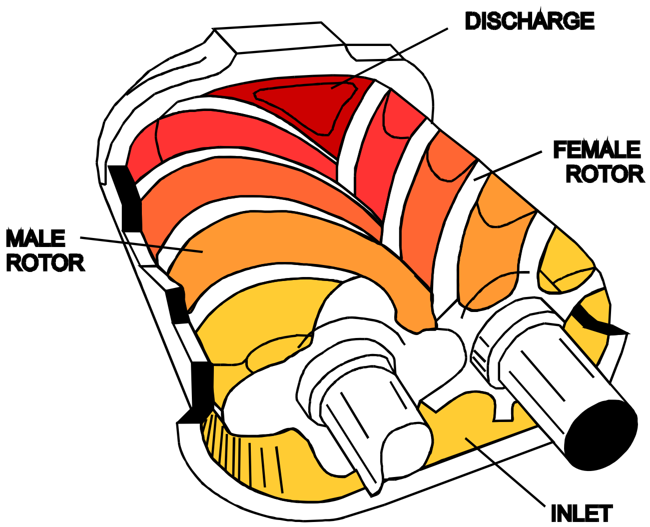
losses caused by throttling and filter contamination

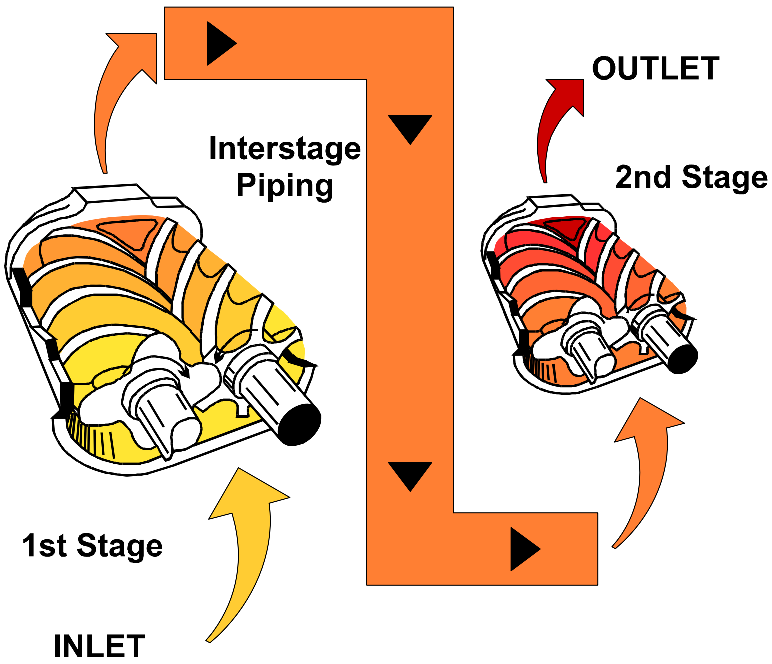
Rotary Screw compressors



Single Stage Rotary Screw

Two Stage Rotary Screw

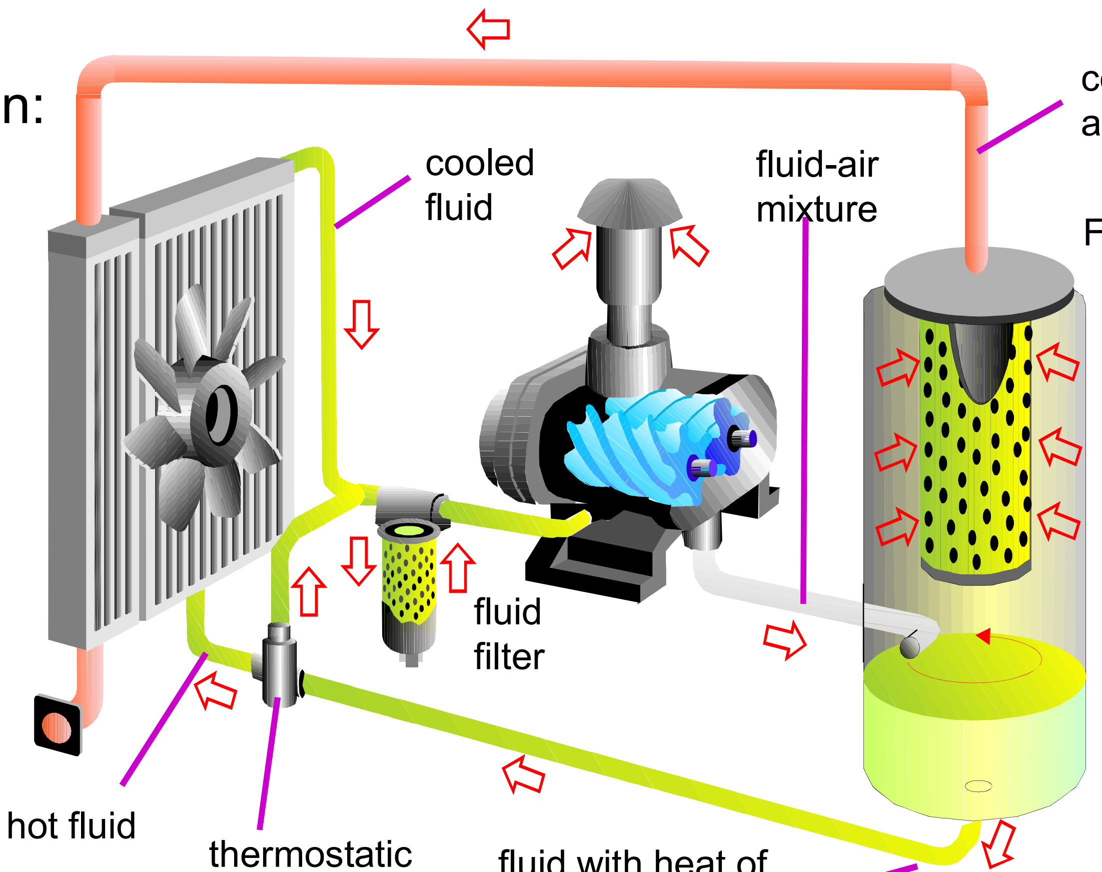




Lubricant-free dry rotary screw compressor air end

Lubricant-injected rotary screw compressor

Construction:



Efficiency - comparison of specific power consumption

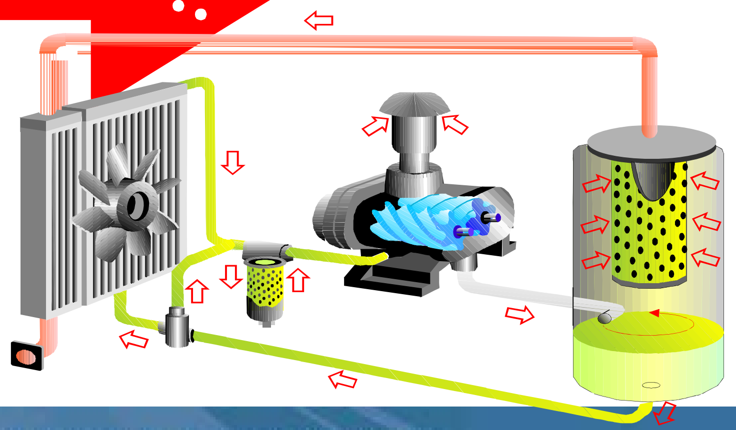
$$\text{Specific Power Consumption*} = \frac{\text{Power* in kW}}{\text{Effective FAD in m}^3\text{ / min}}$$

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

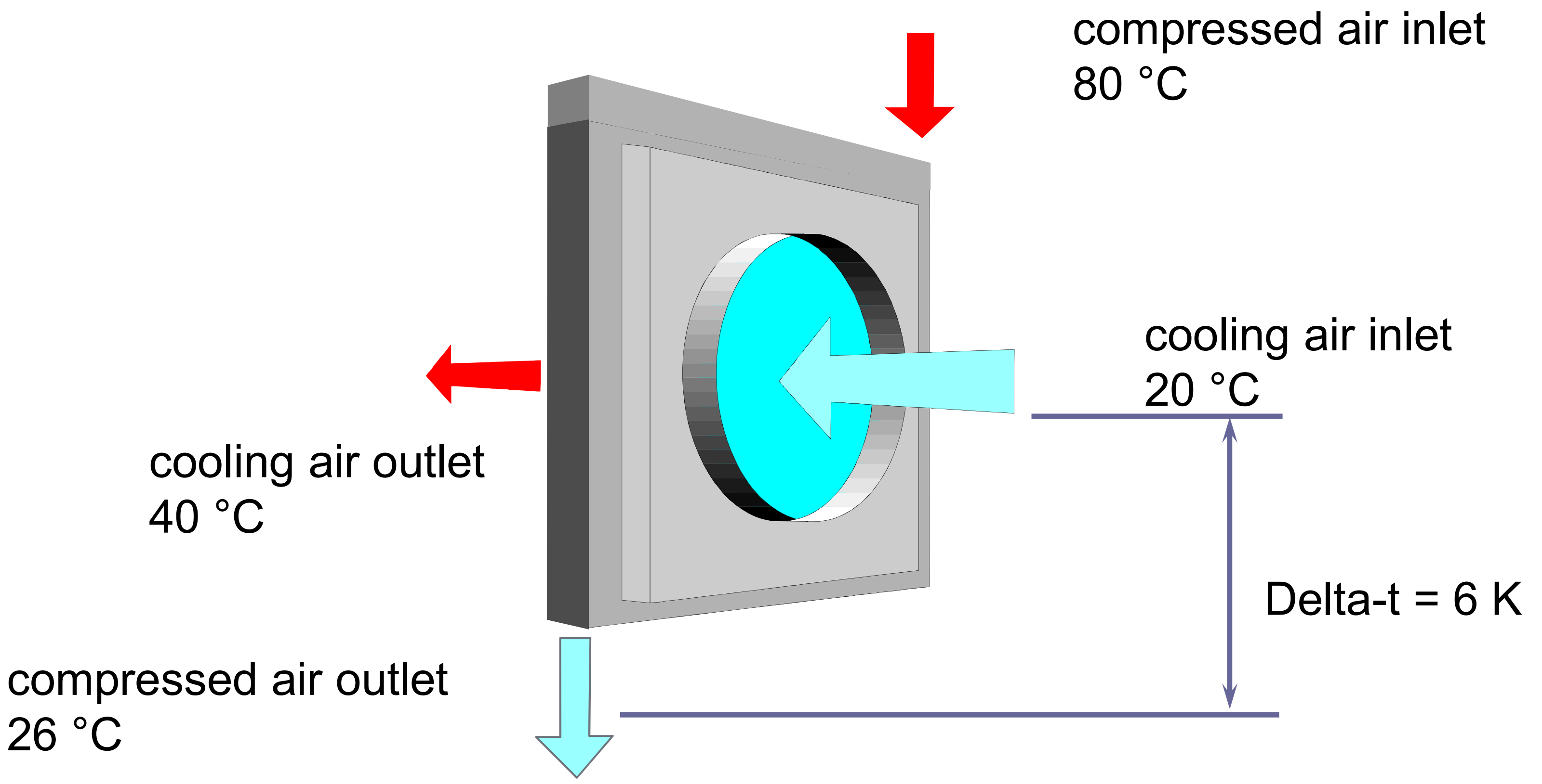
* depending on reference point:
- compressor shaft power
- motor output power
- electric power input

Function of the fluid in a lubricated rotary screw

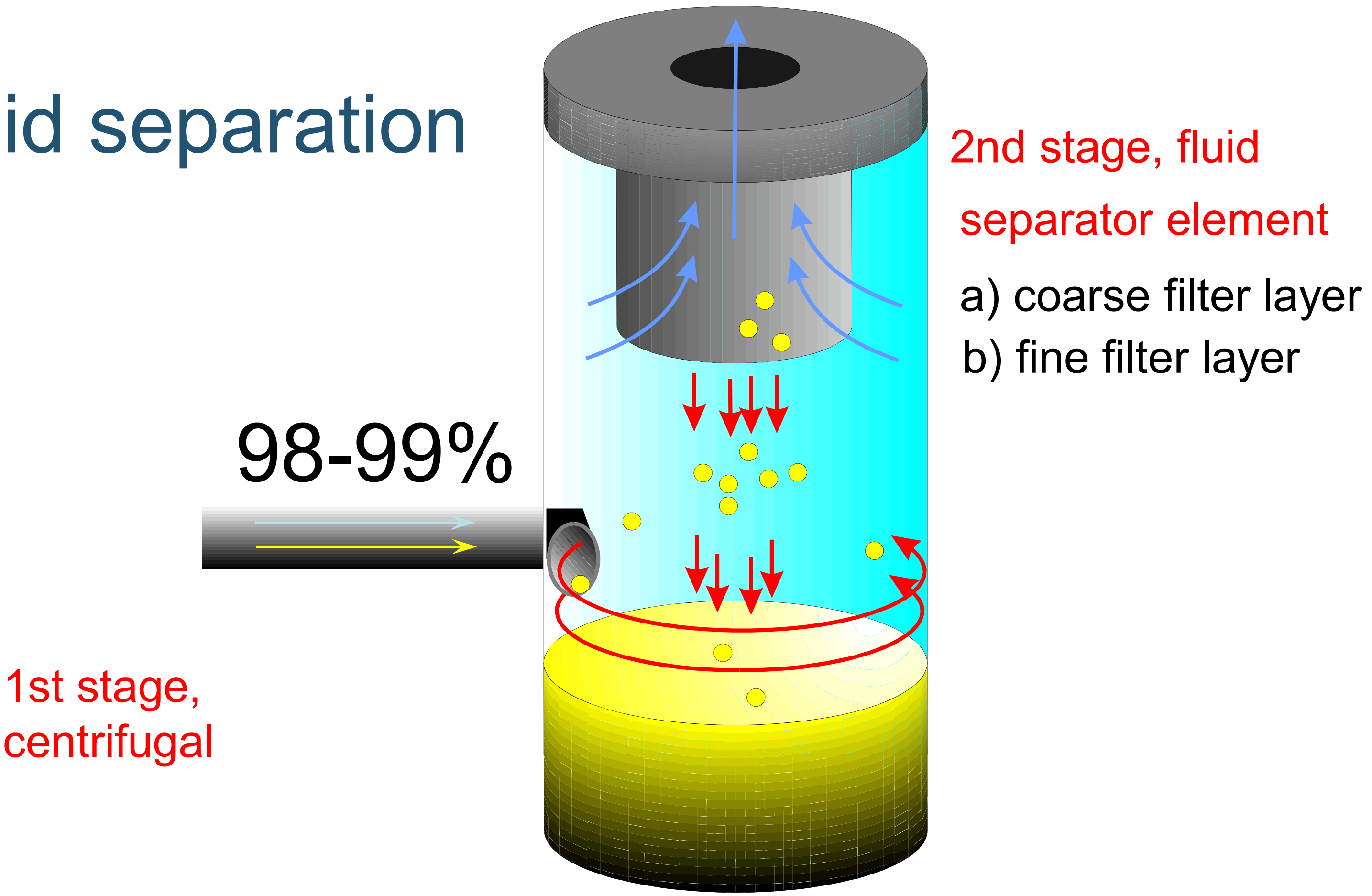
First task:	heat transfer, discharge temperature approximately 75 - 80 °C
Second task:	lubrication of bearings
Third task:	sealing the gap between rotors and casing, prevention of metallic contact
Fourth task	absorbing dust, sulphur, etc.



Fluid and aftercooler:

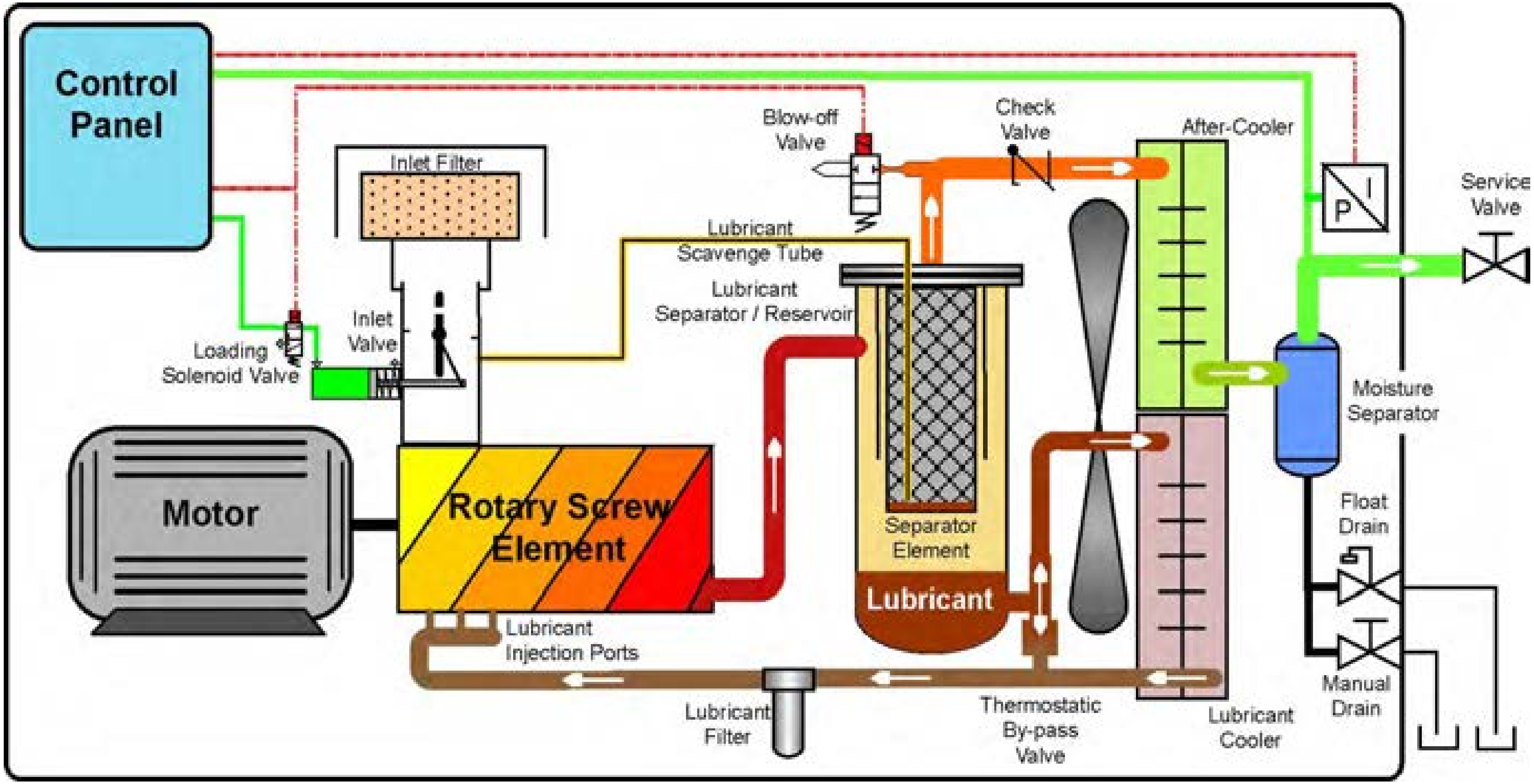


Fluid separation

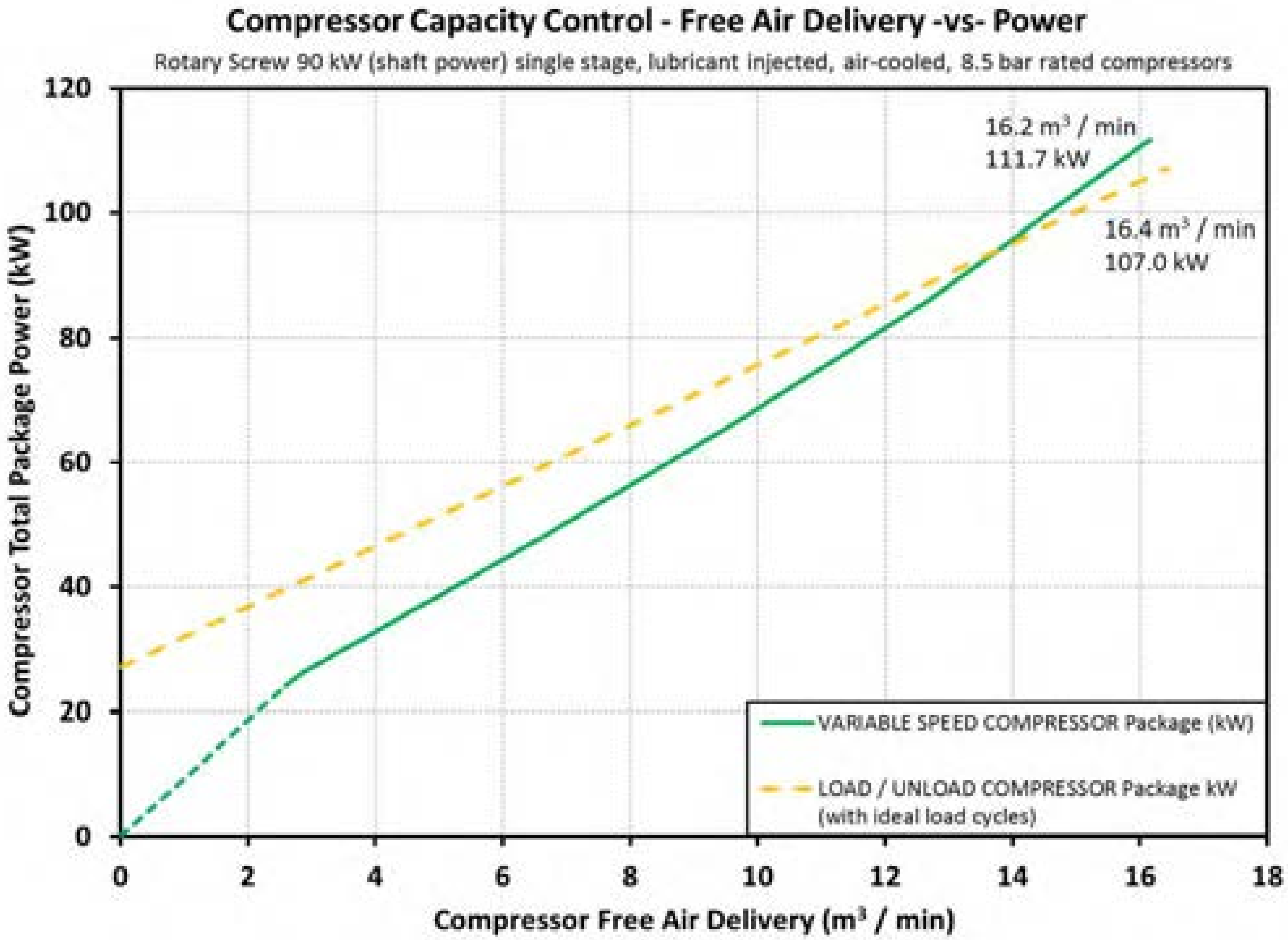


ROTARY SCREW COMPRESSOR CONTROLS

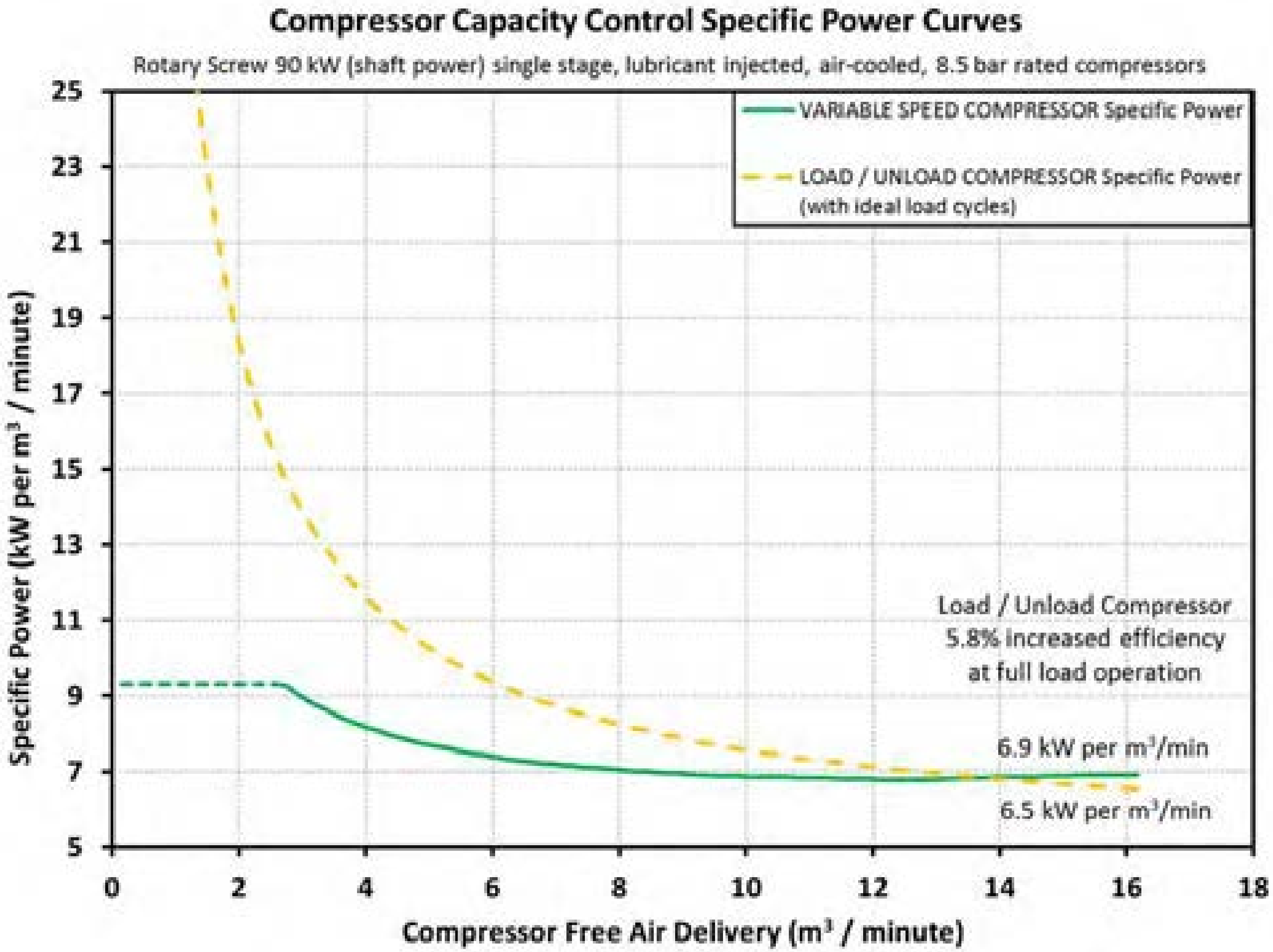
Rotary Screw Compressor Internal



Compressor Performance Curves Free Air Delivery -vs- Power



Compressor Performance Specific Power Curves



Compressor Performance Curves % Capacity -vs- % Power

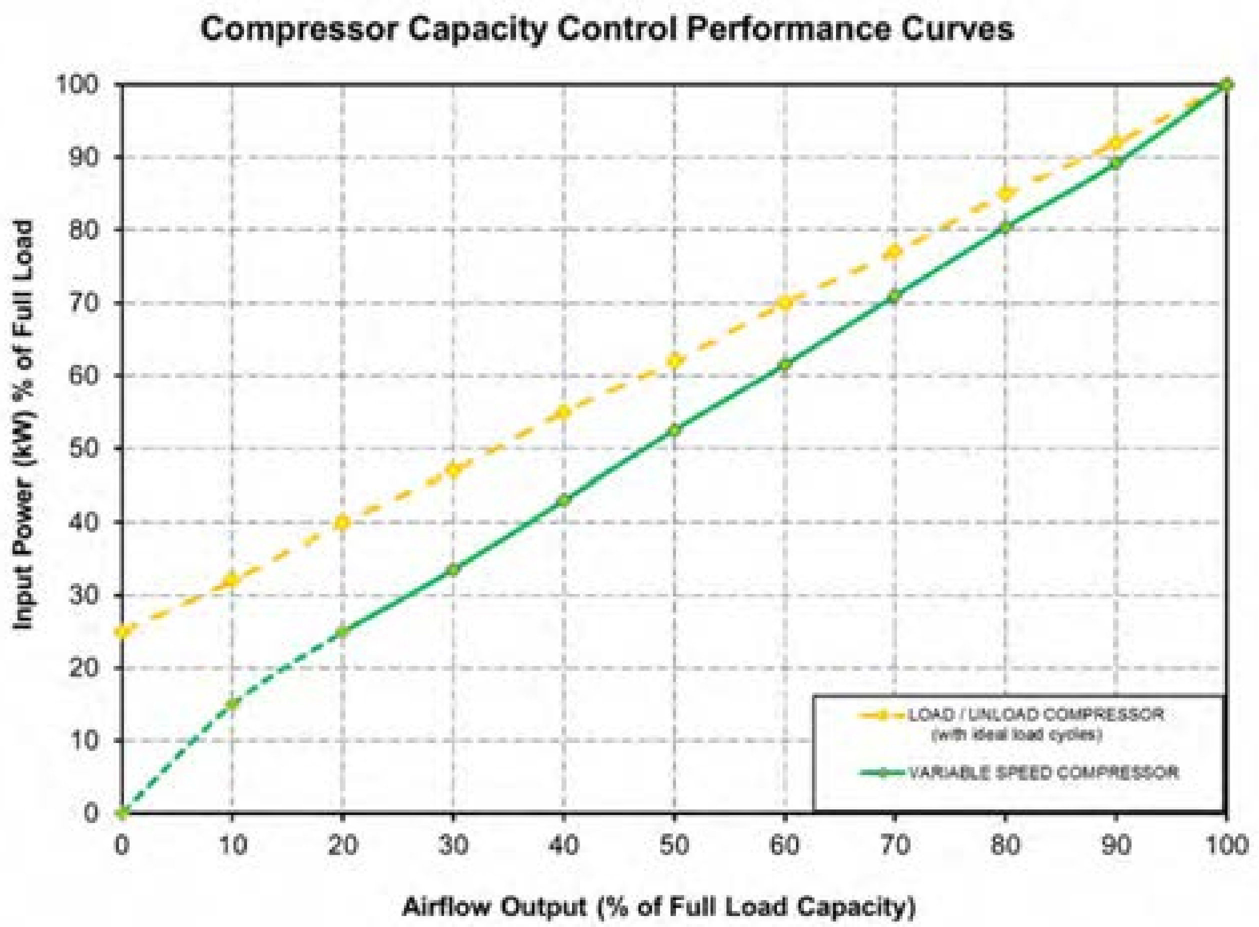
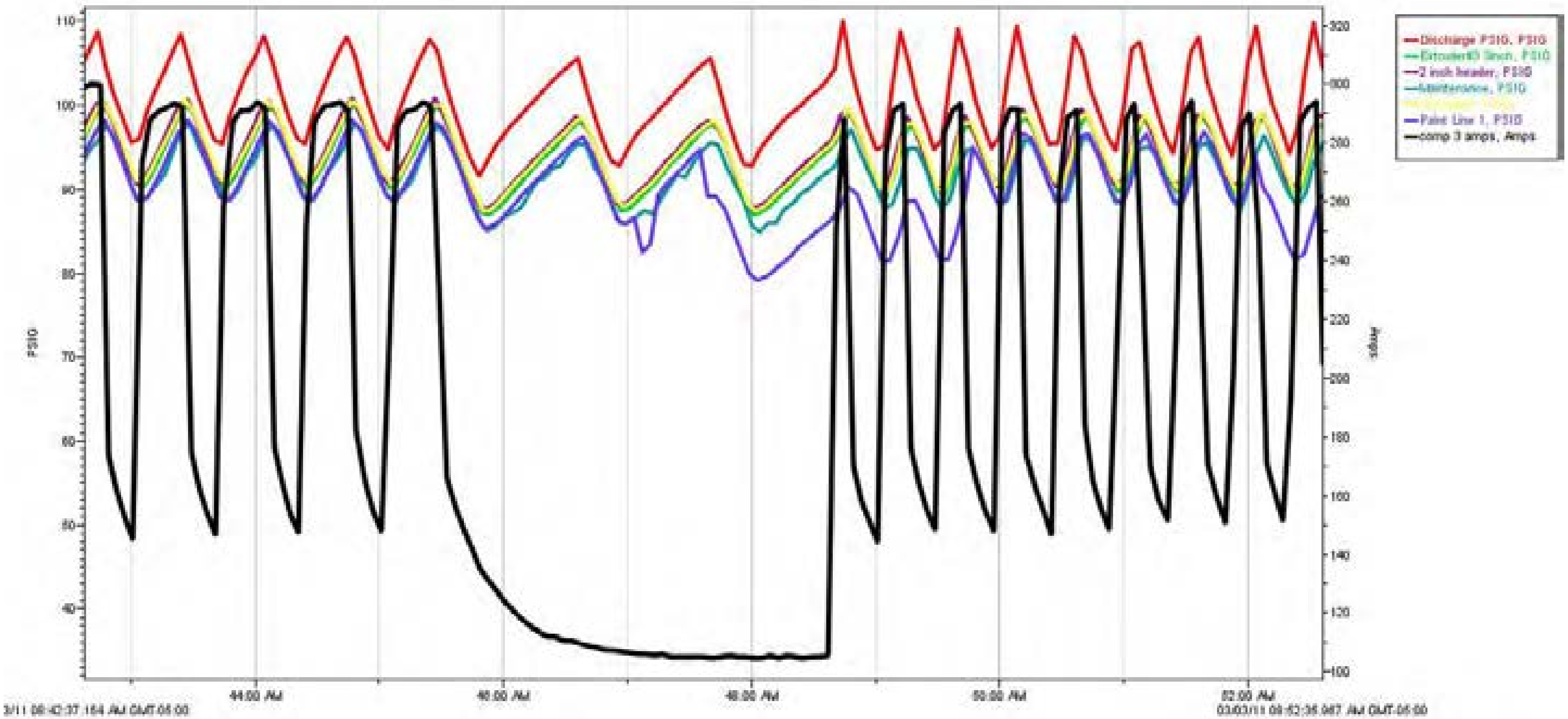
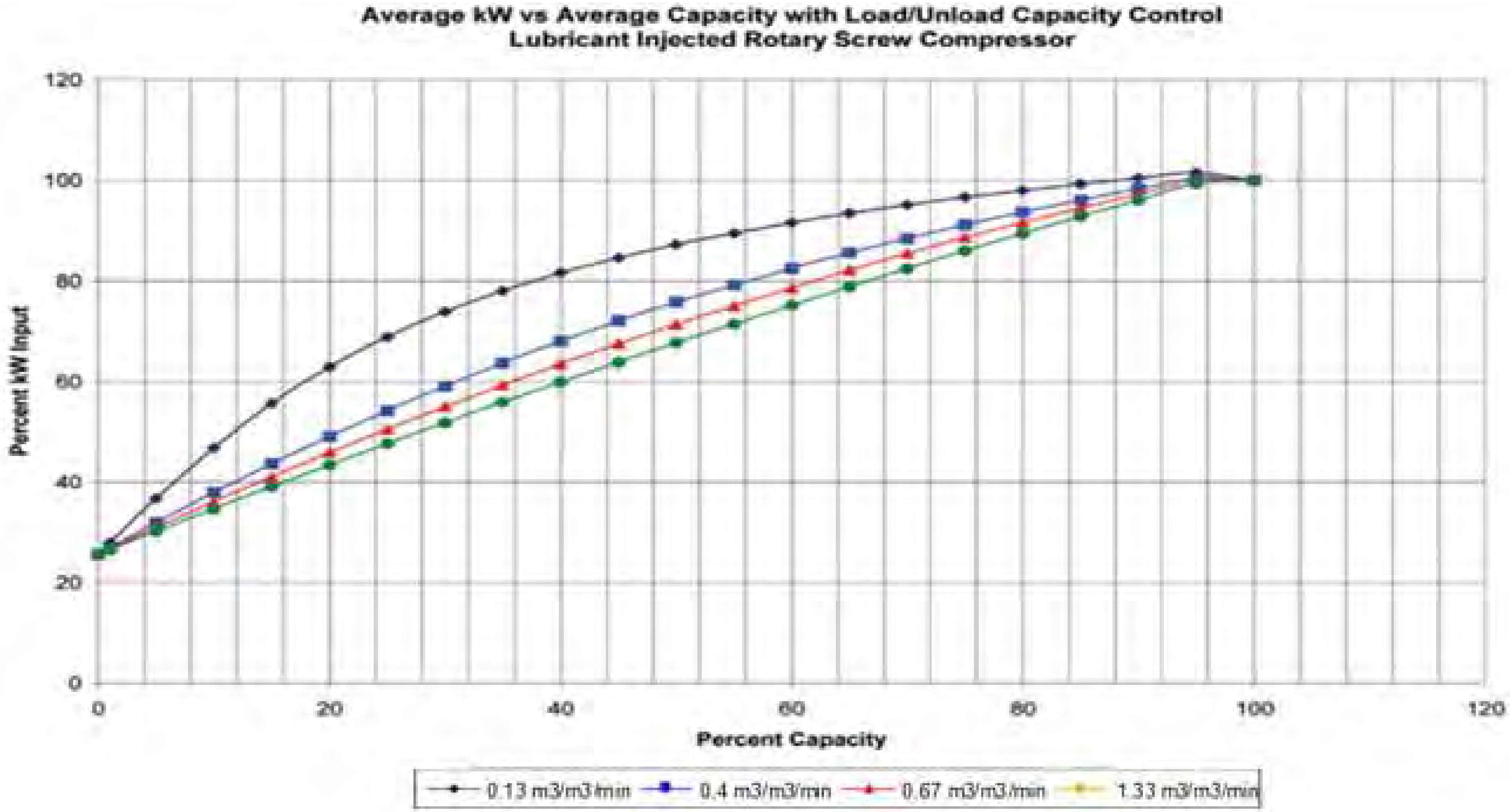


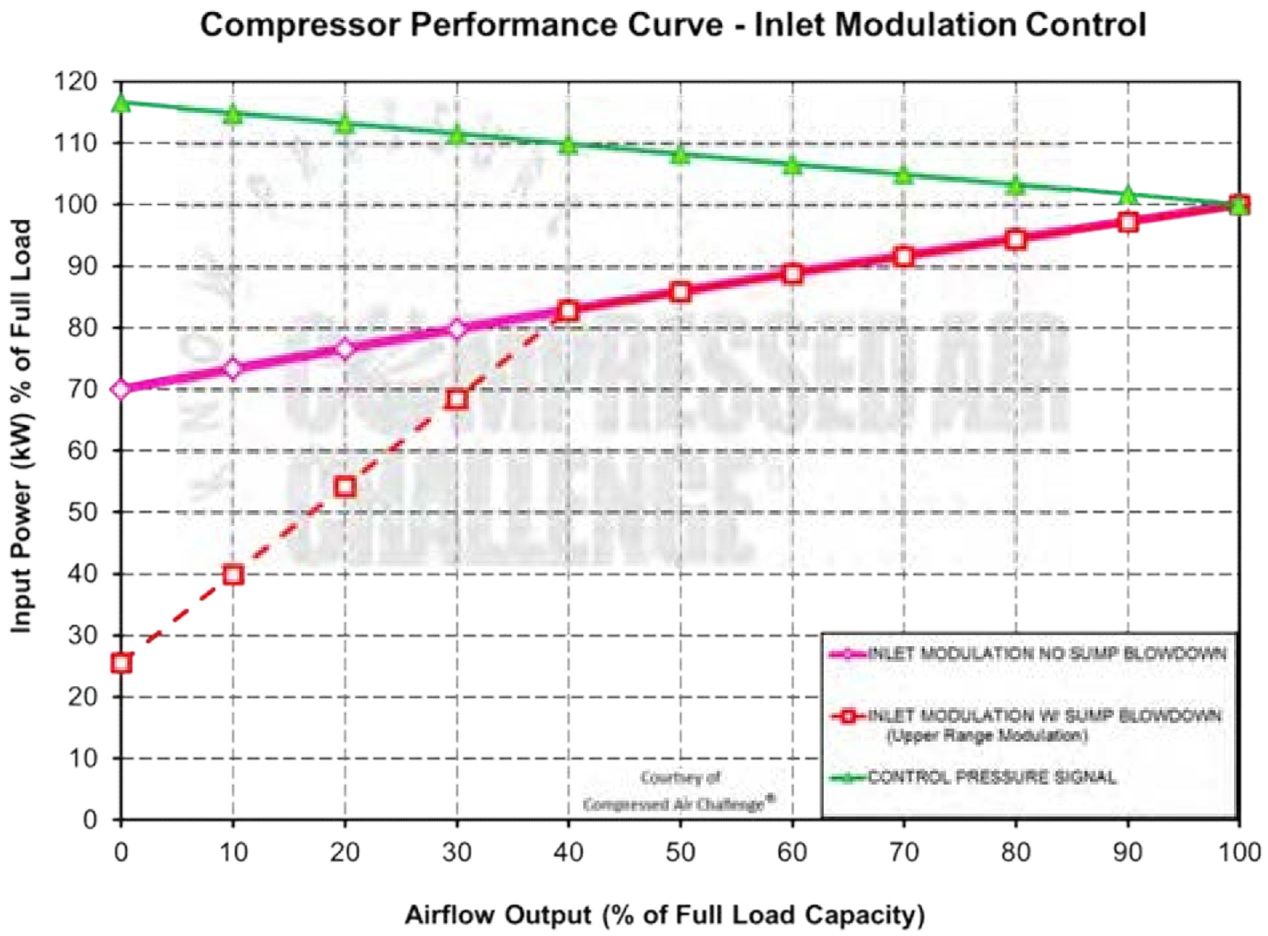
Figure 4 - 3.15 Load / Unload Cycles w/ Amperage –vs – Time



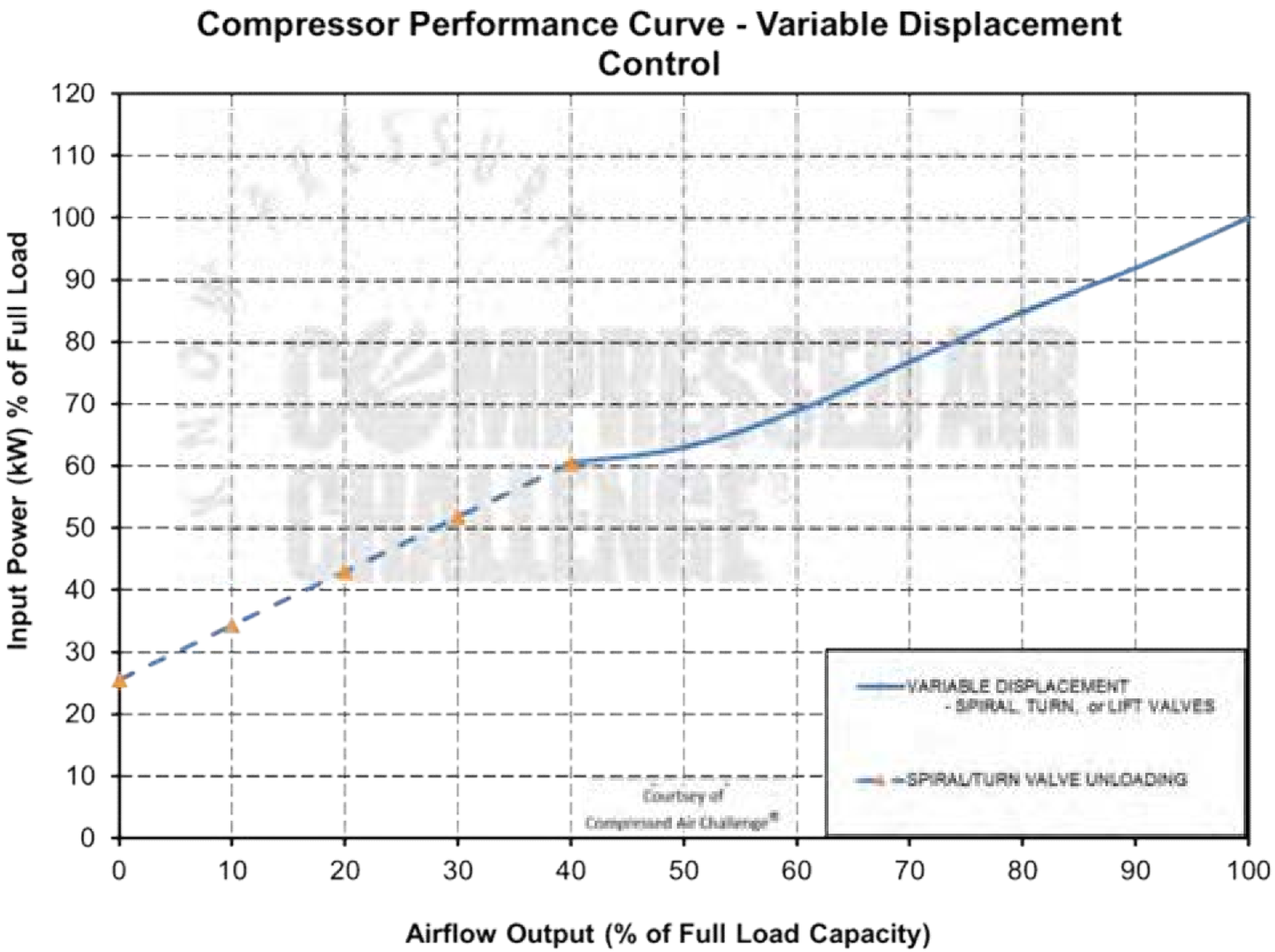
Load / Unload power curve



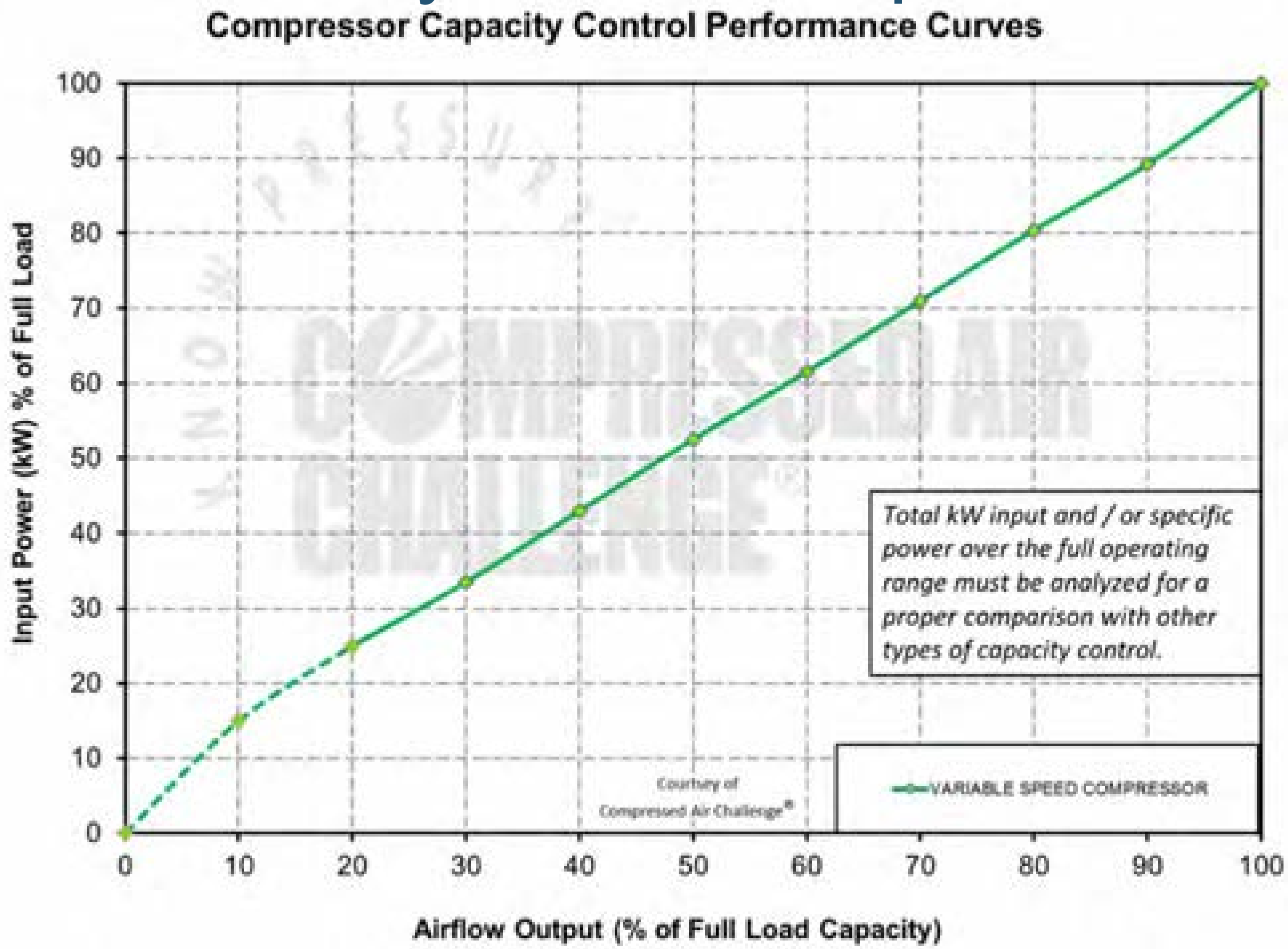
Inlet Modulation power curve for rotary screw compressors



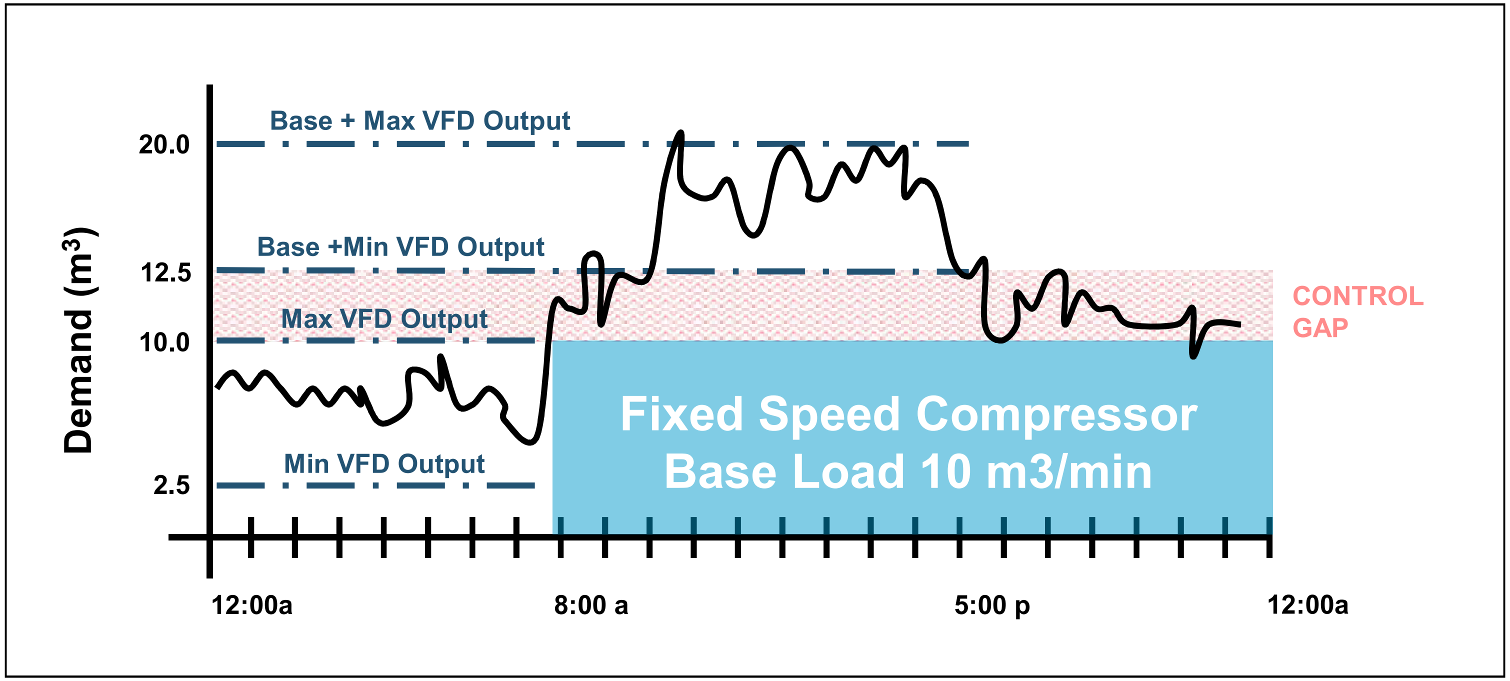
Variable displacement power curve for rotary screw compressors



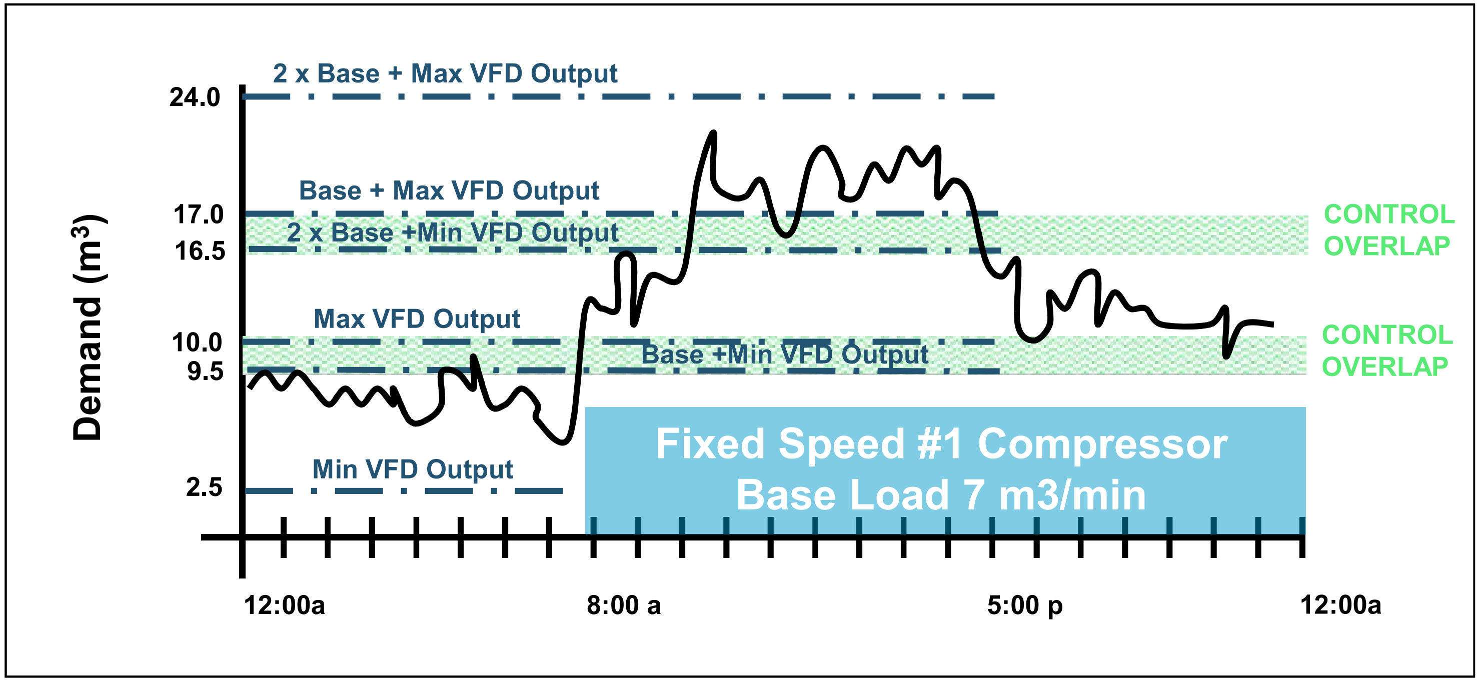
Variable speed drive power curve for rotary screw compressors



Variable Speed Control "Control Gap"



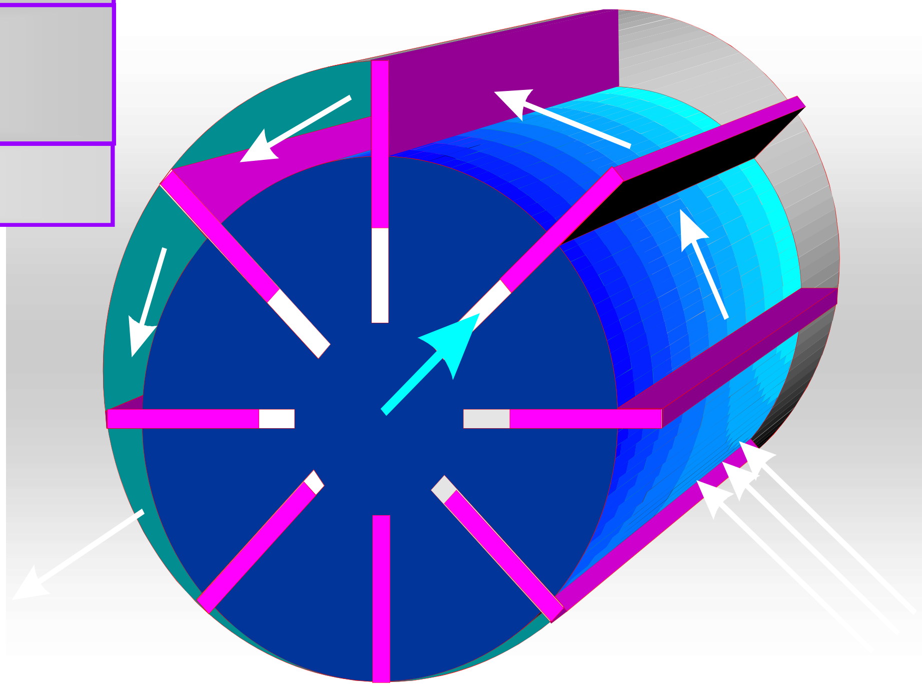
Variable Speed Control Eliminating "Control Gap"



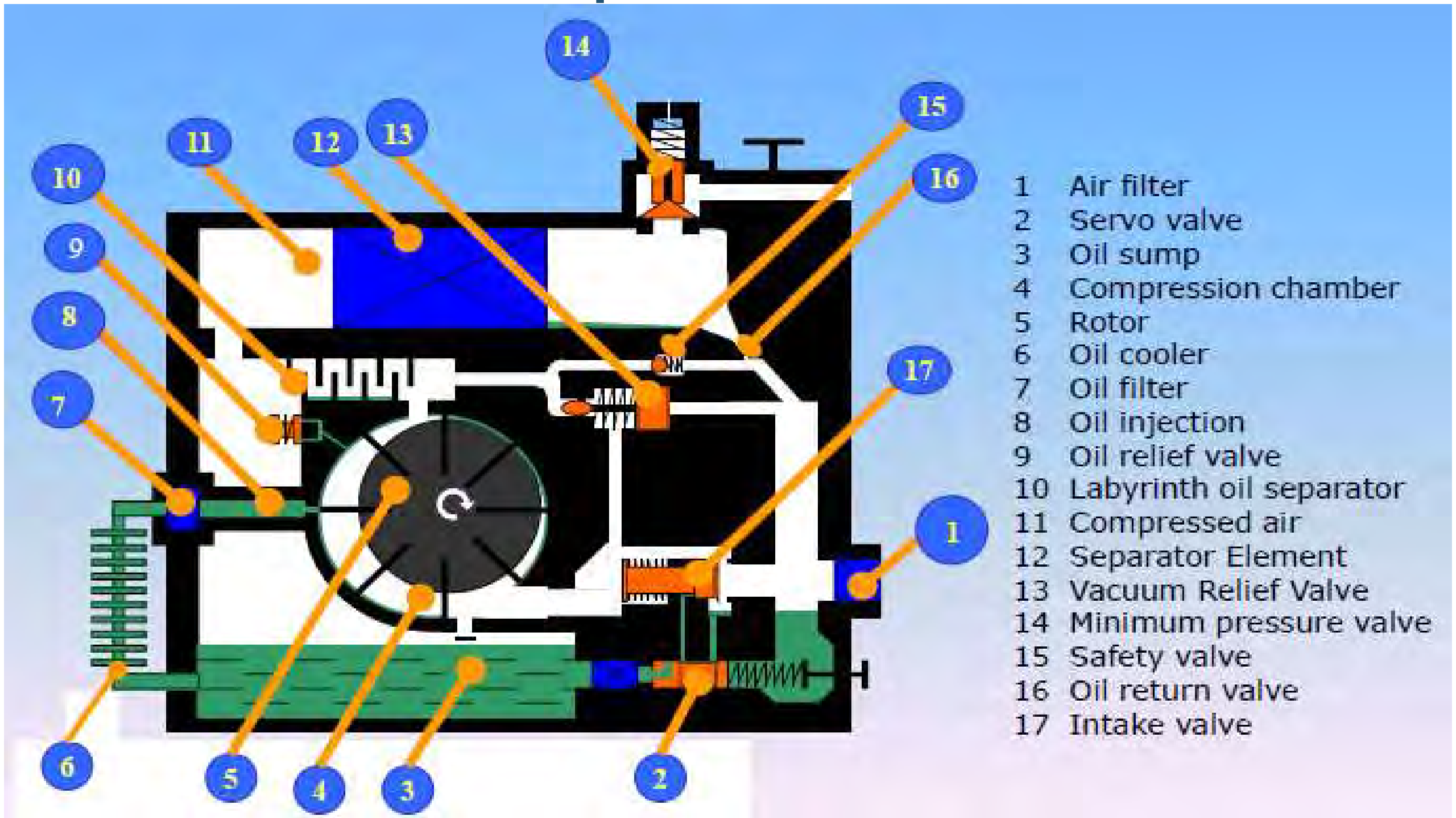
Rotary sliding vane compressors

- 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

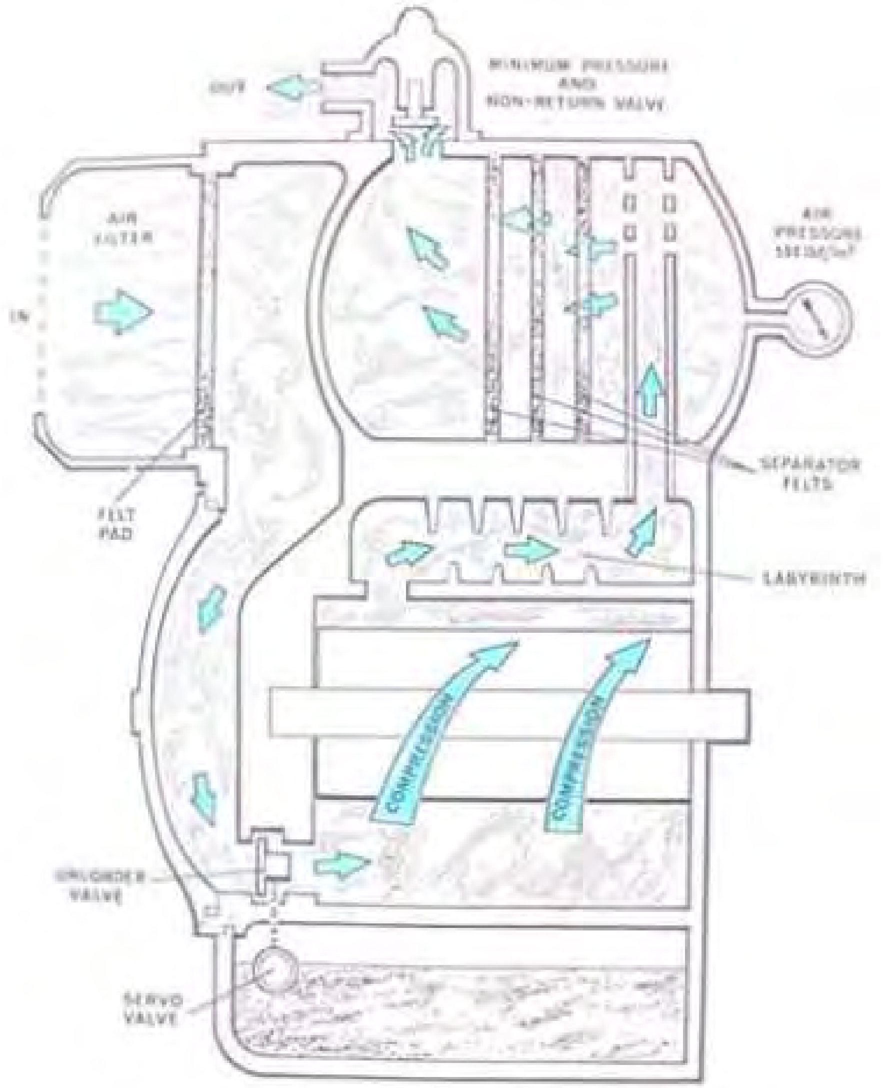
Main applications:
2 - 5 bar
Vacuum down to 1 x 10^{-3} bar



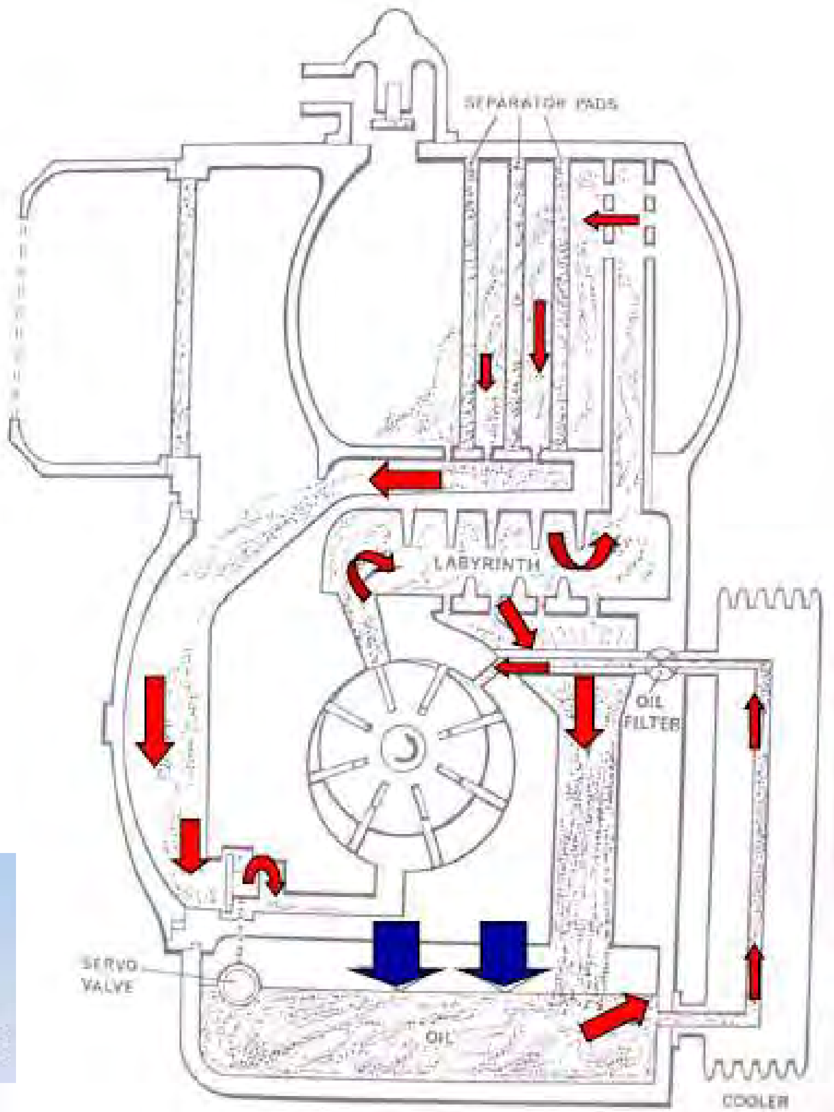
Rotary vane compressor internal operation



Rotary Vane General Air Flow Path



Rotary Vane Oil Flow Path



LEGEND :

OIL PATH

AIR PRESSURE

Advantages of rotary vane versus screw technology

COMPARISON BETWEEN ROTARY VANE & SCREW TECHNOLOGY

ROTARY VANE	OIL INJECTED ROTARY SCREW
Efficiency Superior up to 15KW, equal to or better in some instances up to 90KW.	Mostly equal to rotary vanes or better in some models up to 90KW, superior above 90KW.
Noise Level Superior as units can be offered without noise dampening enclosures.	Units cannot be sold without noise dampening enclosures.
Bearing Life 100 000 operating hours.	Maximum 50 000 hours claimed by certain manufacturers, normally only 25 000 hours.
Major Services At 10 000 operating hours.	Maximum every 6 000 operating hours.
Rotational Speed 1:1 Direct drive – 1 450 r/pm.	Normally gear or belt-driven – running between 3 000-8 000 r/pm.
Repair Costs It costs less to replace white metal bearings and they have a longer life expectancy.	Thrust and gearbox bearings are more expensive to replace and they have a relatively short life expectancy.

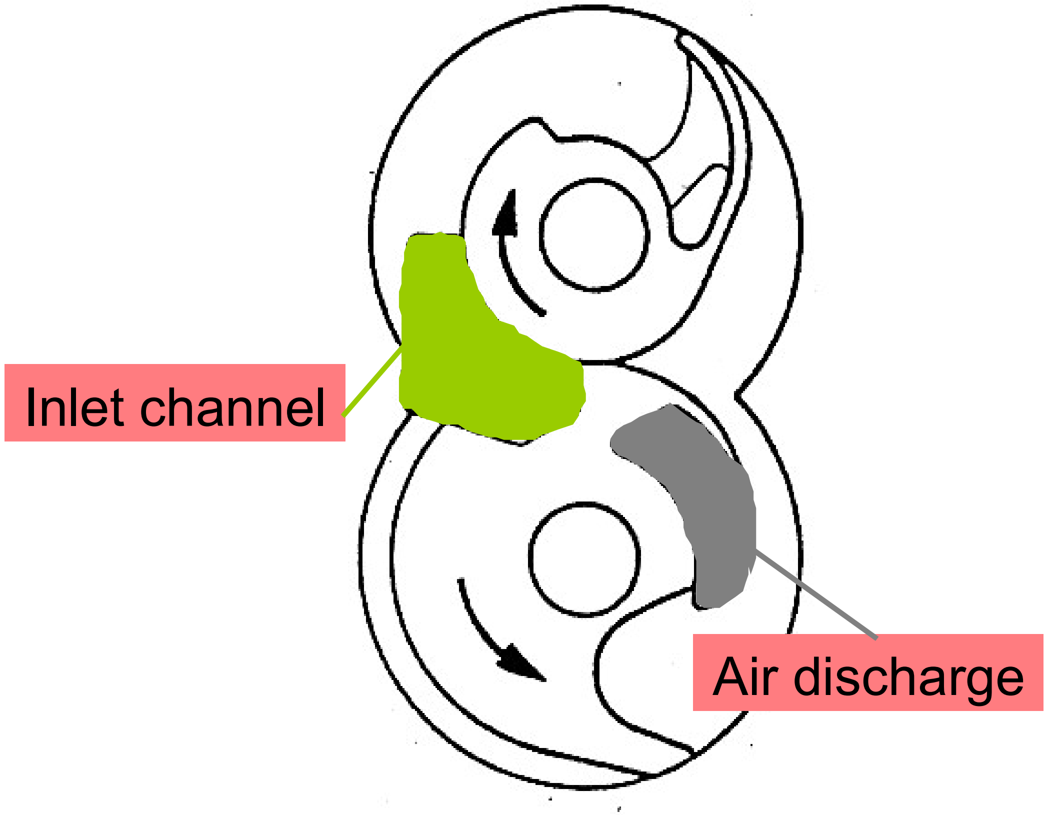
Rotary tooth compressors

Advantages:

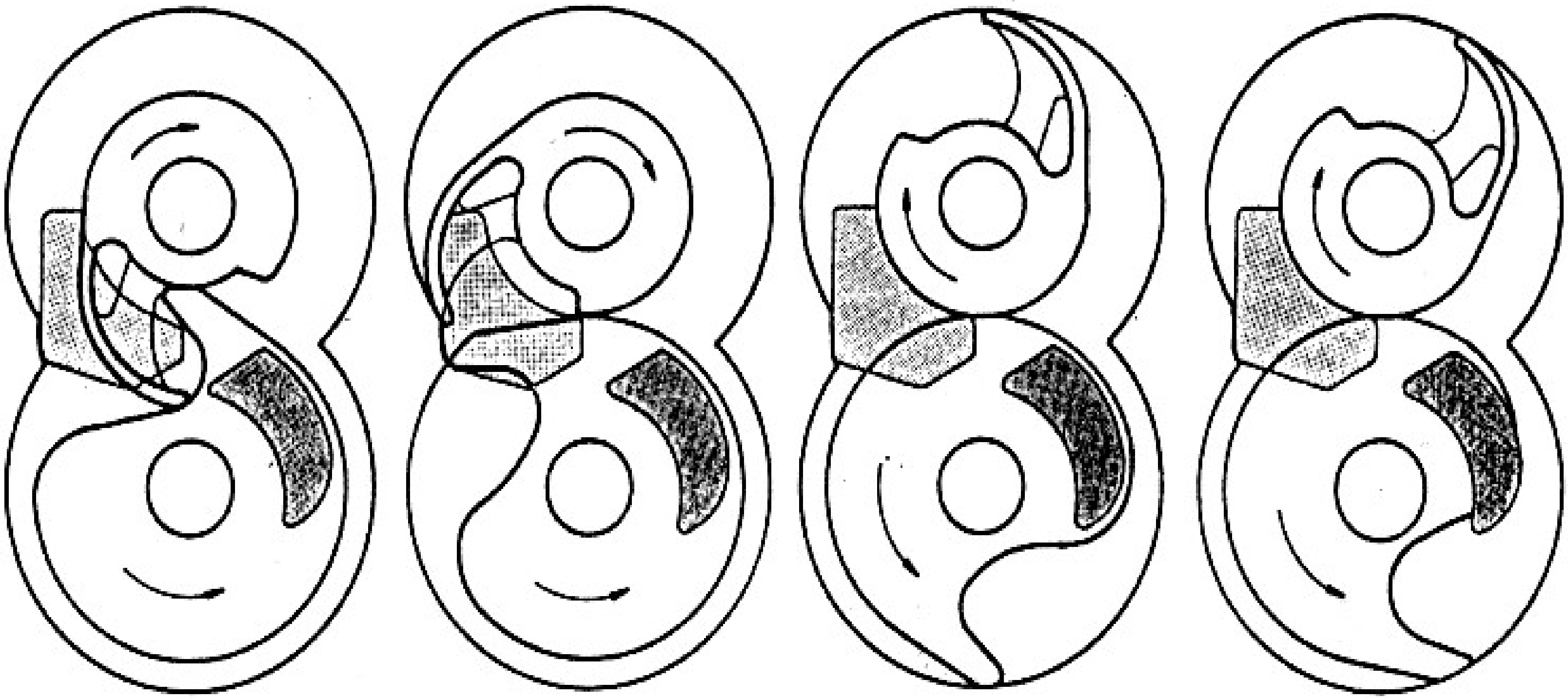
quieter running than reciprocating compressors

Disadvantages:

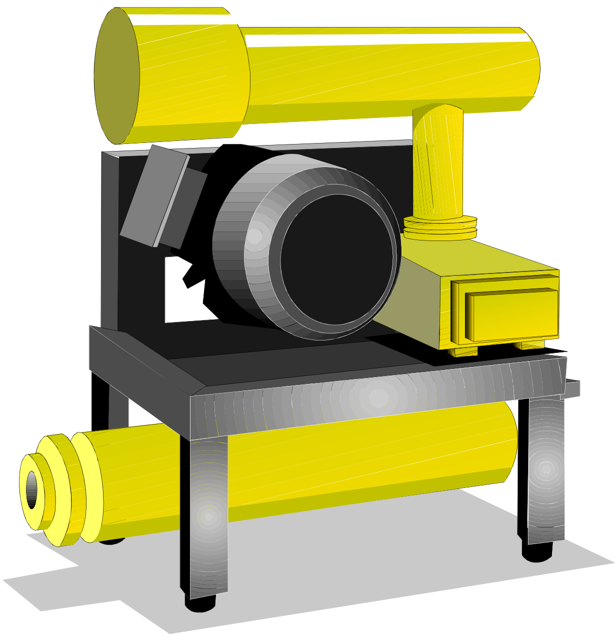
high power consumption
more expensive
8 bar max. gauge pressure



Rotary tooth compressor

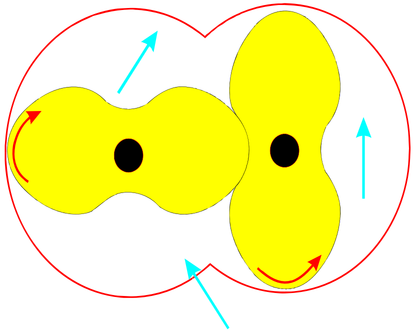


Rotary Blowers



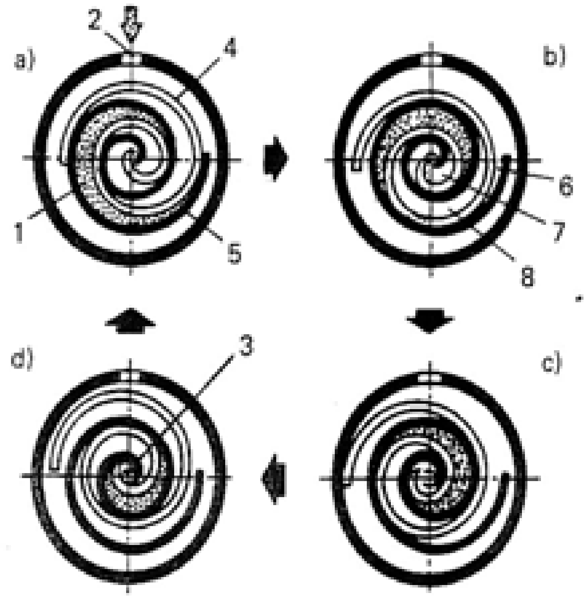
Characteristics:

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}



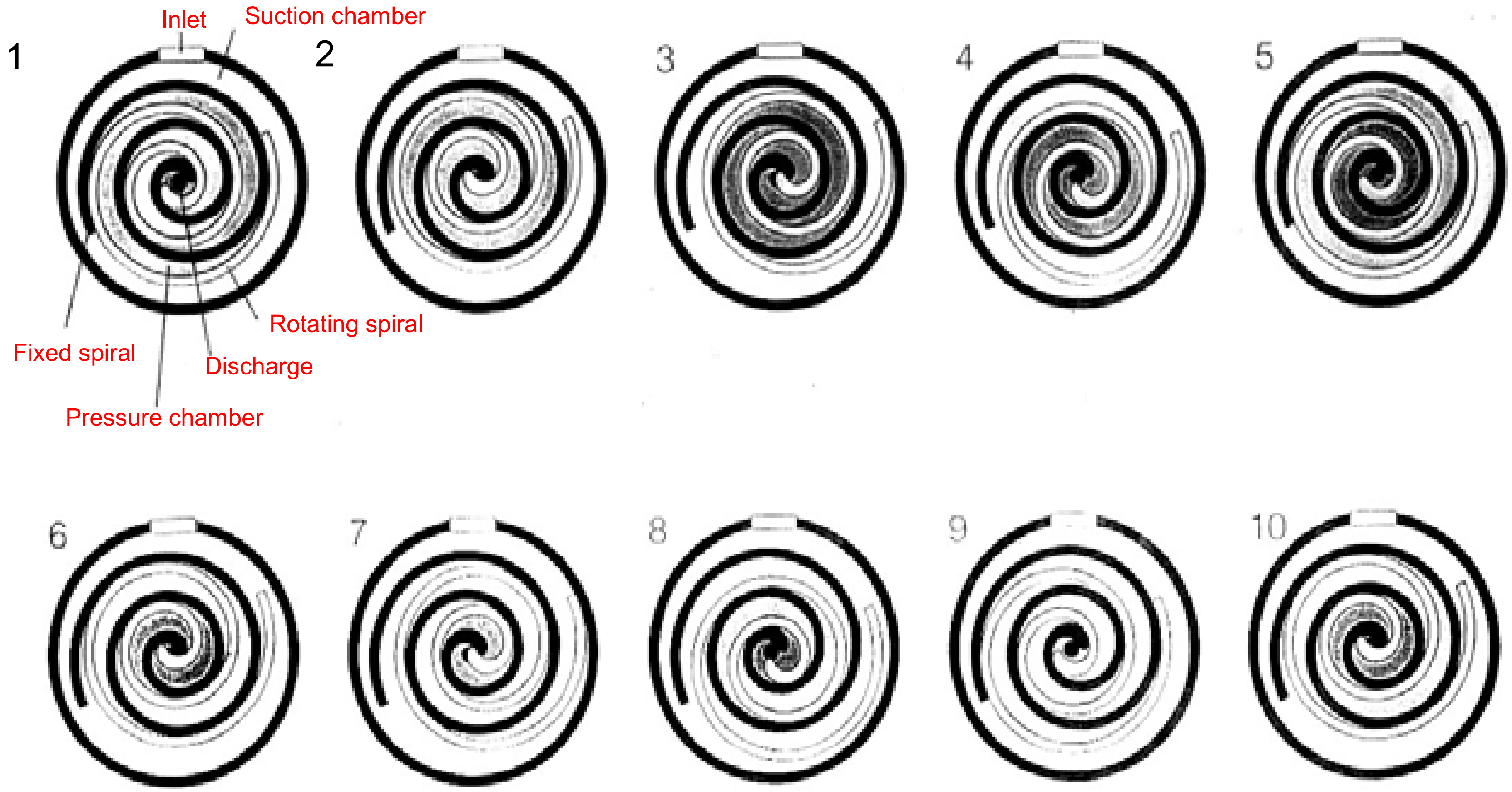
Scroll compressors

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

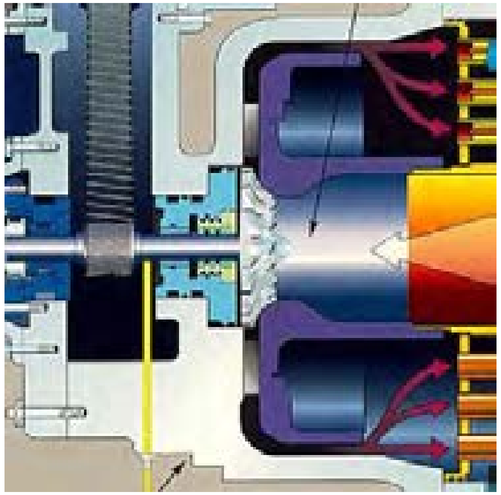
Scroll compressor

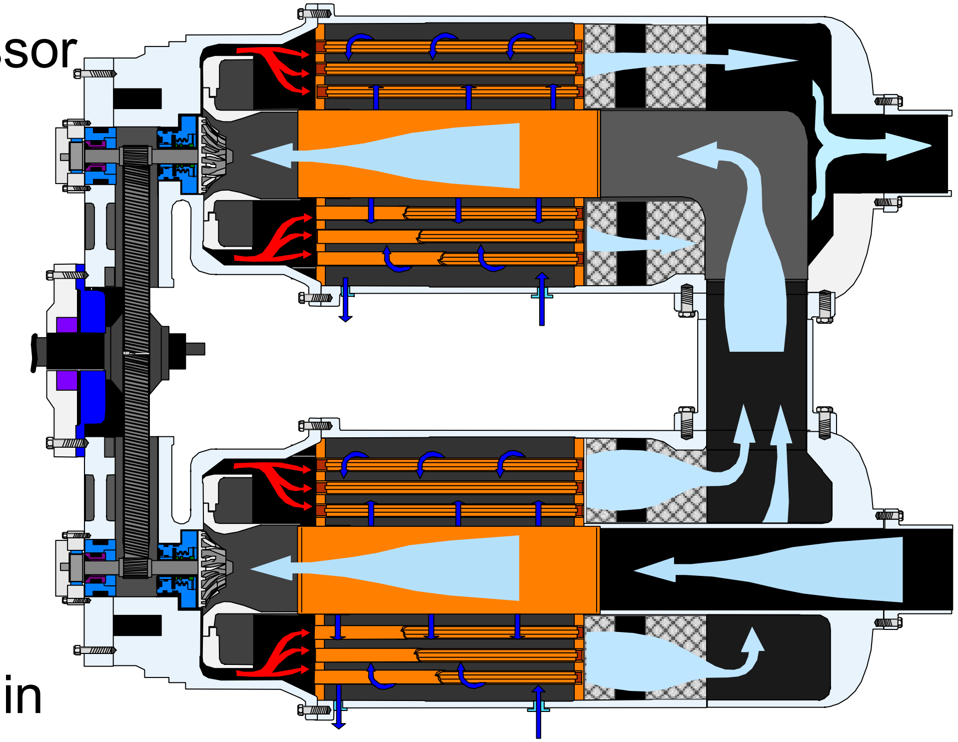


DYNAMIC AIR COMPRESSORS

Turbo compressors

Centrifugal turbo compressor





Characteristics:

Capacity: 35 - 1200 m^3/min

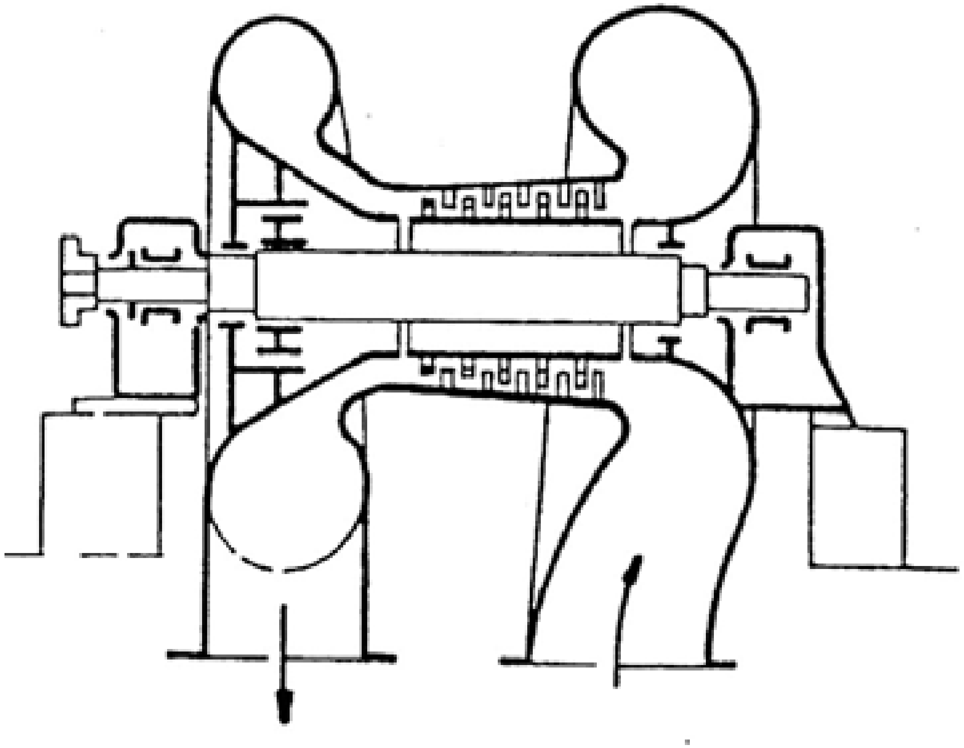
Stages: 1 - 6

Pressure range: 3 - 40 bar (g)

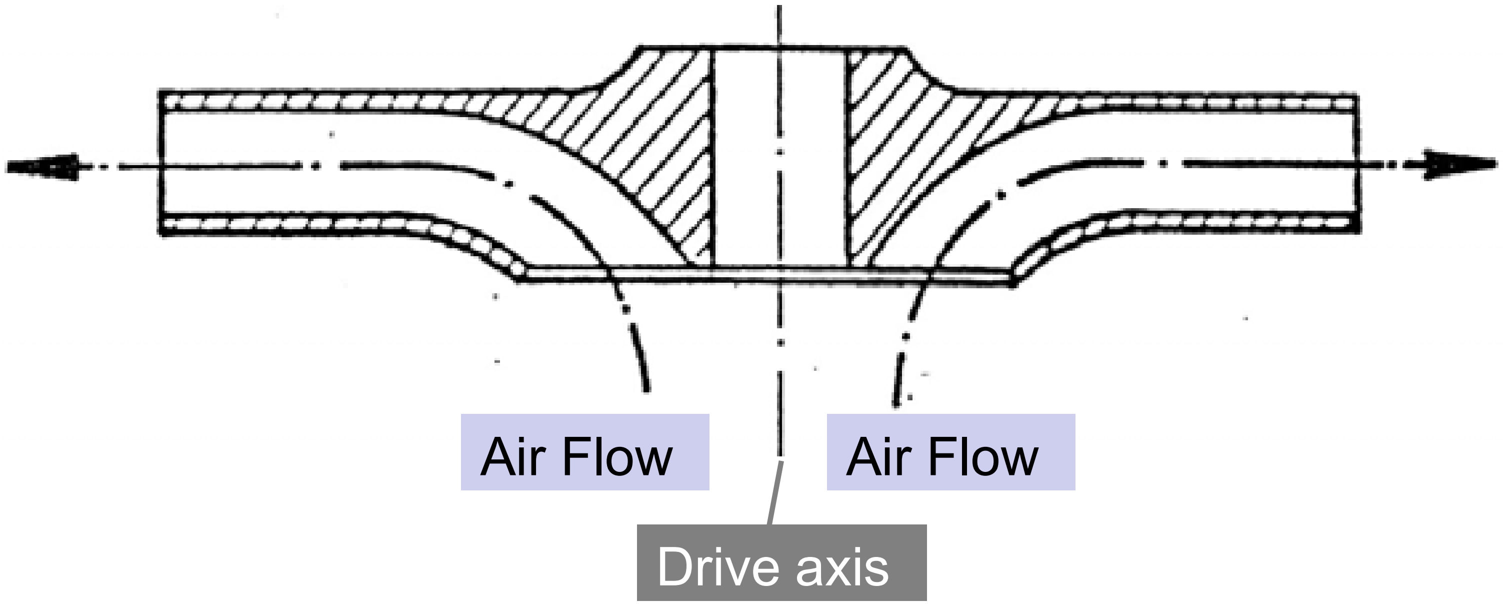
Speed range: 3000 - 80000 min^{-1}

Axial compressor

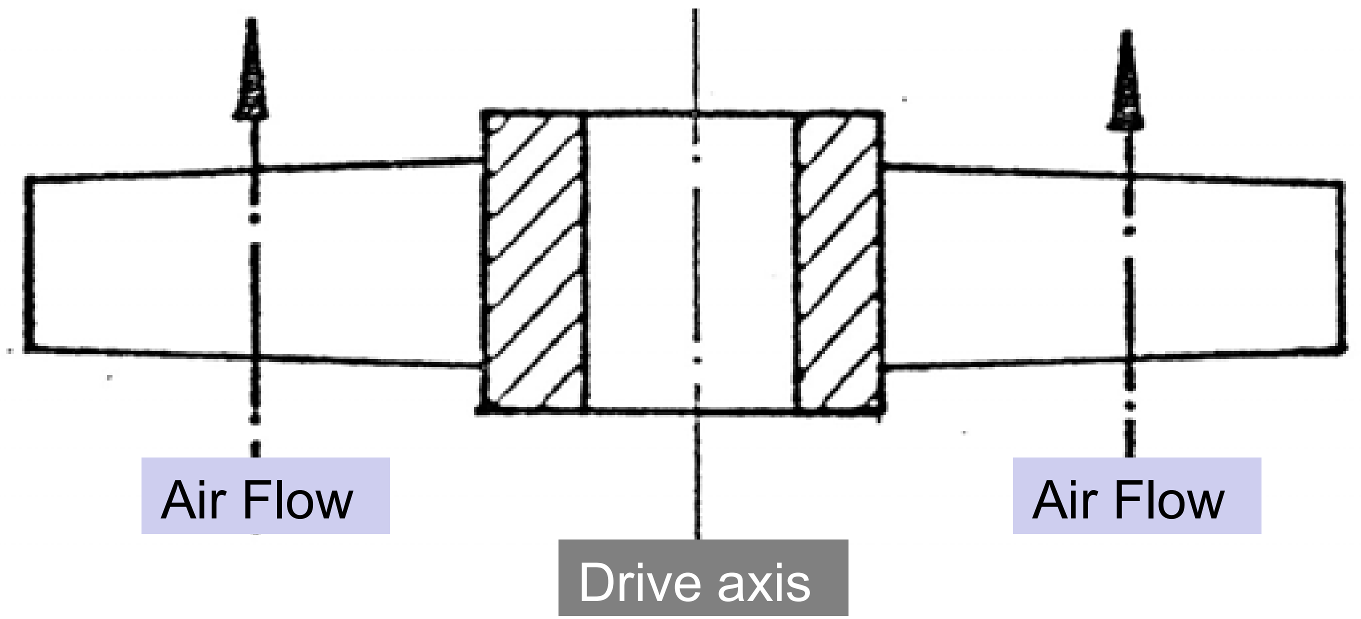
Characteristics:
Capacity: 600 - 30000 m^3/min
Stages: 10 - 25
Pressure range: 0 - 6 bar (g)
Speed range: 6000 - 20000 min^{-1}



Centrifugal turbo compressor - Centrifugal impeller



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

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

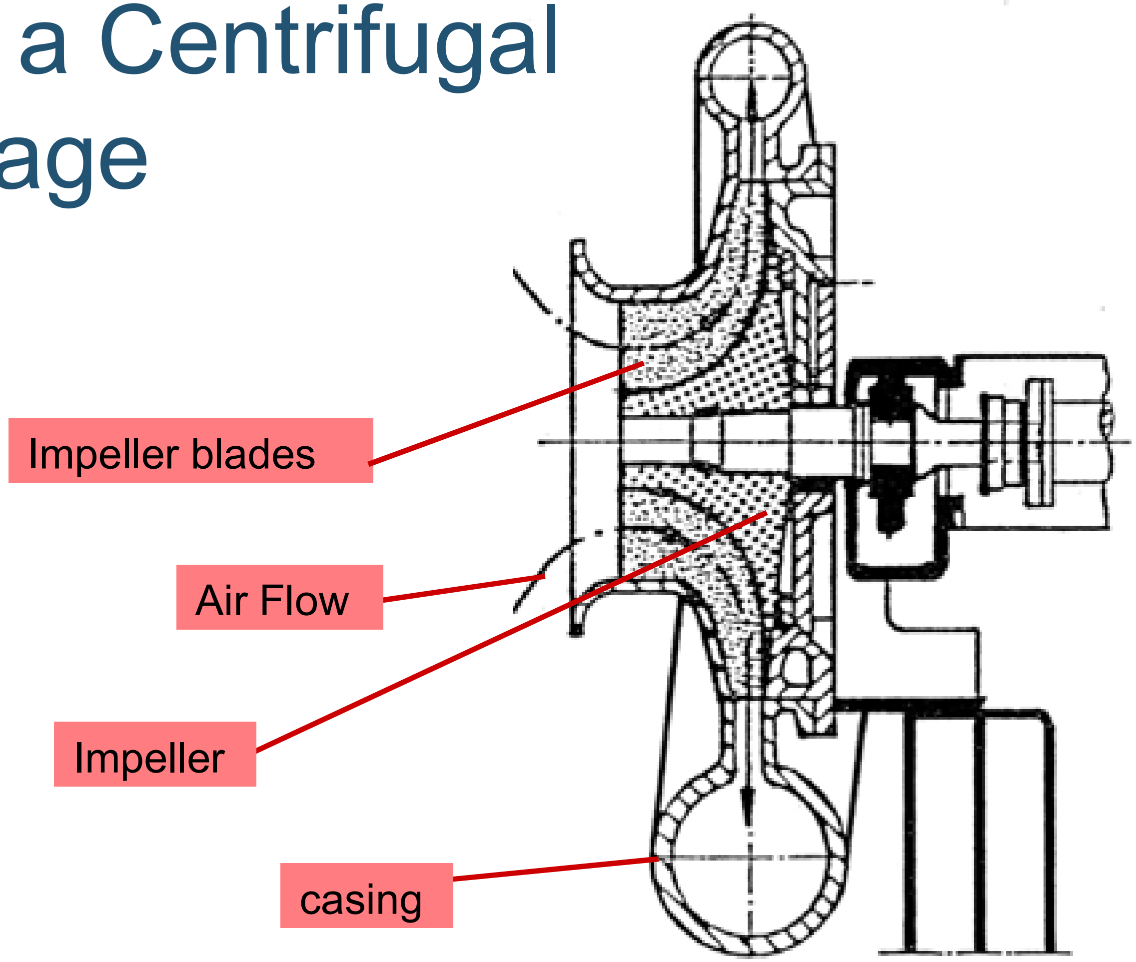
- Displacement Control -> Pressure Band

- Special Considerations when Controlling Mixed Systems

Centrifugal Compressors

- Centrifugal Compressor Drivers
  - Range 150 kW through 10,000+ kW
  - 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

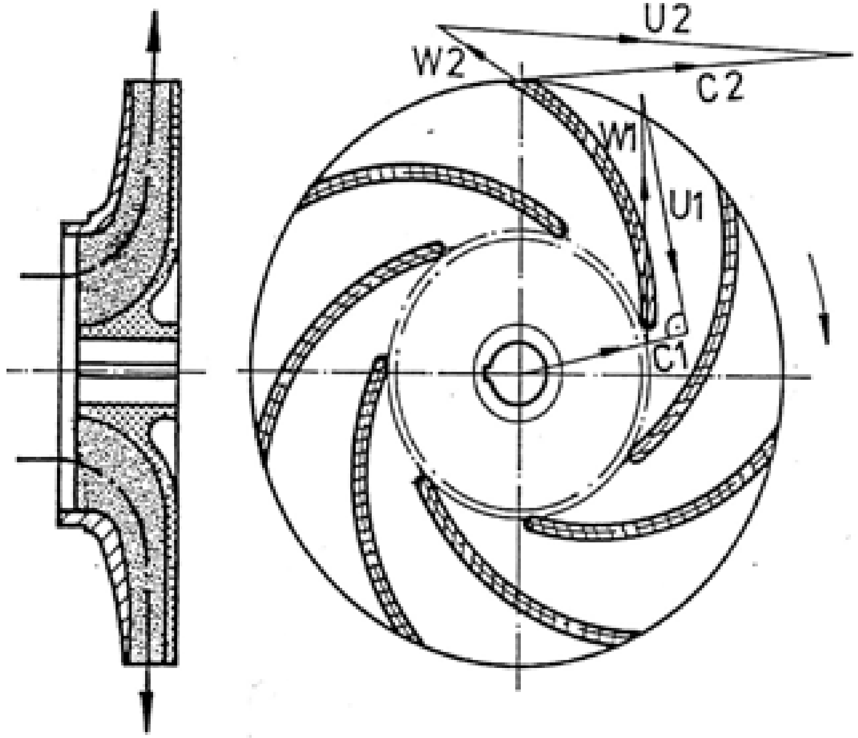
Construction of a Centrifugal compression stage



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

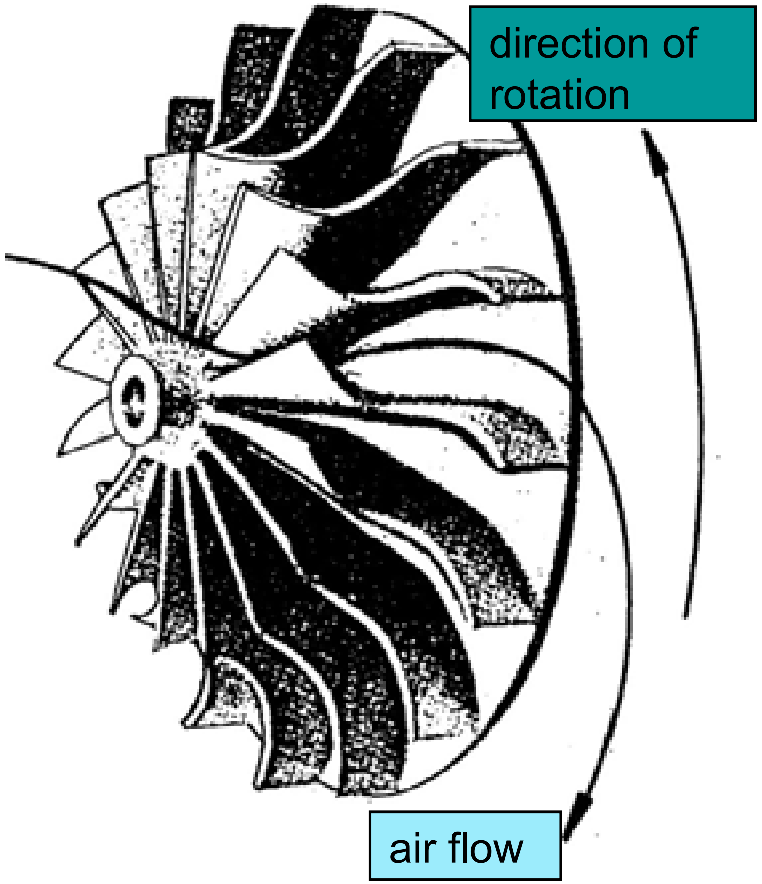
At outlet
C2 = velocity of the air to be compressed
U2 = peripheral speed of the compressor impeller
W2 = relative velocity between air and compressor impeller



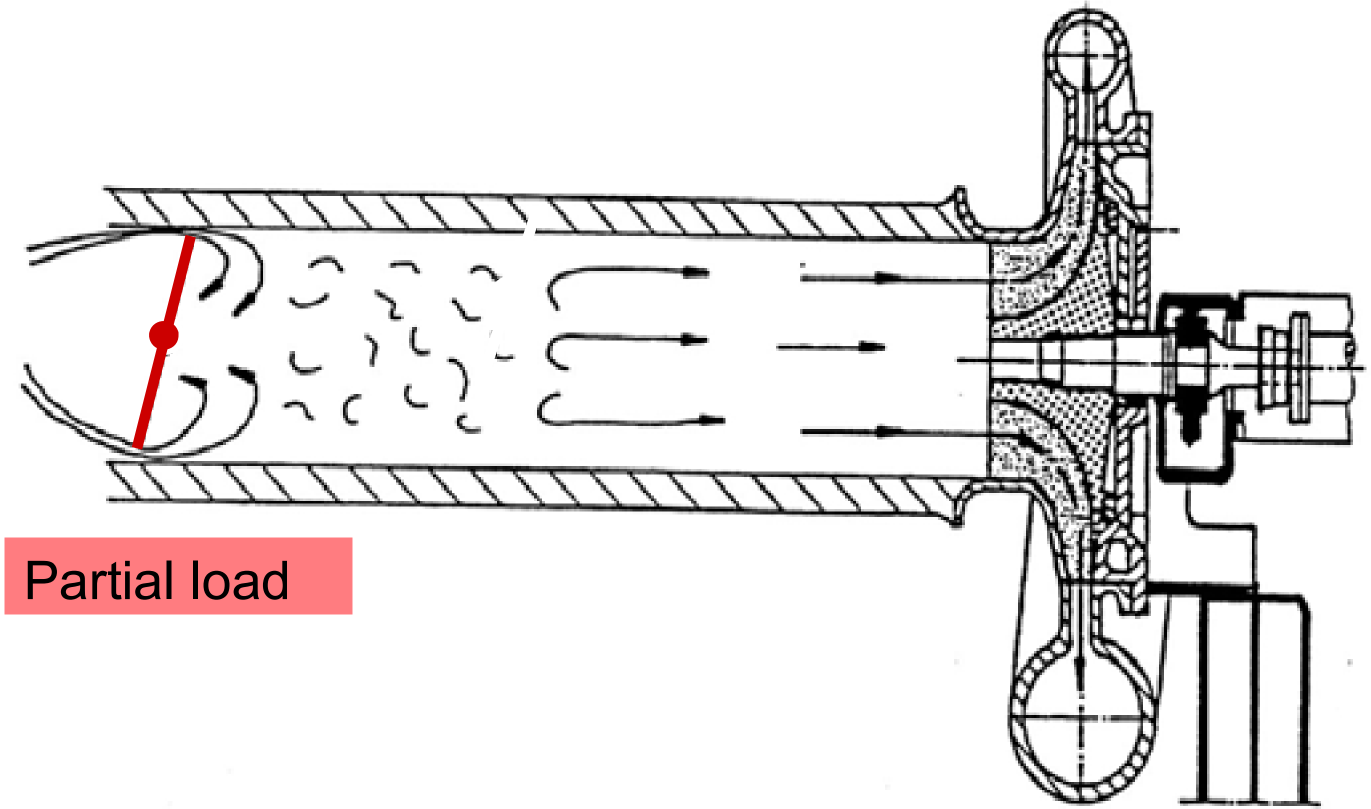
Impeller profile

centrifugal impeller, singlesided

backward-bent impeller vanes

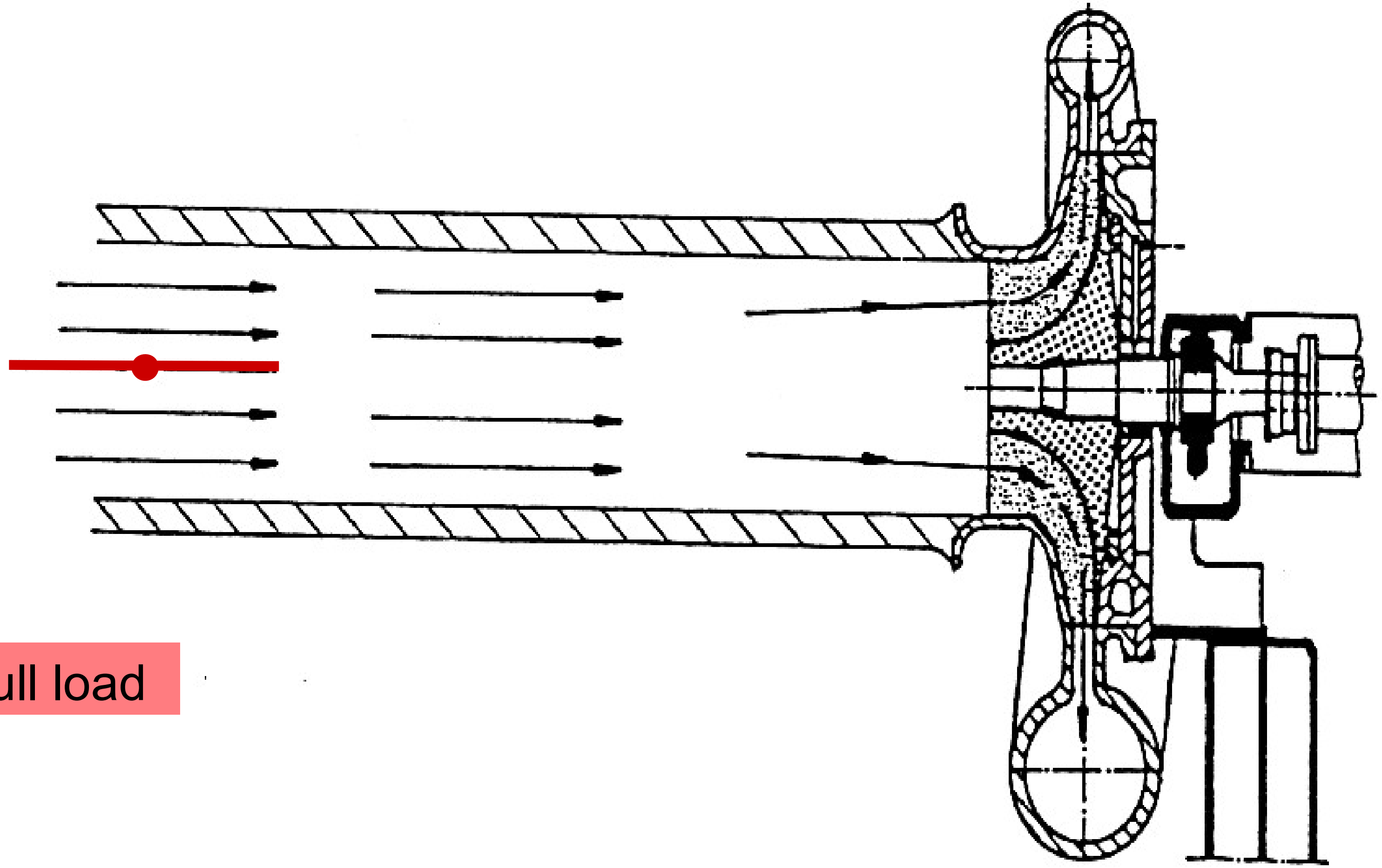


Turbo compressor: Throttle control



Partial load

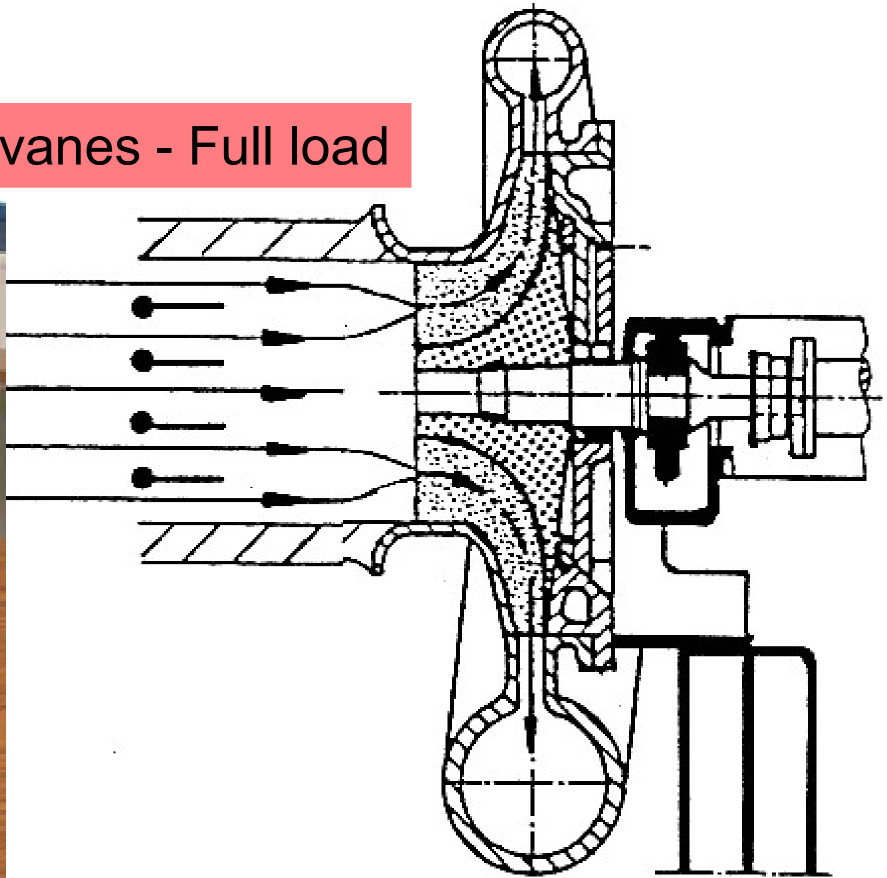
Turbo compressor: Throttle control



Full load

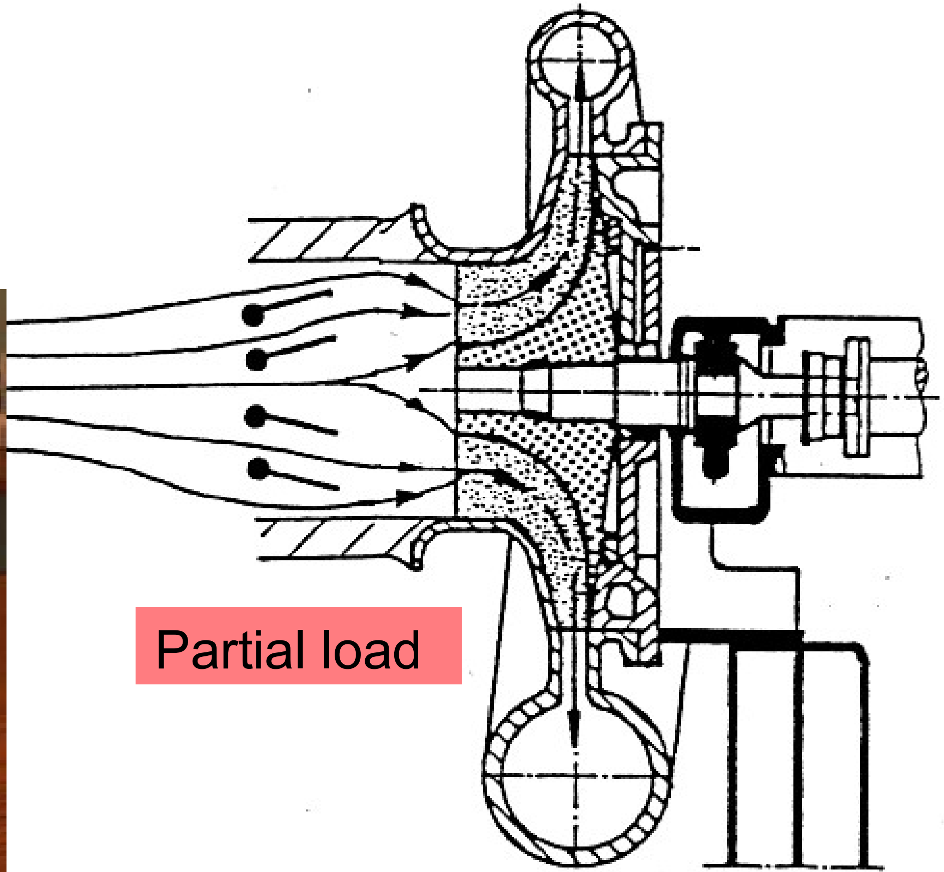
Turbo compressor: Volume control

Inlet guide vanes - Full load



Turbo compressor: Volume control

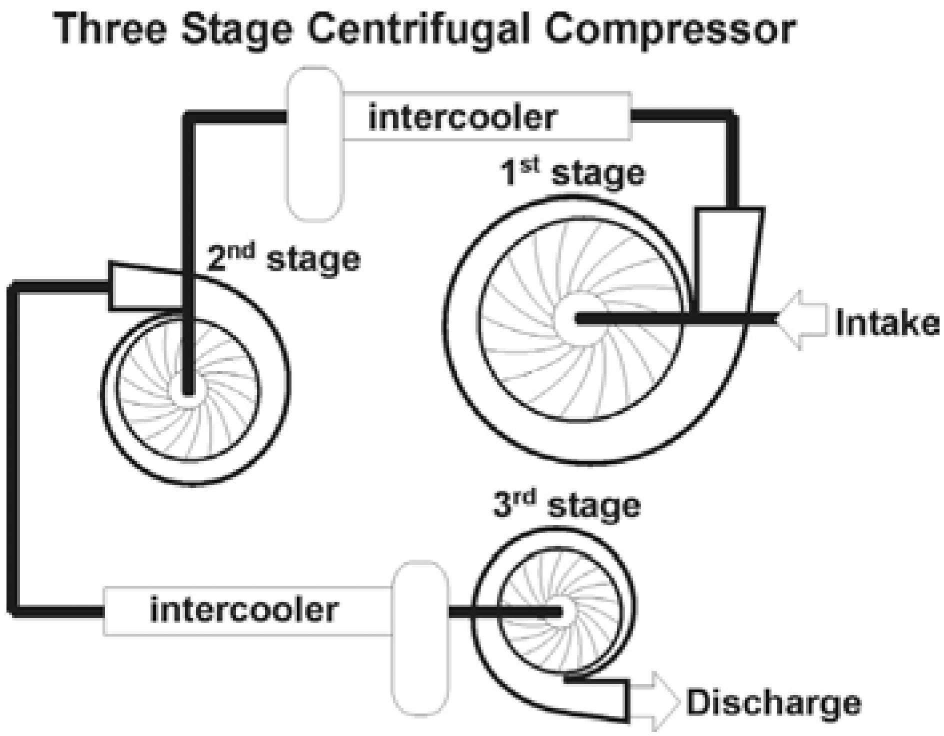
Inlet Guide Vanes – Closed



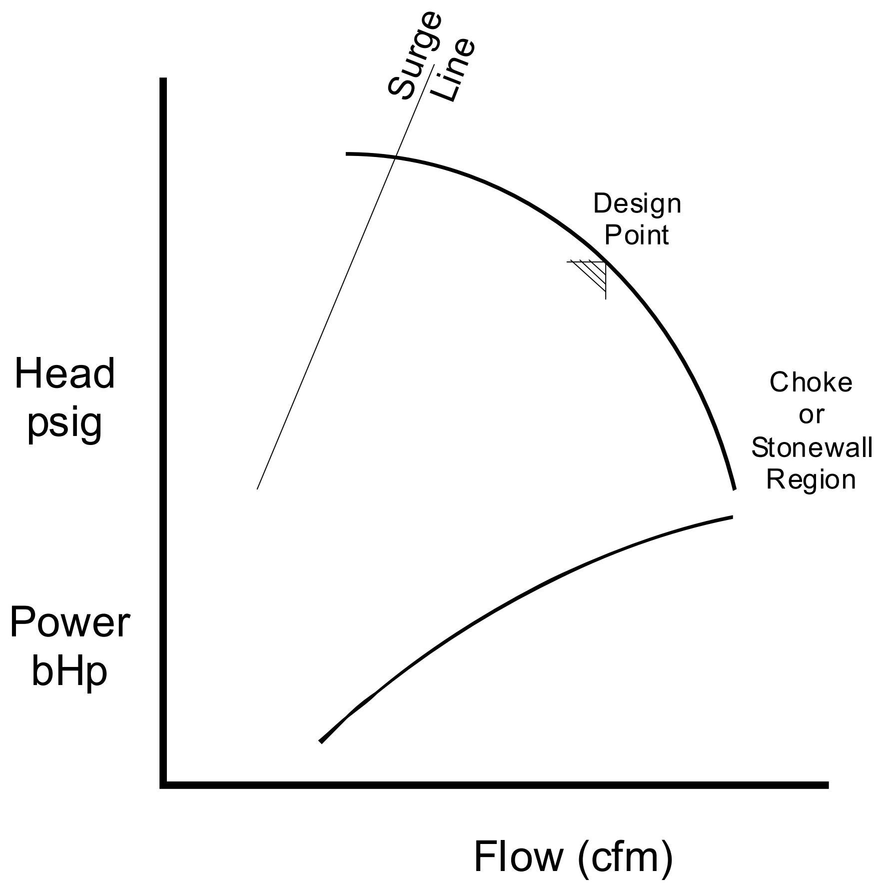
Partial load

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

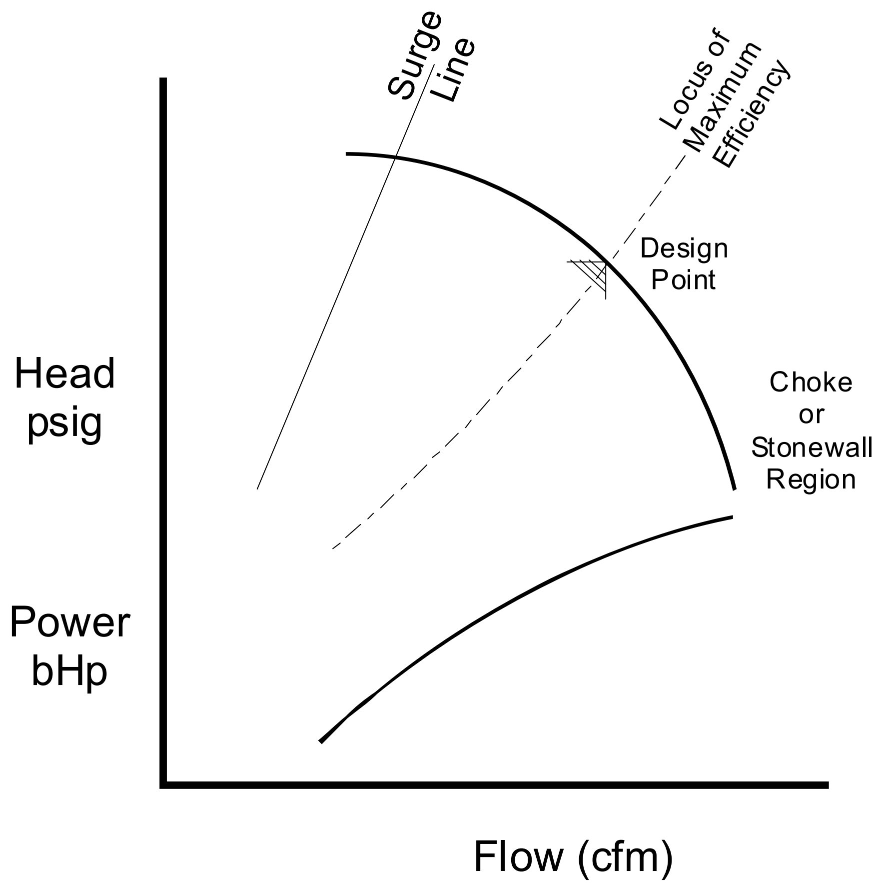


Centrifugal Compressor Performance



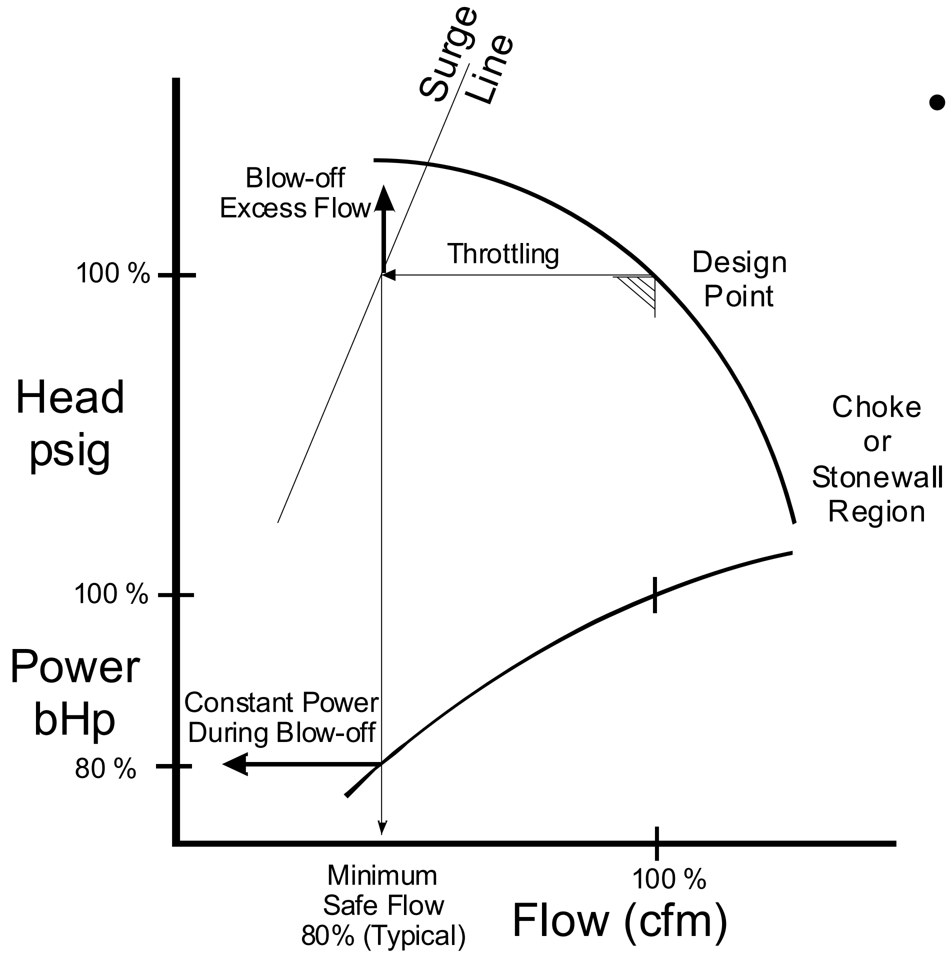
- Dynamic Compression
  - Flow –vs – Pressure – Power Curve

Centrifugal Compressor Performance



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

Centrifugal Compressor Performance



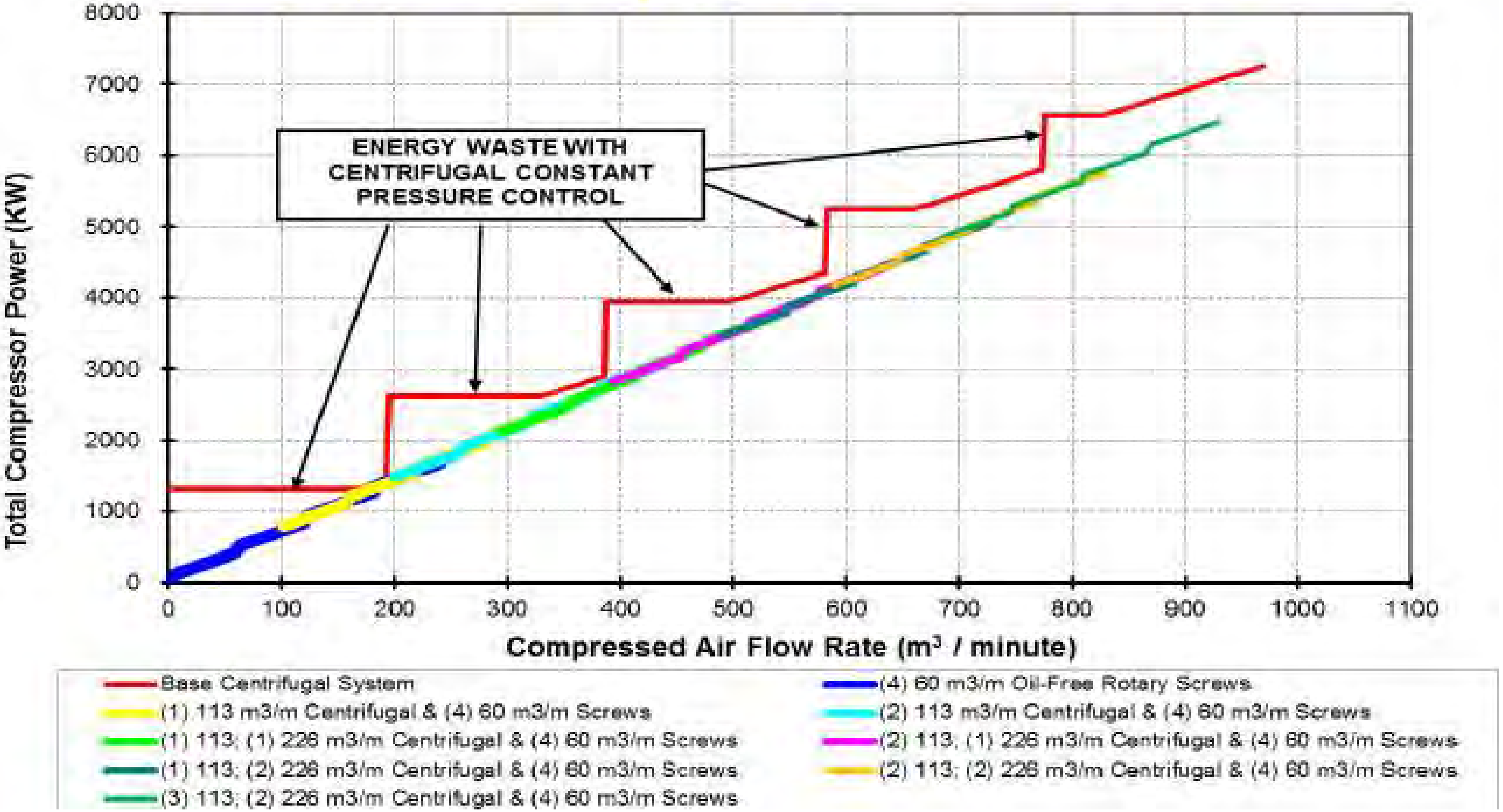
- Dynamic Compression
  - Throttling Range – Blow-off

Compressor Power (KW) -vs- Compressed Air Flow

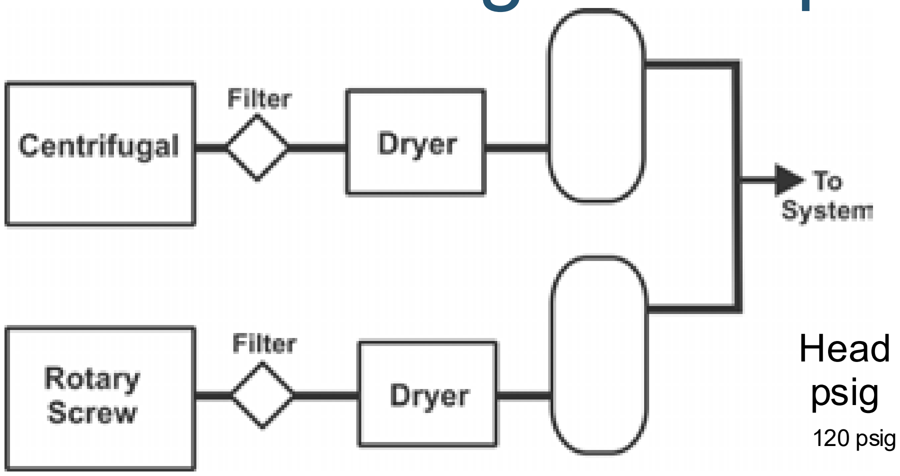
Qty (4) 226 m³/m Centrifugal Compressors (Sequenced w/ Combined Turndown); Constant Pressure

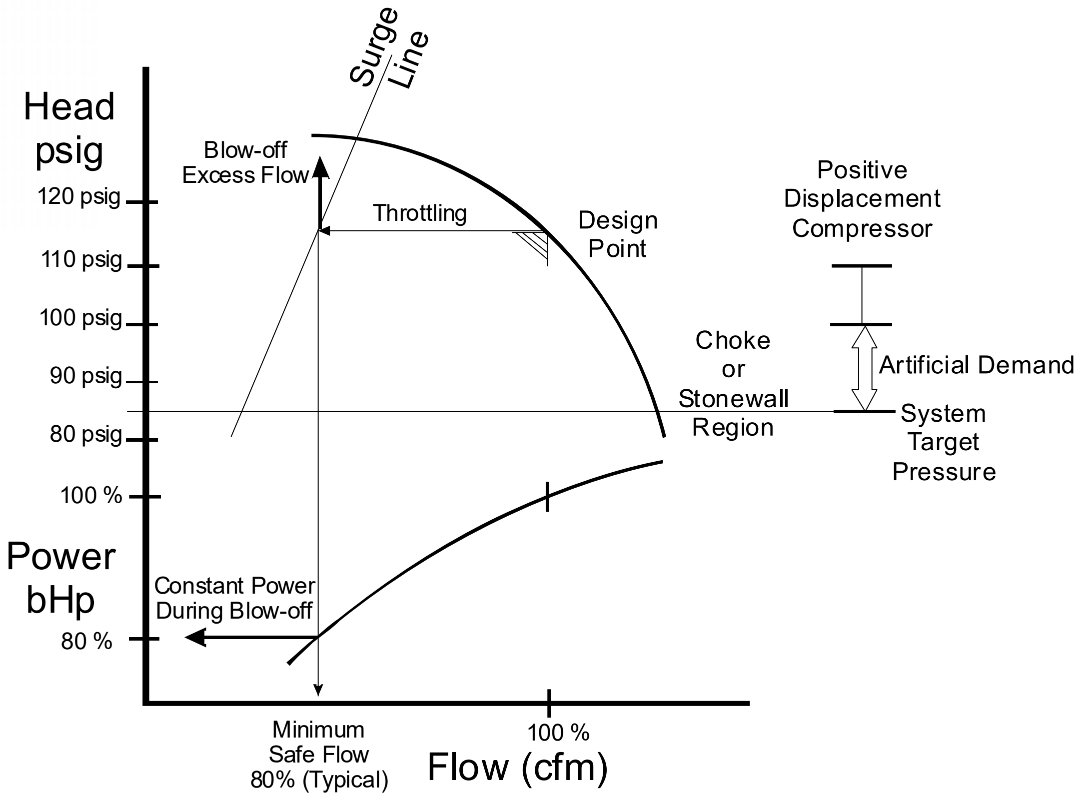
Compared to

Base Load Qty (2) 226 m³/m Centrifugal & Qty (3) 113 m³/m Centrifugal Air Compressors
Trim & Swing Qty (4) 40 m³/m Oil-Free Two Stage Rotary Screw Compressors; On-Line / Off-Line Control

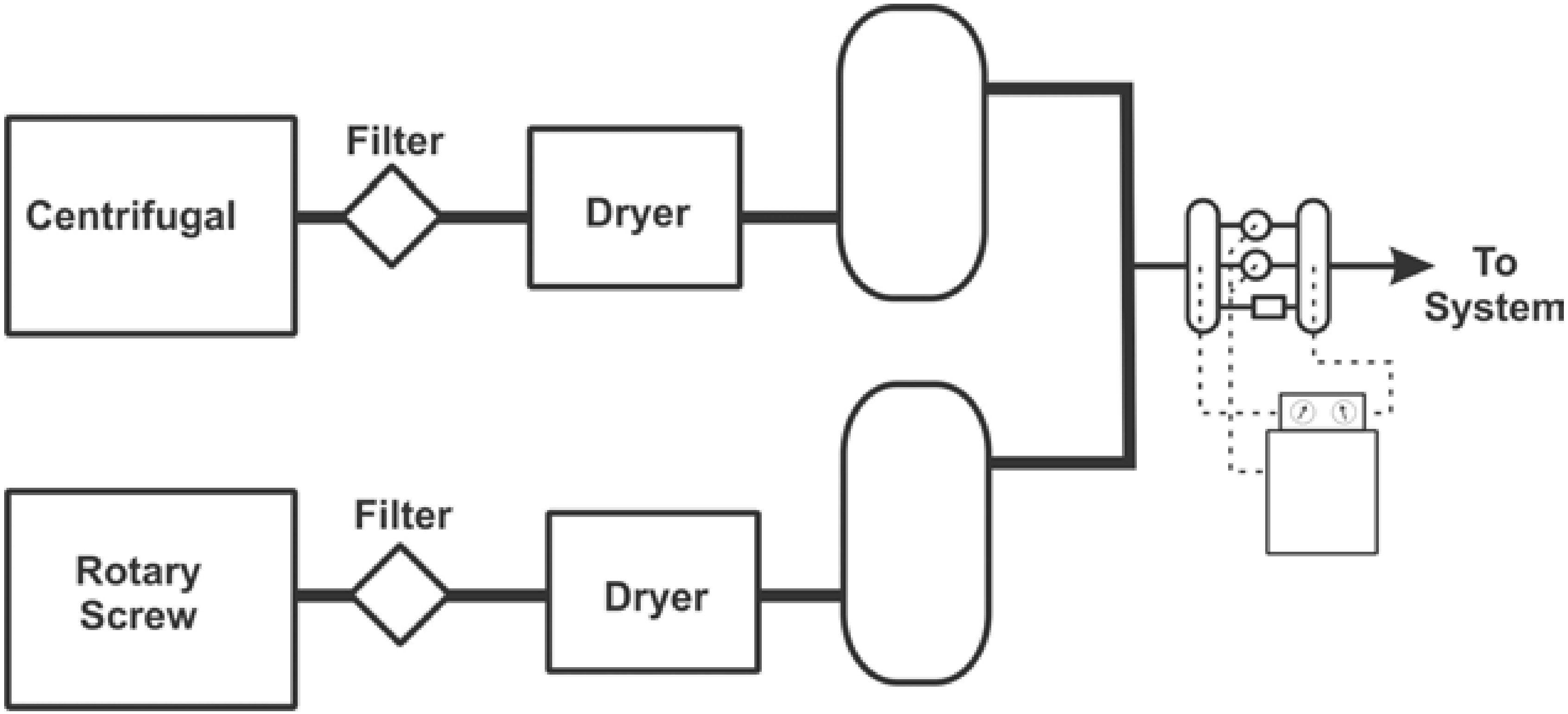


Centrifugal Compressor Performance

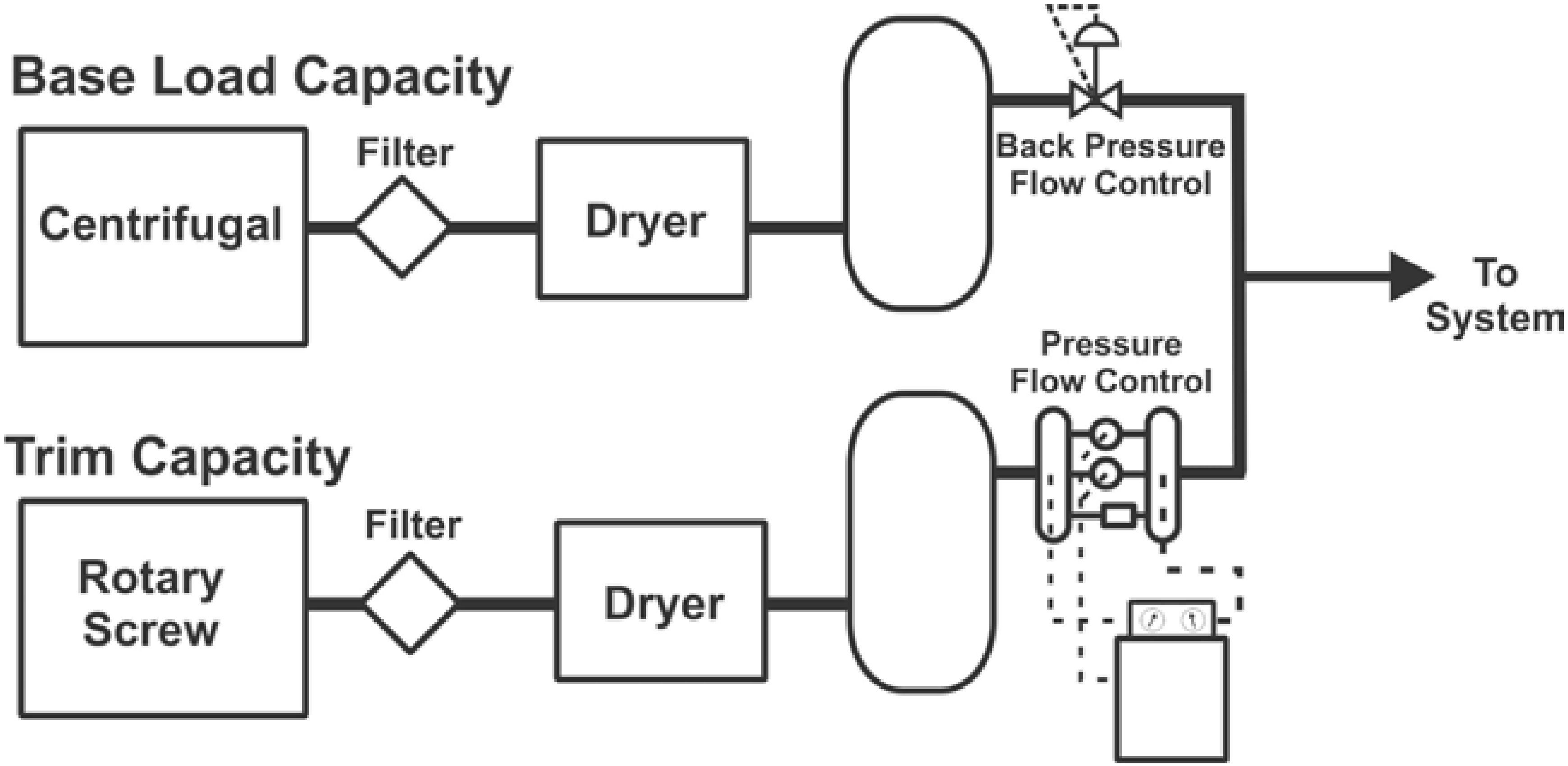




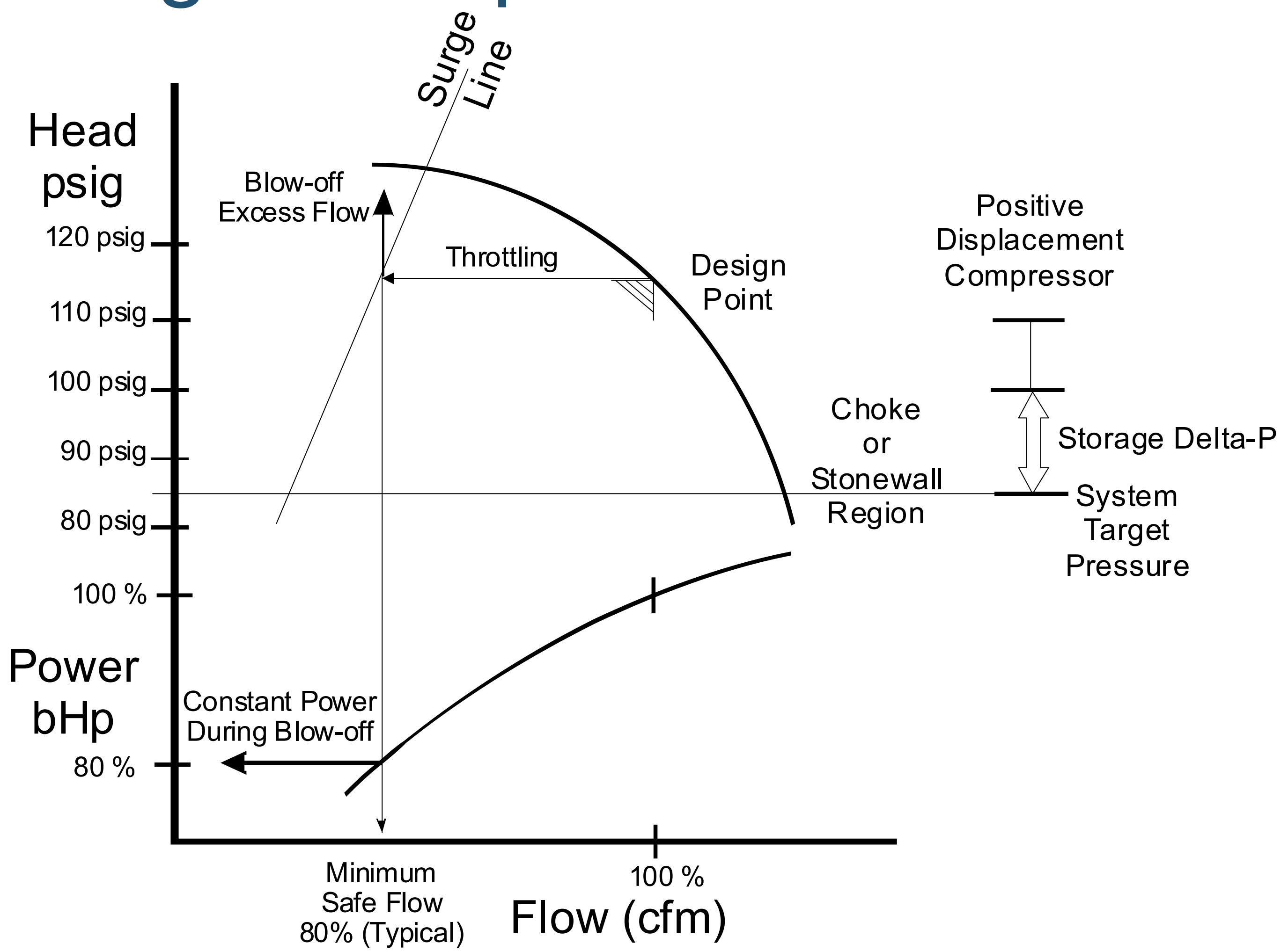
Centrifugal Compressor Performance



Centrifugal Compressor Performance



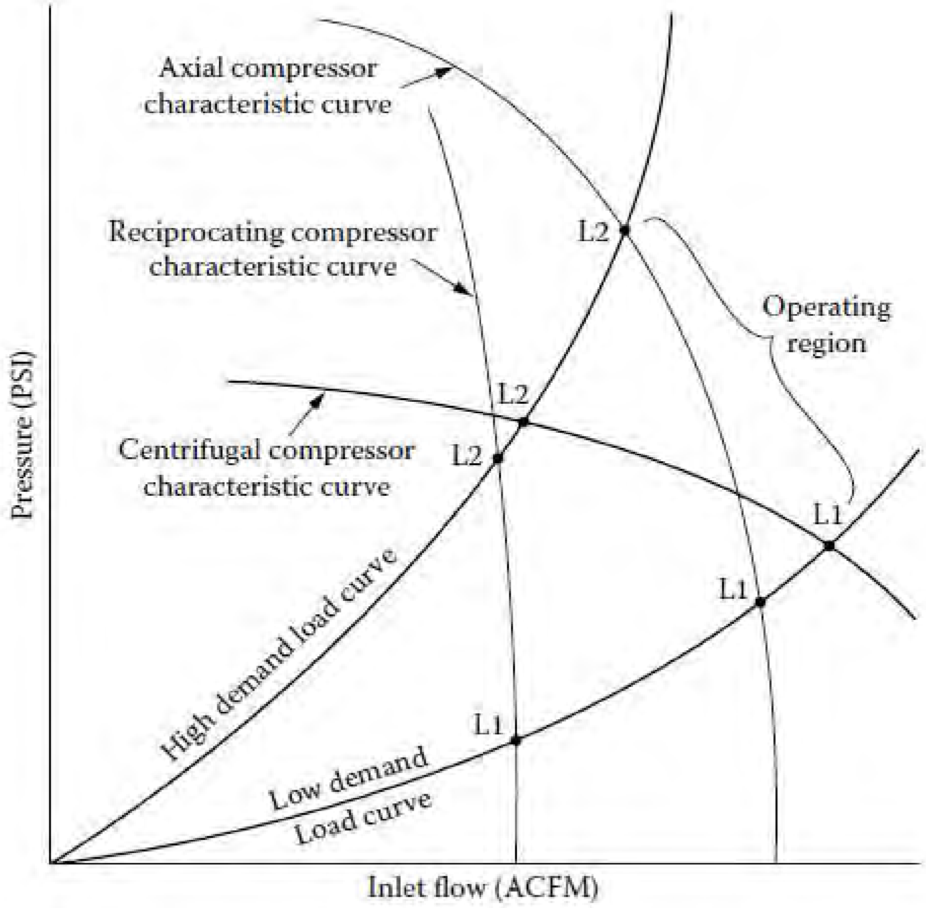
Centrifugal Compressor Performance



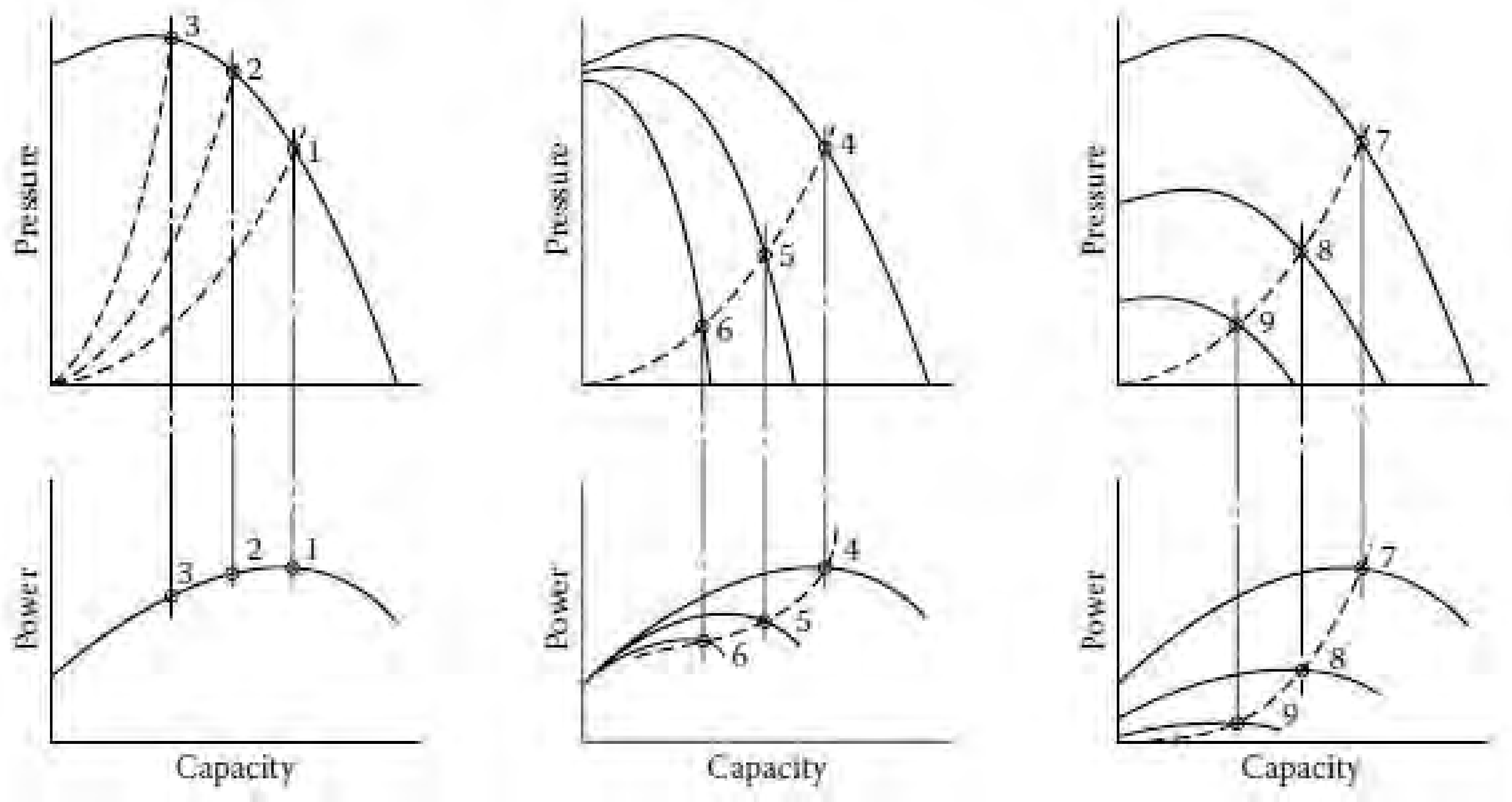
Centrifugal Compressor Performance

- 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

Characteristic curves comparison of different compressor types

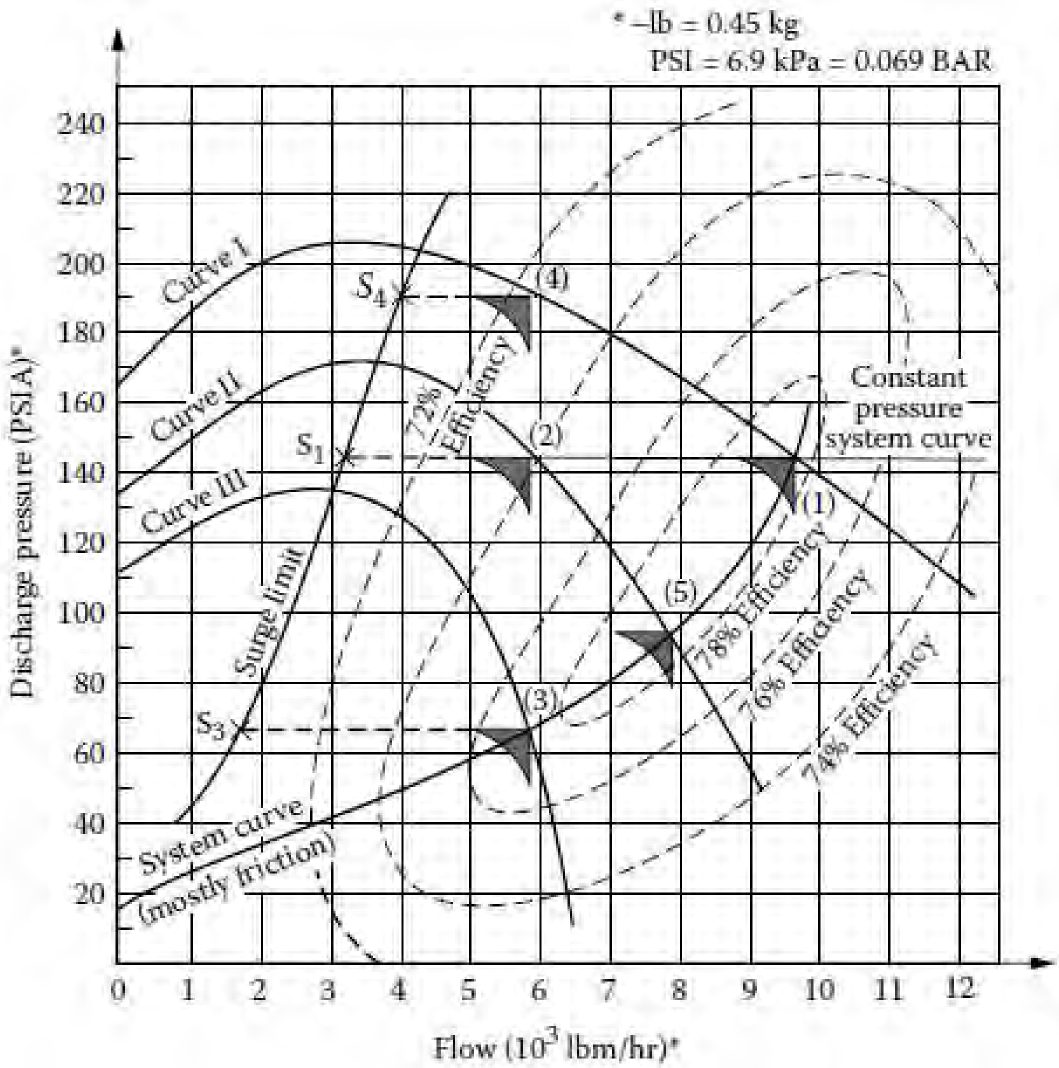


Centrifugal Compressor Throttling



Discharge throttling (left), suction throttling (centre), and variable speed control (right).

Centrifugal Compressor Control Methods

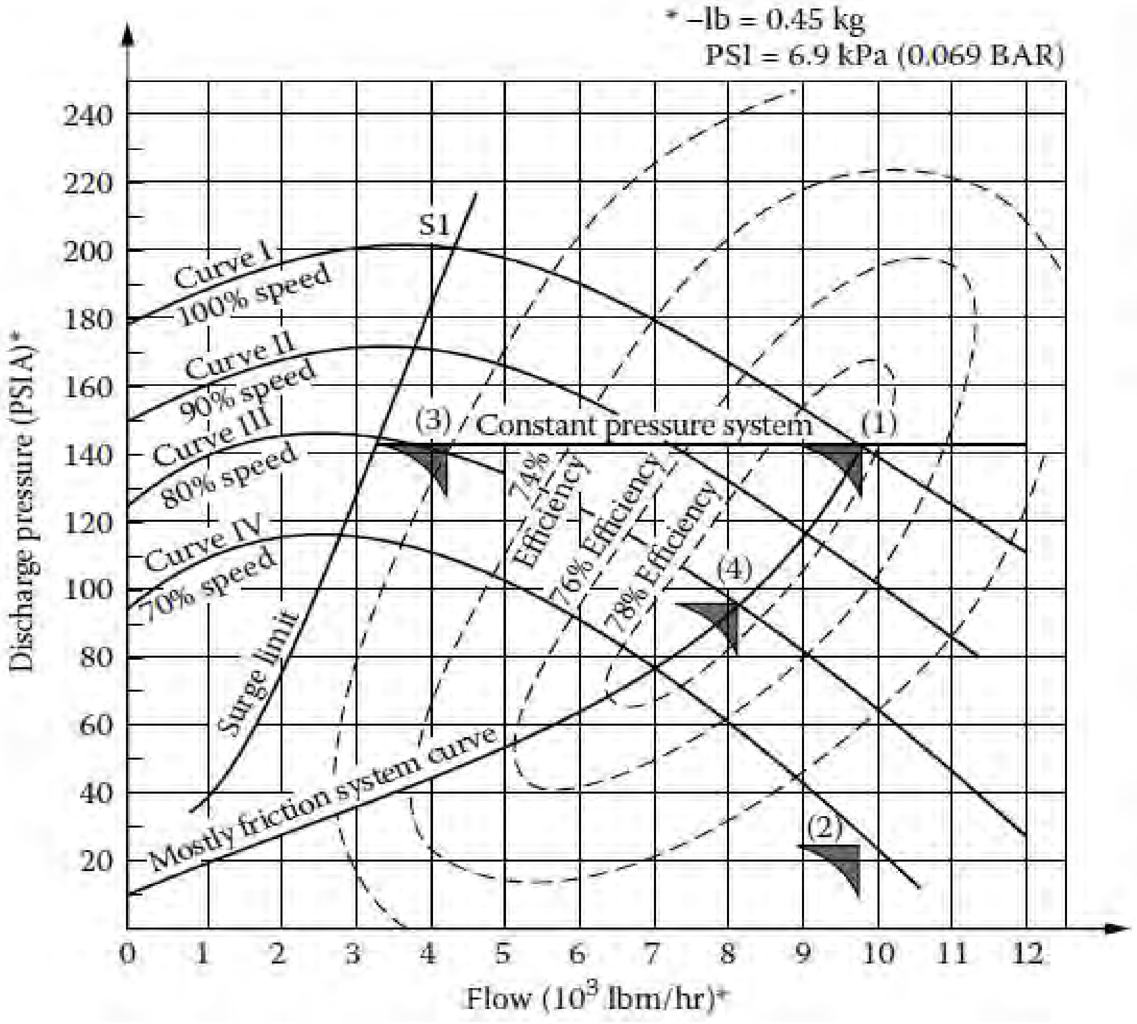


a. Suction Throttling

b. Discharge Throttling

c. Inlet Guide Vanes

Centrifugal Compressor Control Methods



d. Variable Speed

Centrifugal Compressor Performance

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

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**

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

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

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.

Key Learning Points

1. There are two broad categories of industrial air compressors, positive displacement and dynamic.
2. Reciprocating, rotary screw, and rotary vane are positive displacement compressors.
3. Rotary screw compressors are the most common type of industrial air compressor.
4. There are many different types of part load capacity control for rotary screw compressors.
5. Centrifugal air compressors are the most common type of dynamic compressor used by industry.

Key Learning Points

6. Aerodynamic design determines the head -vs- flow performance curve for centrifugal air compressors.
7. Performing poor routine maintenance for centrifugal air compressors can lead to expensive failures of major air compressor components.
8. Different types of part load capacity control have different part load power characteristics.
9. Operating centrifugal compressors with blow-off control or in the stonewall (or choke) region of the performance range is very inefficient.

Key Energy Points

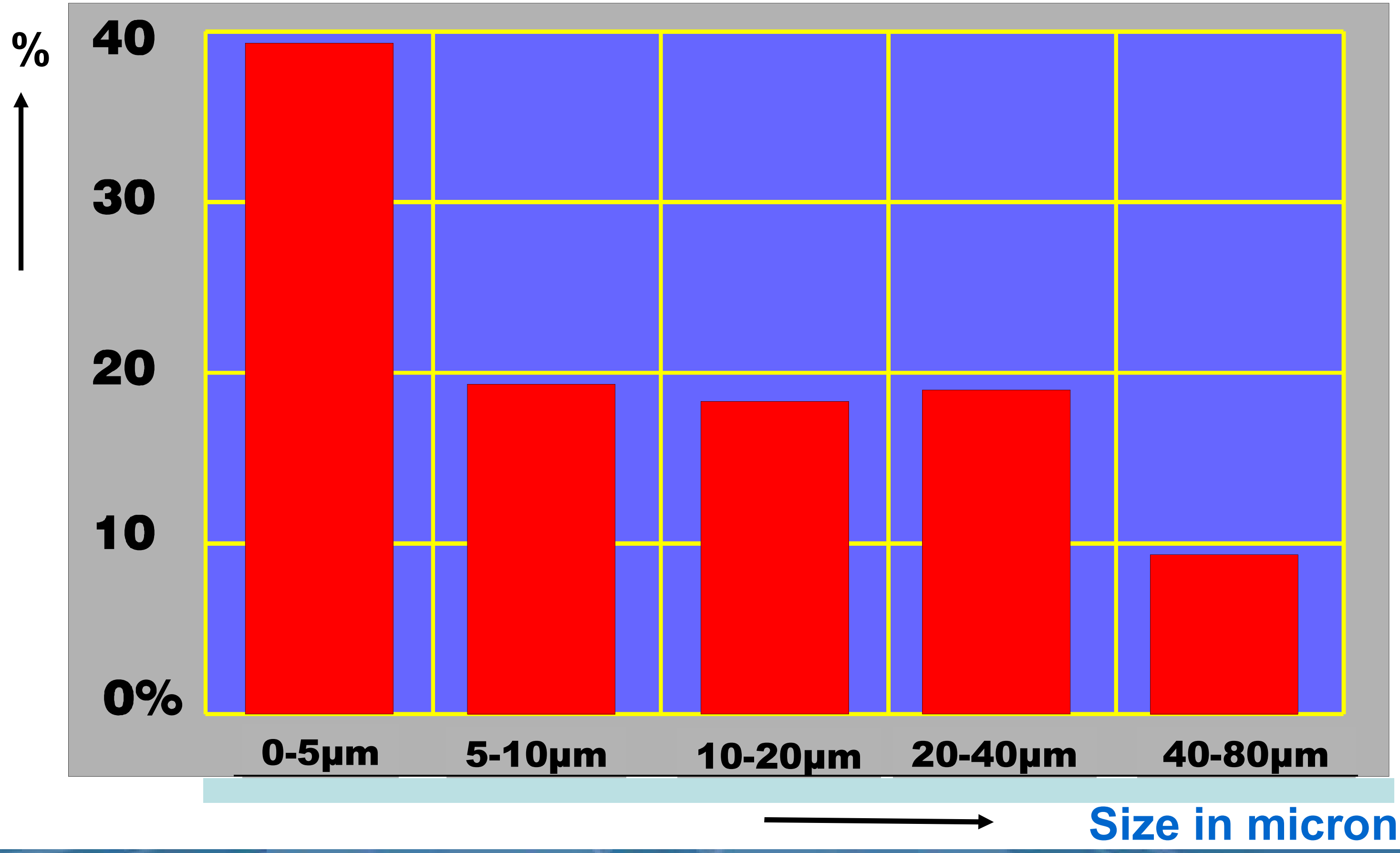
10. In systems with rotary screw compressors it is most efficient to have all compressors operate at full load, with only one at part load for trim capacity.
11. When operating multiple centrifugal air compressors in a system it is more efficient to have multiple compressors operate at part load within their throttle throttling range as opposed to operating in blow-off.
12. 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.

4. 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

Solid particles in the air

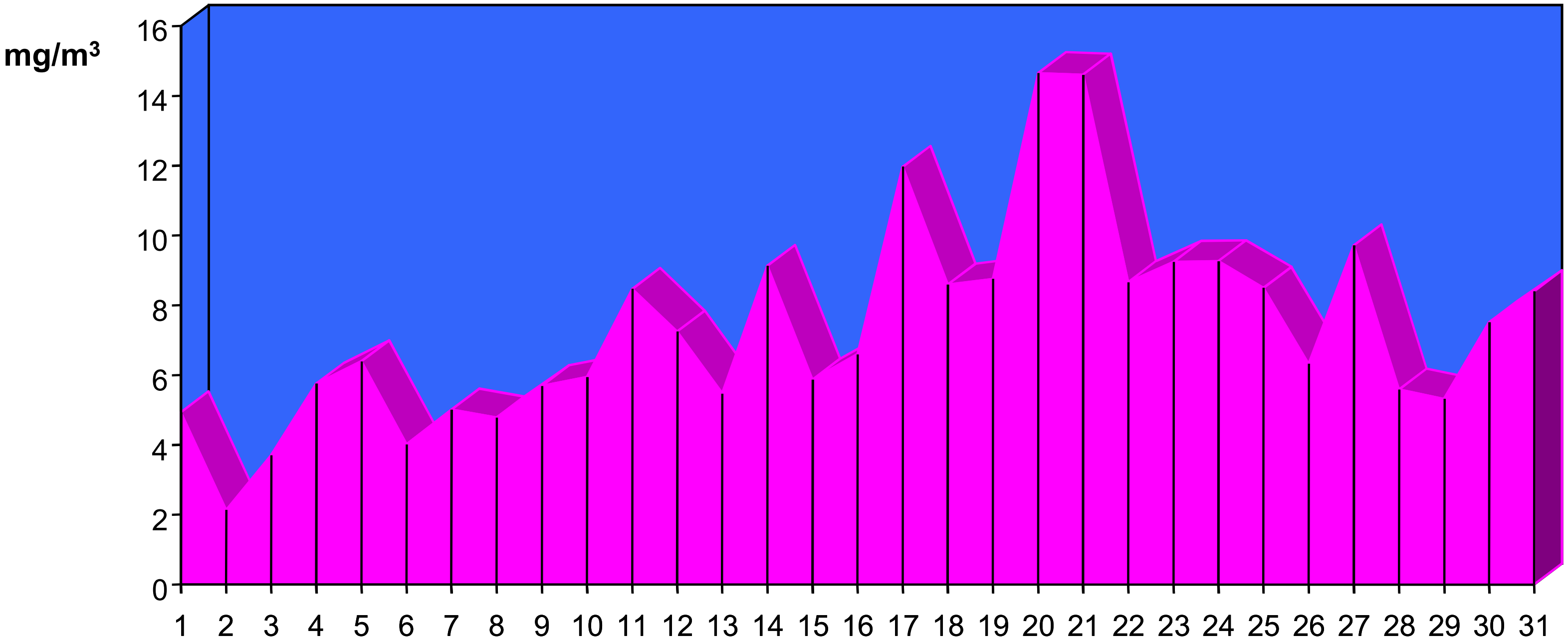


Overall hydro carbon concentration

Mean daily value (mg/m³)

Location: a small German town

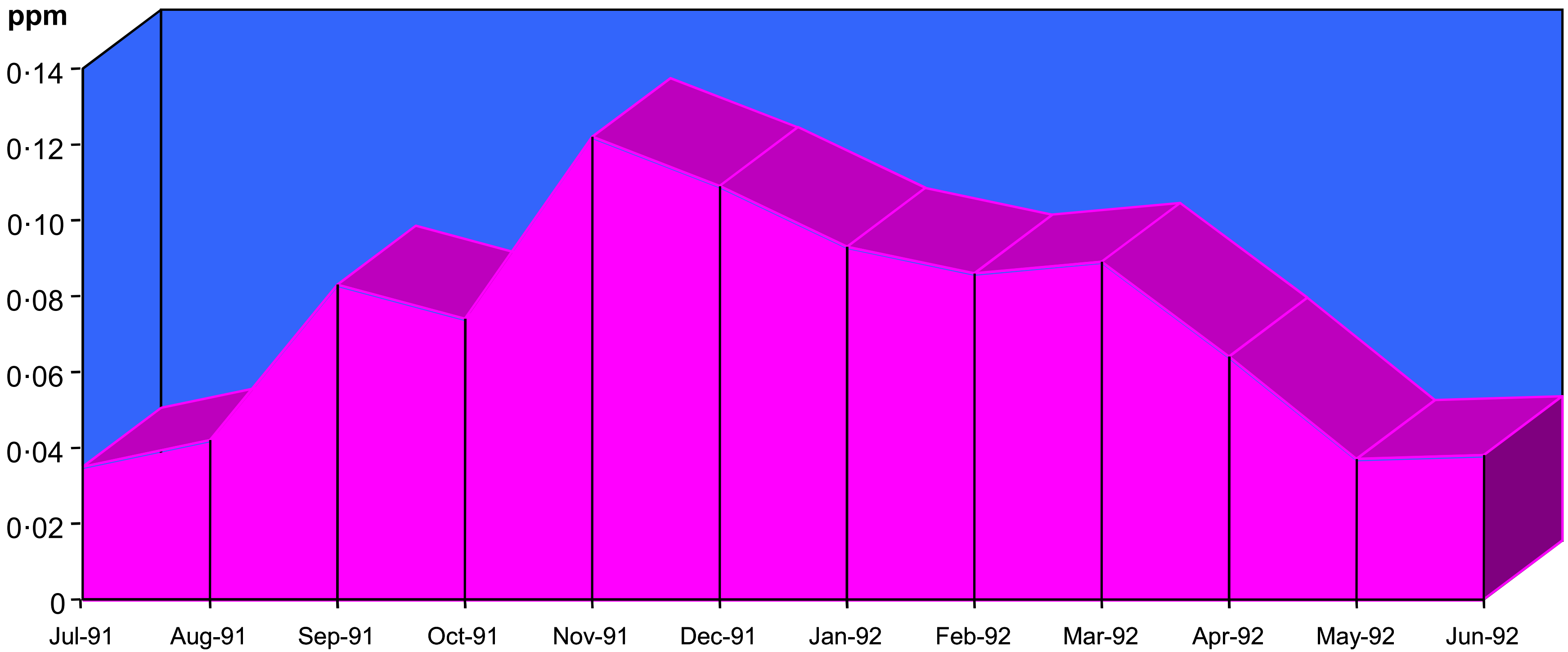
Period: July 1992



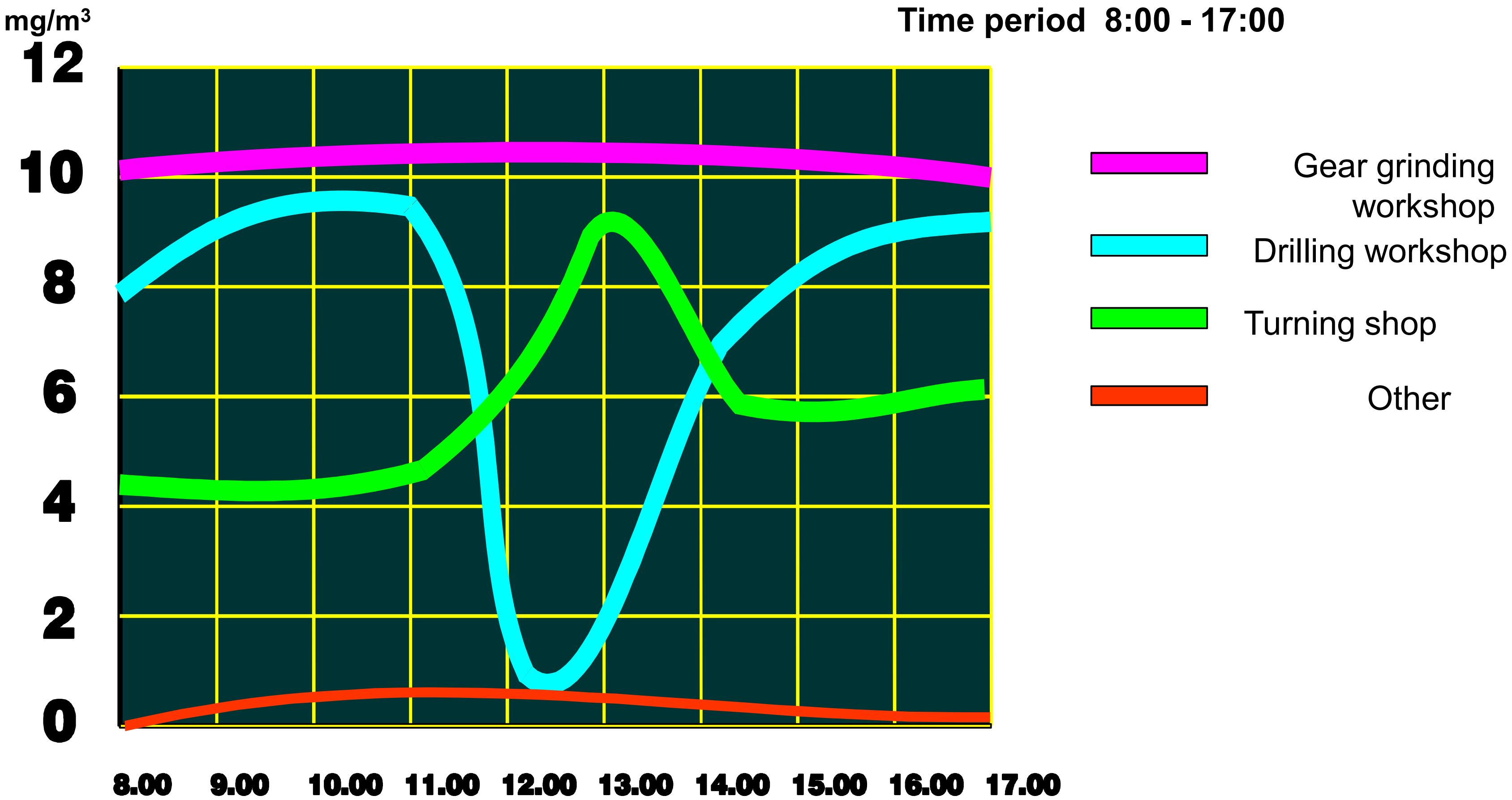
Sulphur-dioxide (SO_2) concentration

Period: July 1991 - June 1992

Location: a small German town



Concentration in mg of mineral oil / m^3 air



Quality classification of compressed air

to ISO 8573-1: 2010 (E)

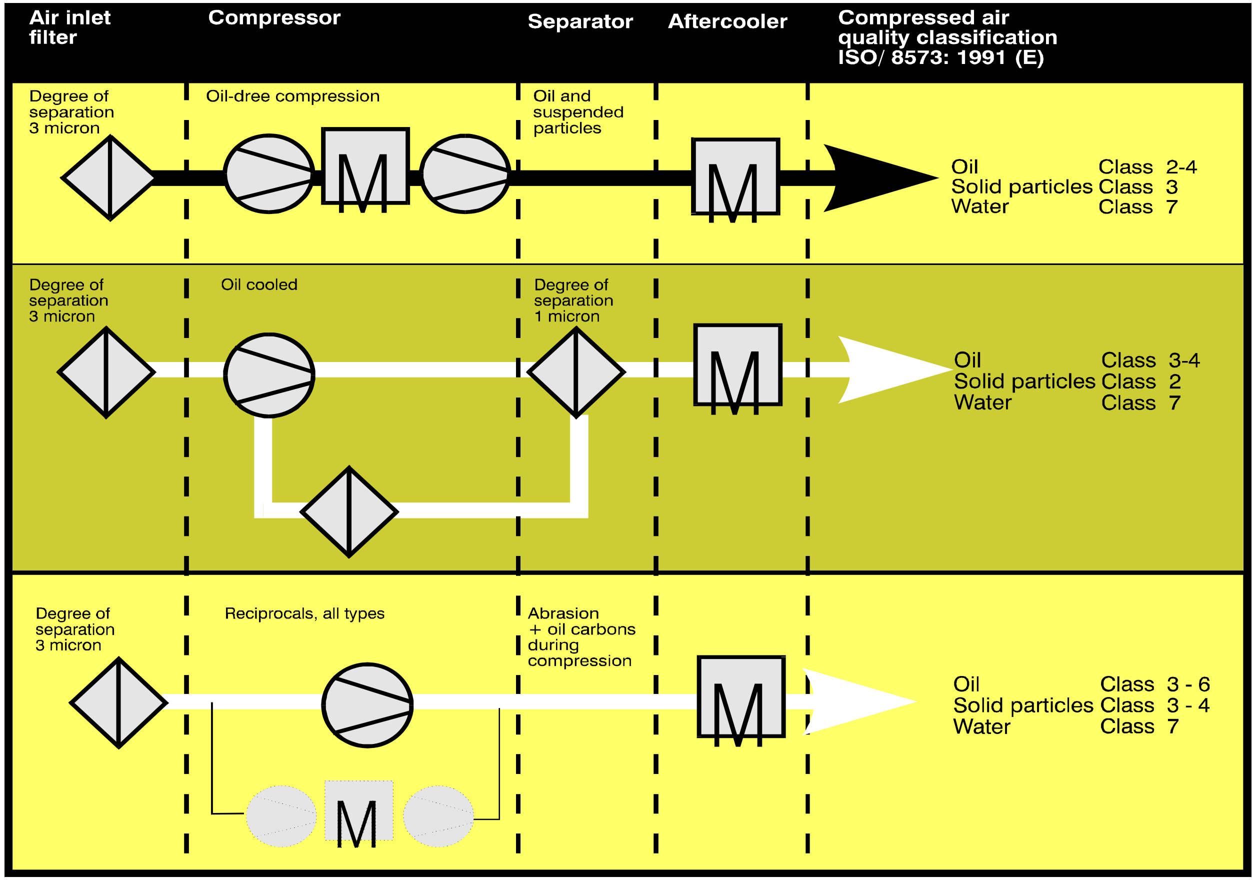
ISO 8573-1 Class	Solid particle content					Moisture content	Oil content
	max. number of particles per m³ sized *d* [µm]				Mass Concentration C_P (mg/m³)	PDP / (*x=liquid water content g/m³*)	mg/m³
	≤ 0,1	0,1< *d* ≤ 0,5	0,5< *d* ≤ 1,0	1,0< *d* ≤ 5,0			
0	as specified by the equipment user or supplier and more stringent than class 1						
1	-	≤ 20 000	≤ 400	≤ 10	-	≤ -70 °C	≤ 0,01
2	-	≤ 400 000	≤ 6 000	≤ 100	-	≤ -40 °C	≤ 0,1
3	-	-	≤ 90 000	≤ 1 000	-	≤ -20 °C	≤ 1,0
4	-	-	-	≤ 10 000	-	≤ +3 °C	≤ 5,0
5	-	-	-	≤ 100 000	-	≤ +7 °C	-
6	-	-	-	-	< 0 C_P ≤ 5	≤ +10 °C	-
7	-	-	-	-	< 5 C_P ≤ 10	*x* ≤ *0,5*	-
8	-	-	-	-	-	*0,5 ≤ x ≤ 5,0*	-
9	-	-	-	-	-	*5,0 ≤ x ≤ 10,0*	-

Typical Air Quality Class Recommendations

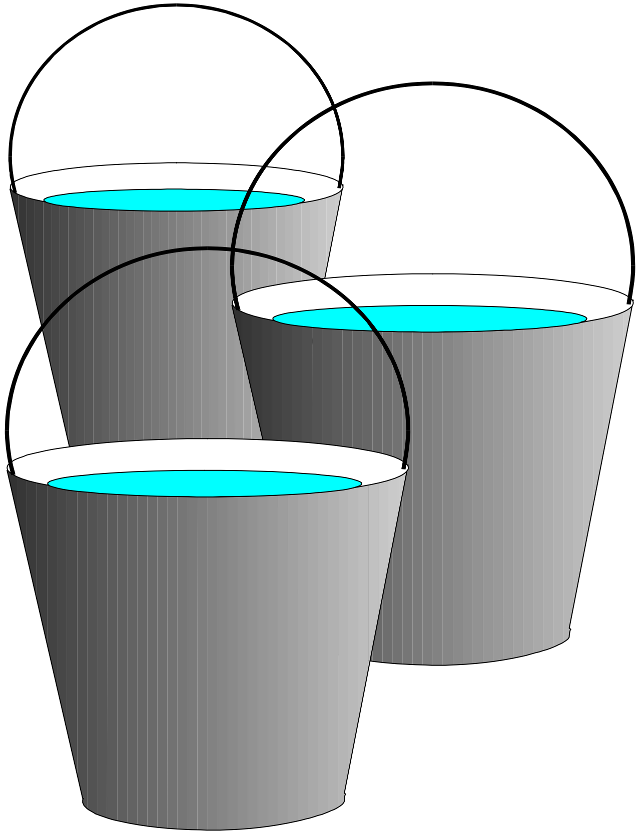
Typical Air Quality Classes[4]

Application	Dirt	Water	Oil	Application	Dirt	Water	Oil
Air agitation	3	5	3	Industrial hand tools	4	5-4	5-4
Air bearing	2	2	3	Handling, food, beverages	2	3	1
Air gauging	2	3	3	Machine tools	4	3	5
Air motors, heavy	4	4-1	5	Mining	4	5	5
Air turbines	2	2	3	Packaging & textile machines	4	3	3
Brick & glass machines	4	4	5	Plant air, general	4	4	5
Cleaning machine parts	4	4	4	Precision pressure regulators	3	2	3
Construction	4	5	5	Process control instruments	2	2	3
Conveying powder products	2	3	2	Rock drills	4	5-4	5
Fluidics, power circuits	4	4	4	Sand blasting	-	5-2	5
Fluidics, sensors	2	2-1	2	Spray painting	3	3-2	3
				Welding machines	4	4	5

Air quality downstream of the compressor



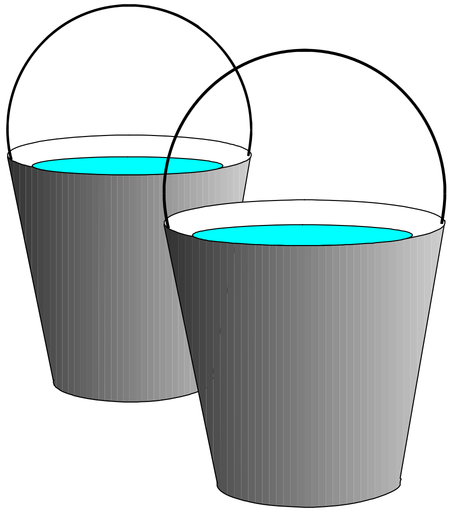
CONDENSATE:



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

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)



CONDENSATE:

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

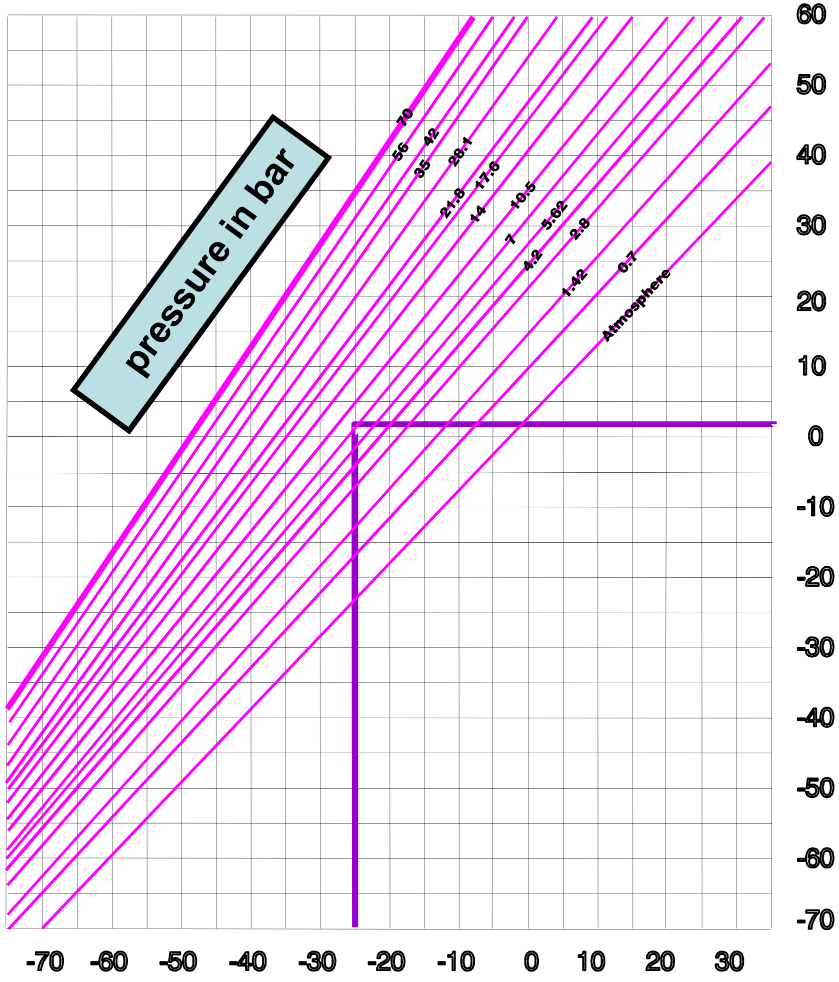
the results are expensive maintenance, repairs and defects in production

Water Content of Ambient Air

Dewpoint	g/m^3	Dewpoint	g/m^3
+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

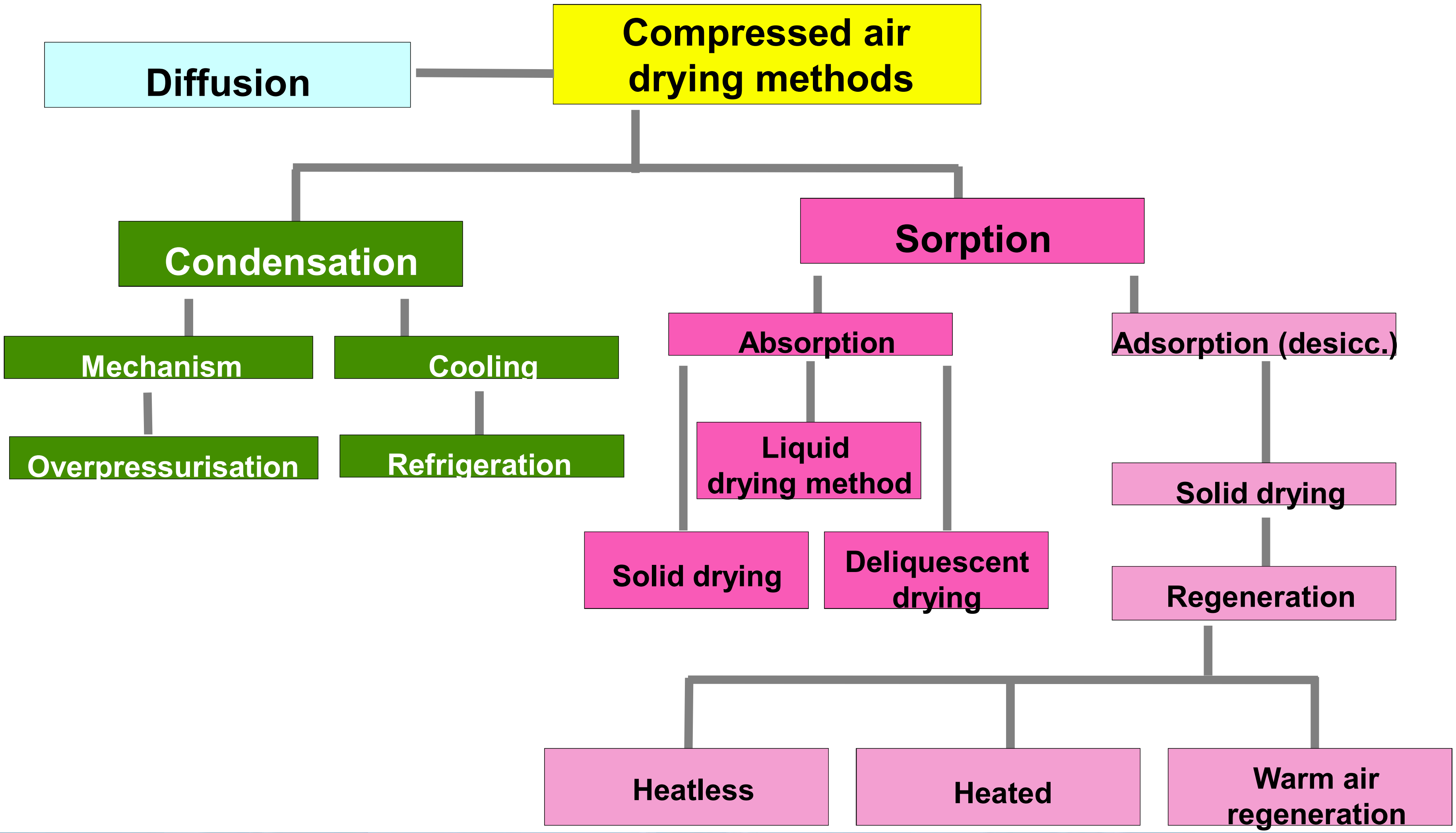
Pressure dewpoint - atmospheric dewpoint

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



pressure dewpoint in degrees °C.

atmospheric dewpoint in °C.


Compressed air drying methods
Diffusion
Condensation
Mechanism
Overpressurisation
Cooling
Refrigeration
Sorption
Absorption
Liquid drying method
Solid drying
Deliquescent drying
Adsorption (desicc.)
Solid drying
Regeneration
Heatless
Heated
Warm air regeneration

Why Dry Compressed Air?

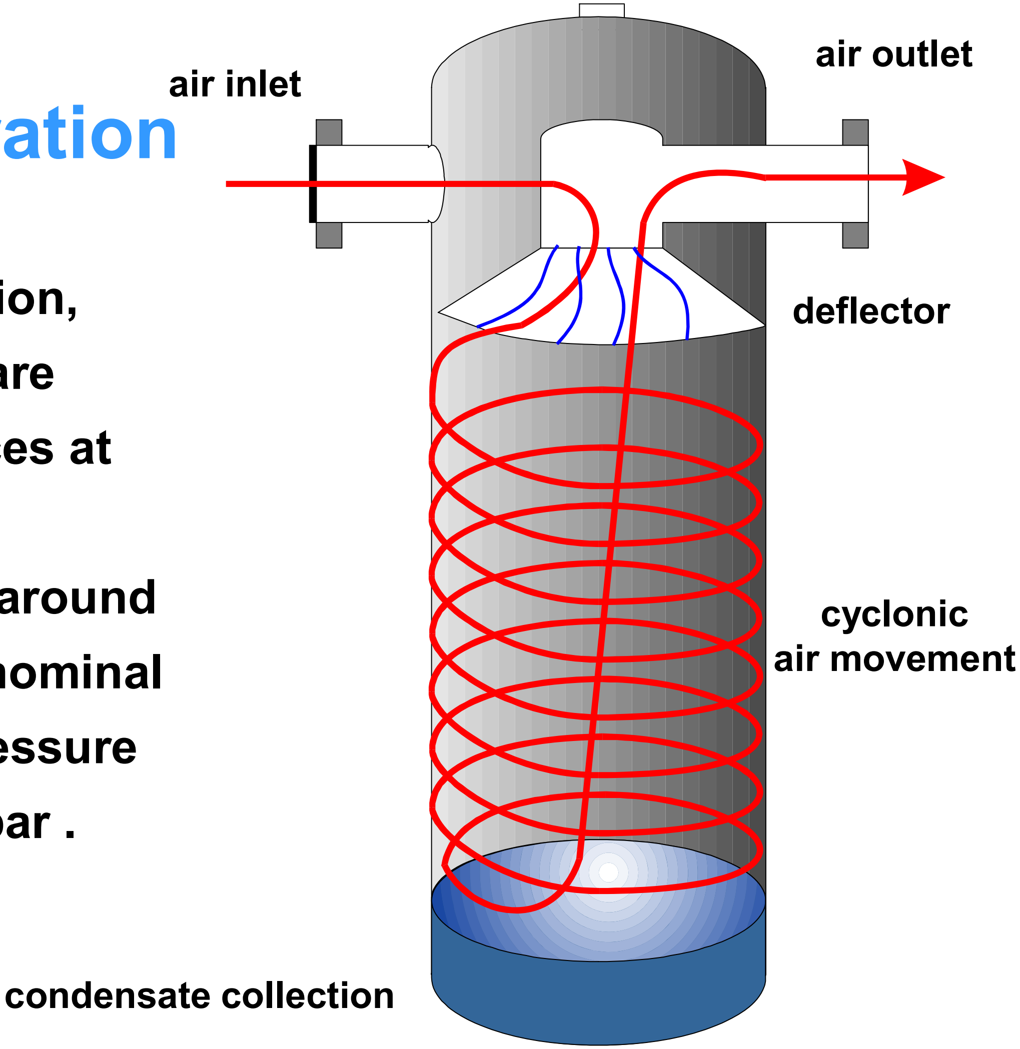
Untreated air	Problems in the air main	Problems with equipment
dirt	corrosion	contamination
oil aerosols	pressure loss	tool wear
moisture	contamination	scrap
	freezing	downtime
	maintenance	

COSTS

COSTS

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 .

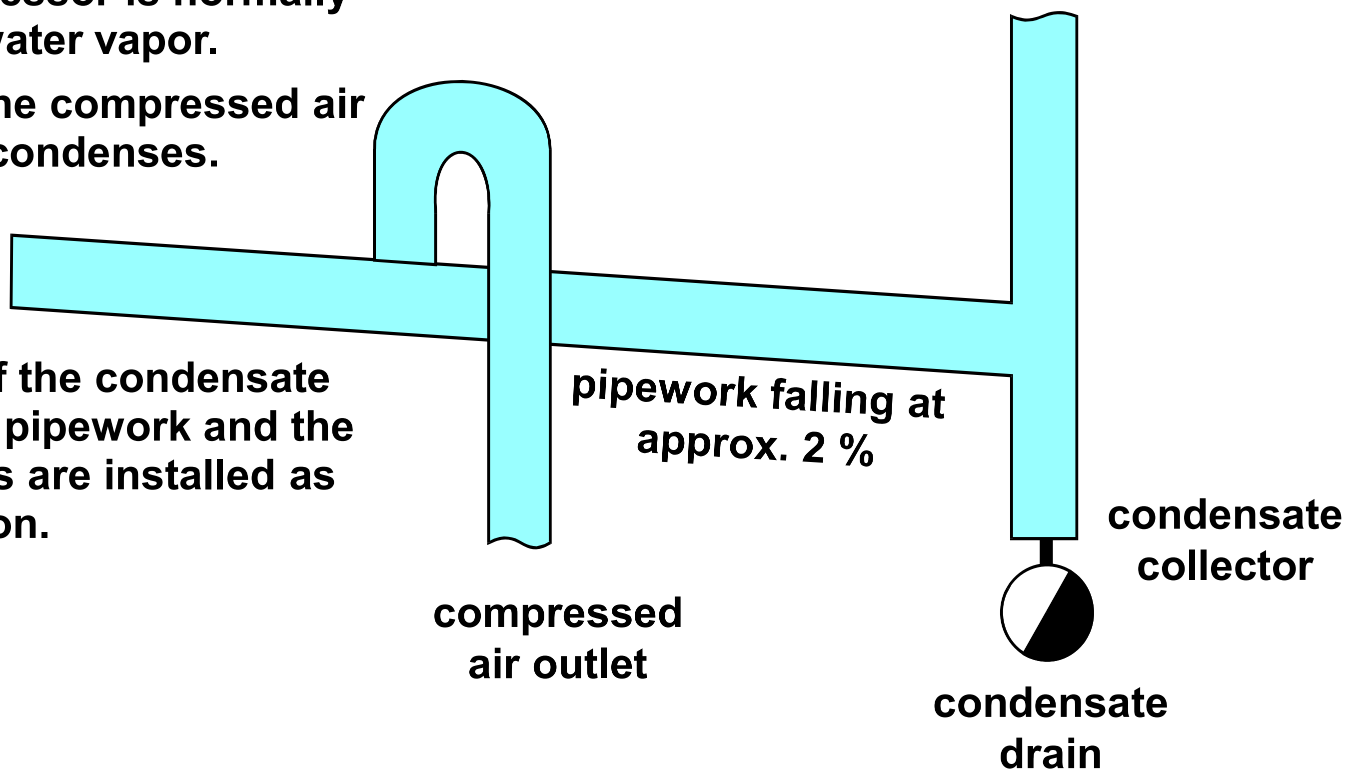


Condensate separation

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.

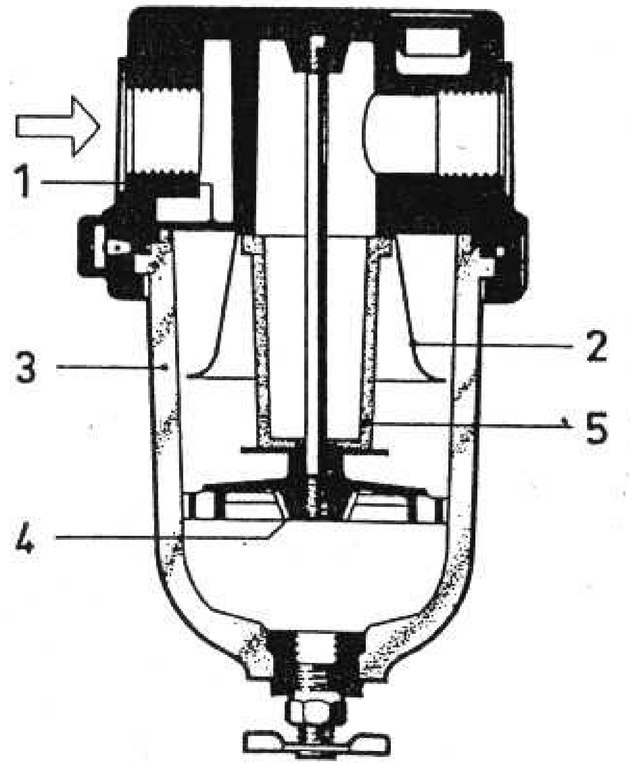
A coarse separation of the condensate can be achieved if the pipework and the compressed air outlets are installed as shown in the illustration.



Condensate separation

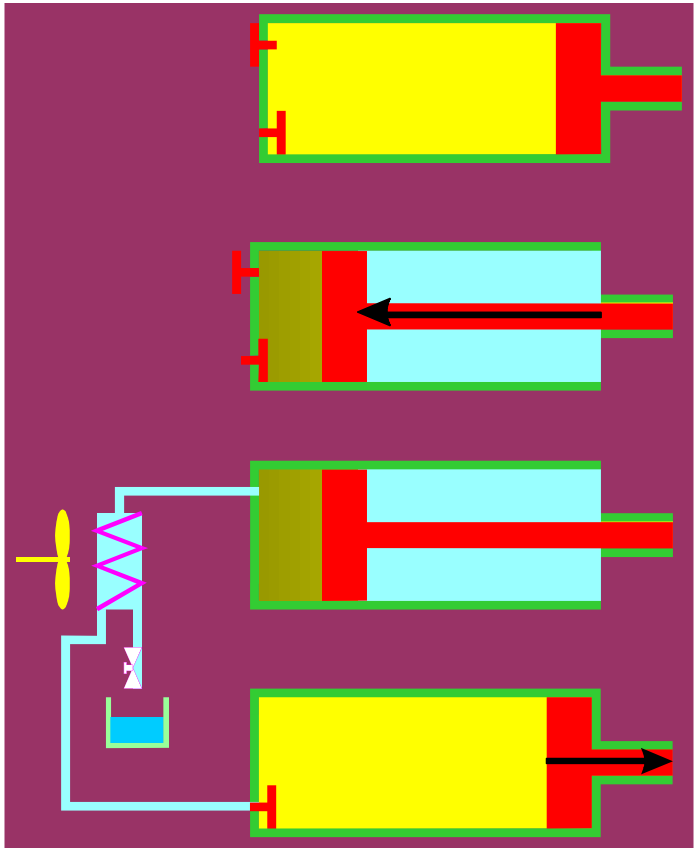
Fine filter

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



Over-compressing

Simplest method
Disadvantage: high energy requirement



Example:

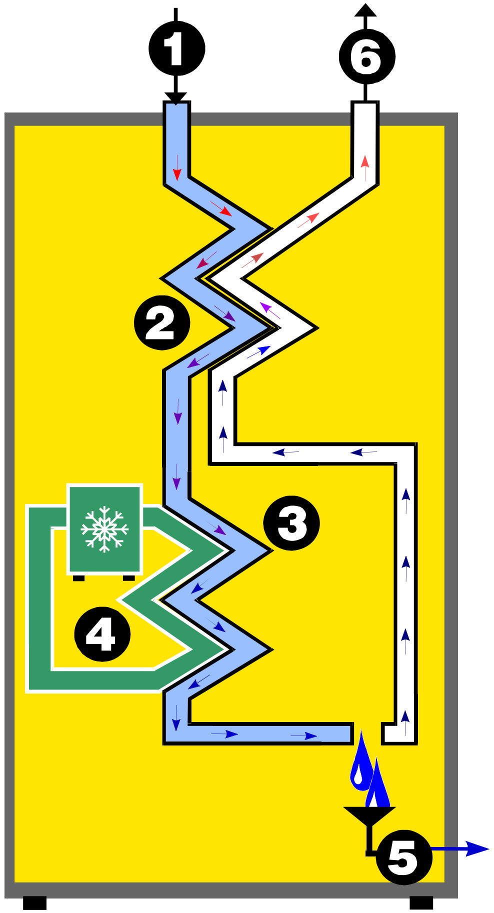
High-voltage safety switch
Working pressure 15 bar (g)
Preliminary compression to 300 bar (g)

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

- high humidity
- low humidity

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



High Inlet Temperature Refrigerated Dryer

Description:

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

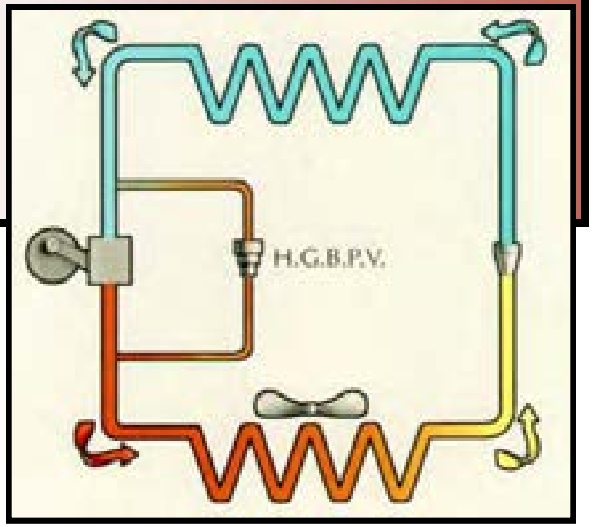
Advantages:

- **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**

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

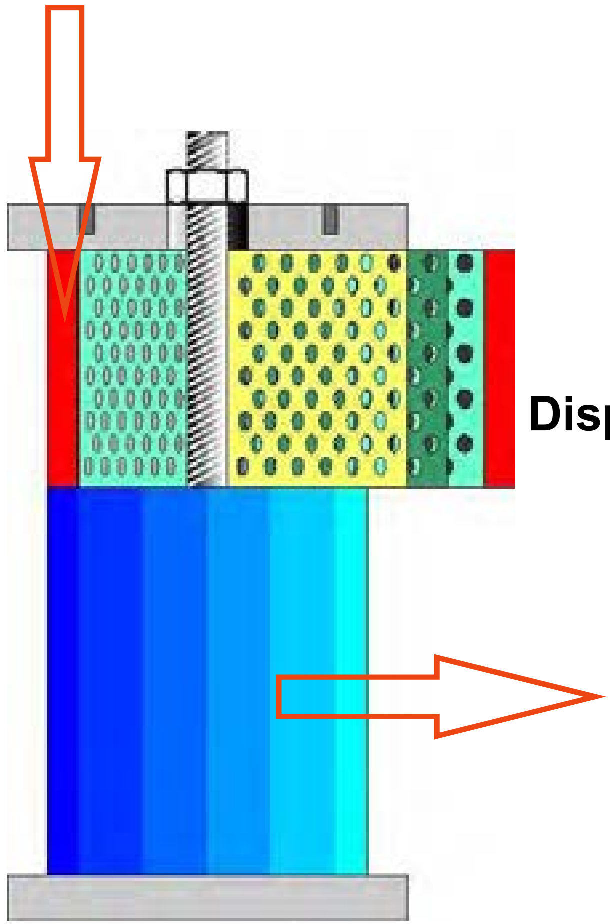


Separator systems

for refrigeration dryers

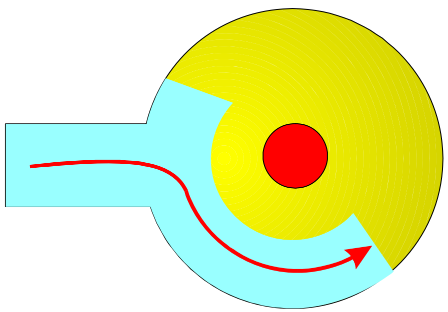
Centriflex

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.

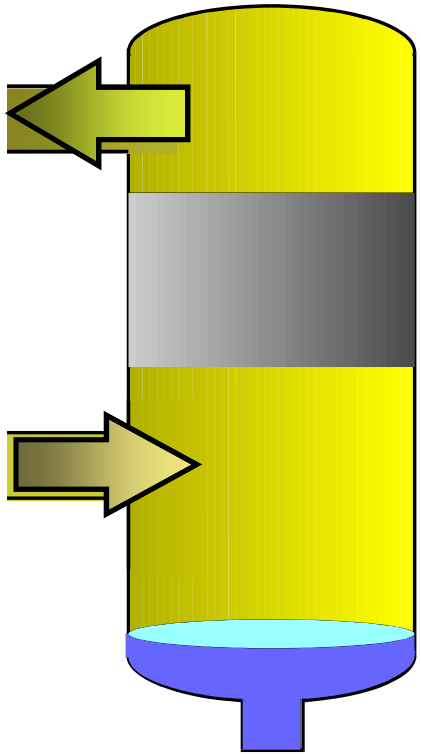


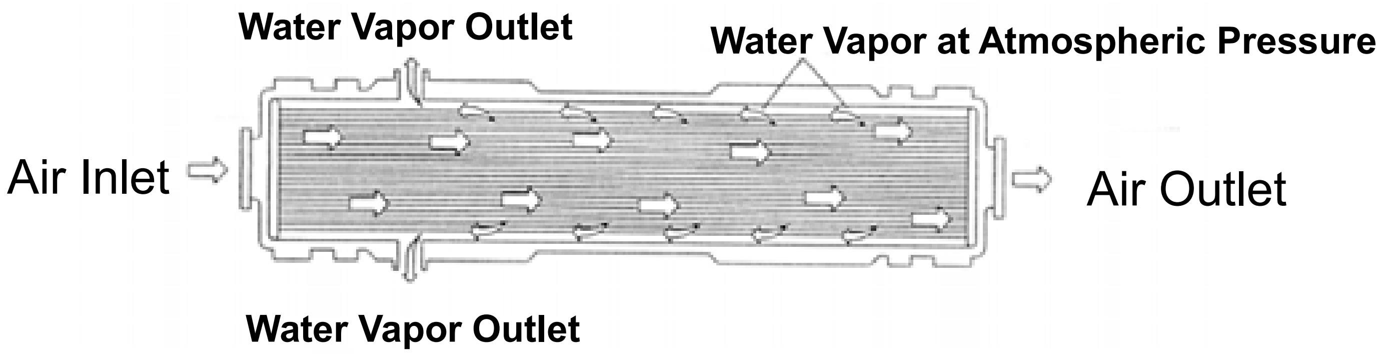
Separator systems for compressed air dryers

Type: Zentri-Dry



stainless steel housing





Membrane Dryer

Absorption drying

Chemical process

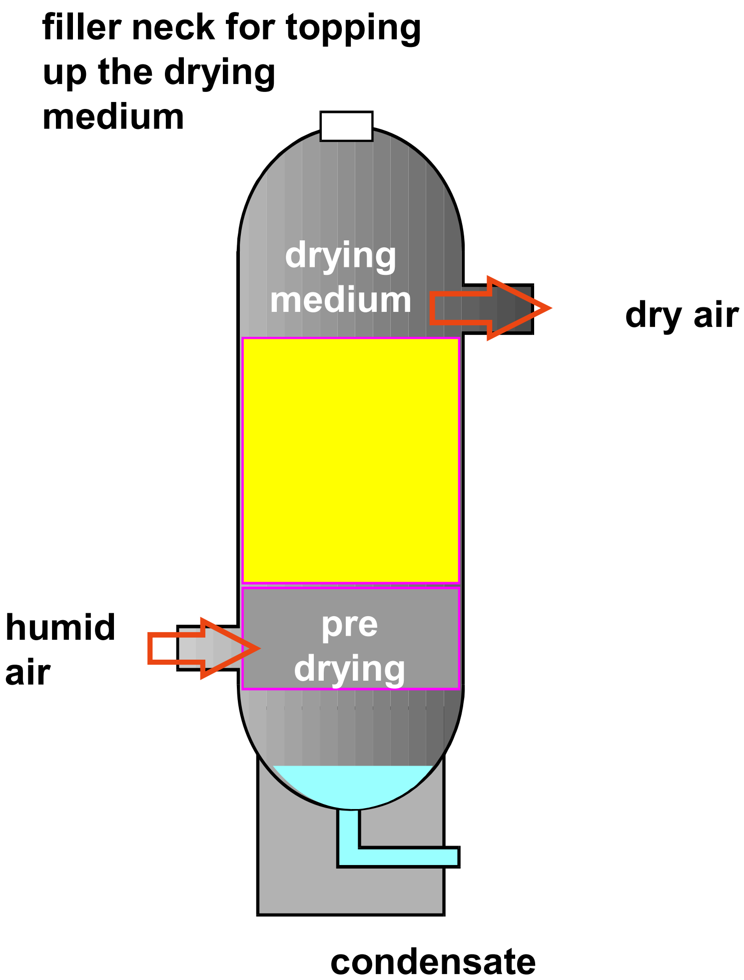
Solid soluble drying medium

Deliquescent drying medium

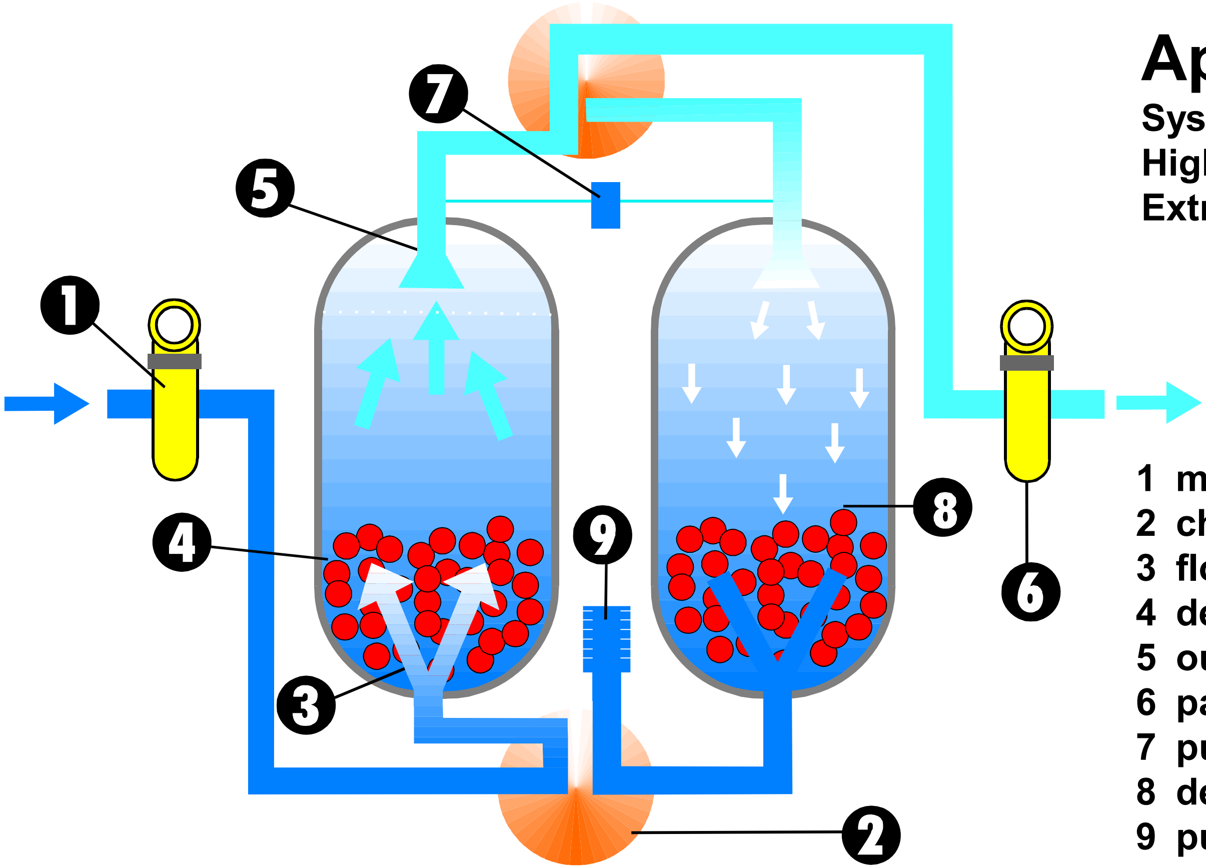
Periodic renewal of the drying medium

Dewpoint: + 15 ° Celsius

Low compressed air inlet temperatures



Desiccant drying - heatless



Application:

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

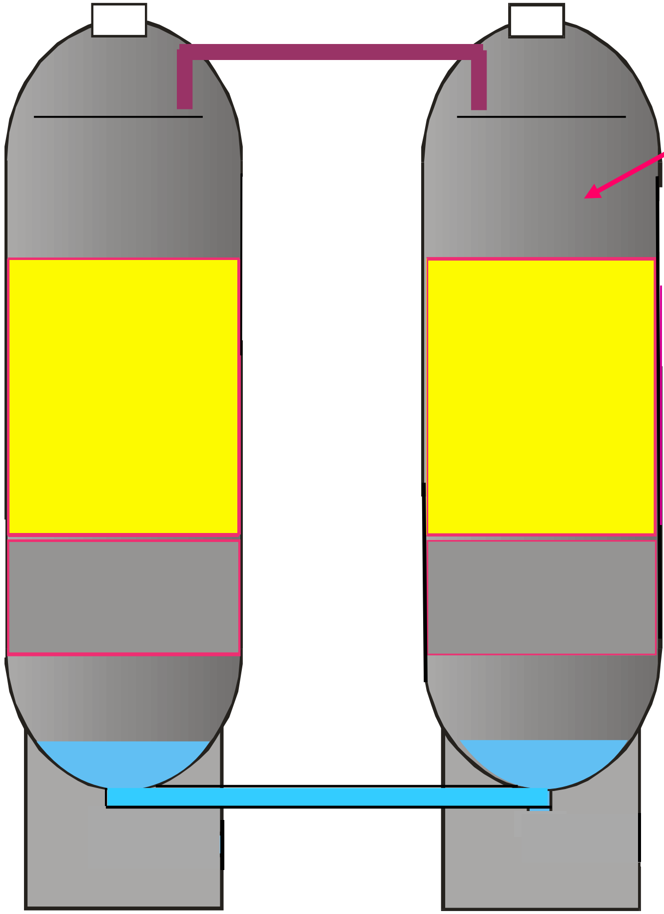
1 microfilter (0.01 µm, 0.01 ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: moisture adsorption
5 outlet collector
6 particulate filter 1 µm
7 purge (regeneration) air valve
8 desiccant bed: regeneration
9 purge air exhaust silencer

Design of the heatless regenerating desiccant dryers

Standard Cycle

time (min)

10 — 0.5 min standby
0.5 min pressurising
4 min regenerating
5 — 5 min drying
0



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

Regenerating air requirement:

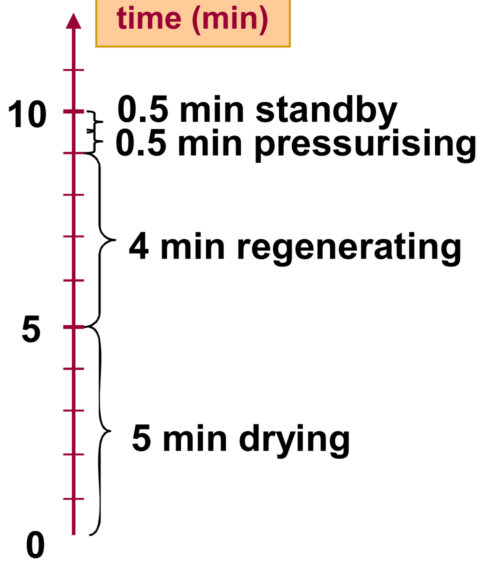
average	**14 %**
+ chamber filling	**1 %**
total average	**15 %**

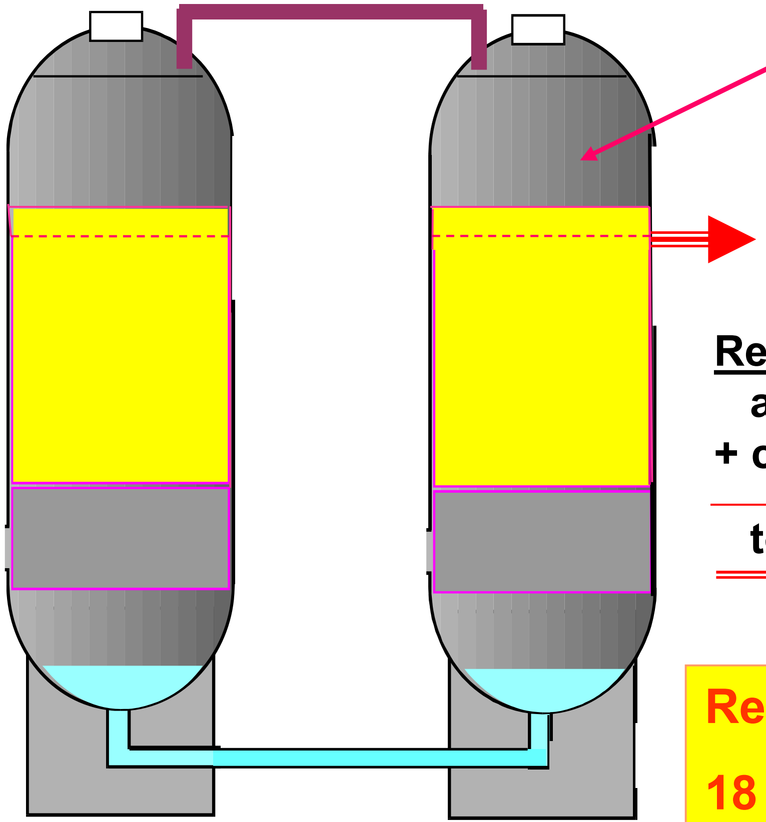
Regenerating air (max.)

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

Conventional dryers

Standard Cycle





80 % desiccant volume

100 % air flow

35 °C inlet temperature

7 bar (g)

pressure dew point - 40 °C

<u>Regenerating air requirement:</u>

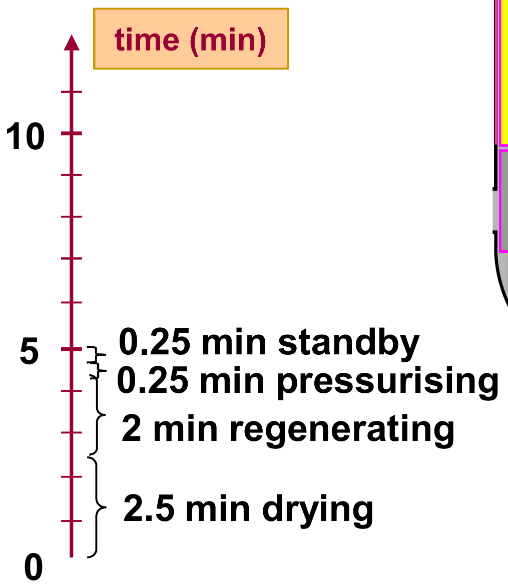
average	**17 %**
+ chamber filling	**1 %**
total average	**18 %**

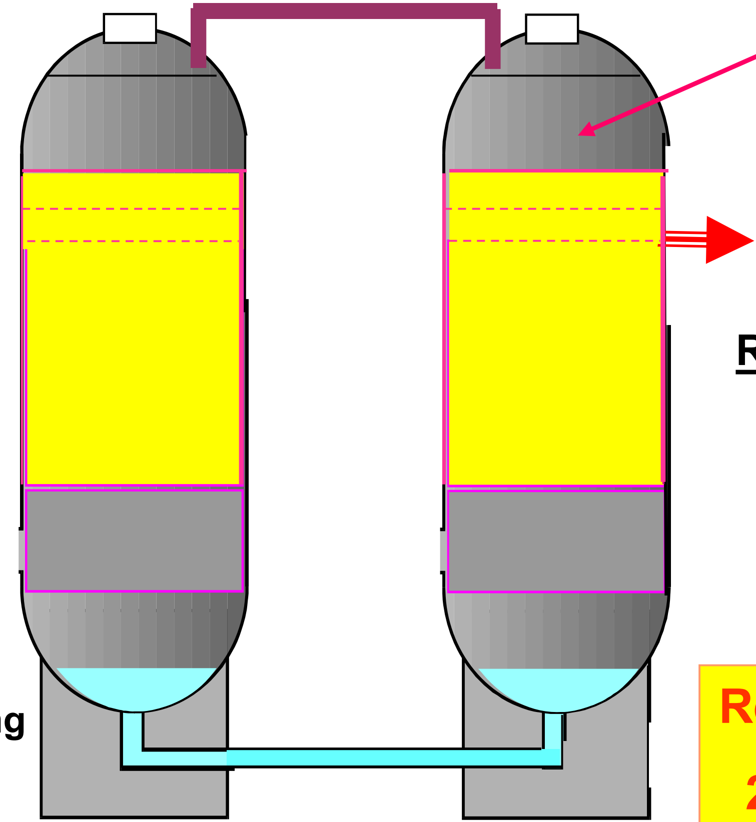
Regenerating air (max.)

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

Economy Dryer

Economy Cycle





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

Regenerating air requirement:

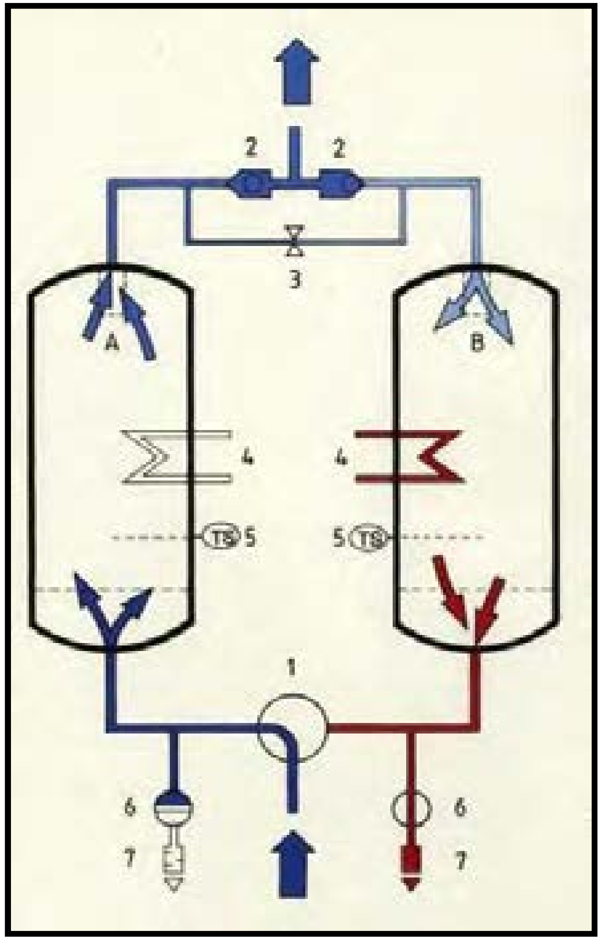
average	22 %
+ chamber filling	2 %
total average	24 %

Regenerating air (max.)

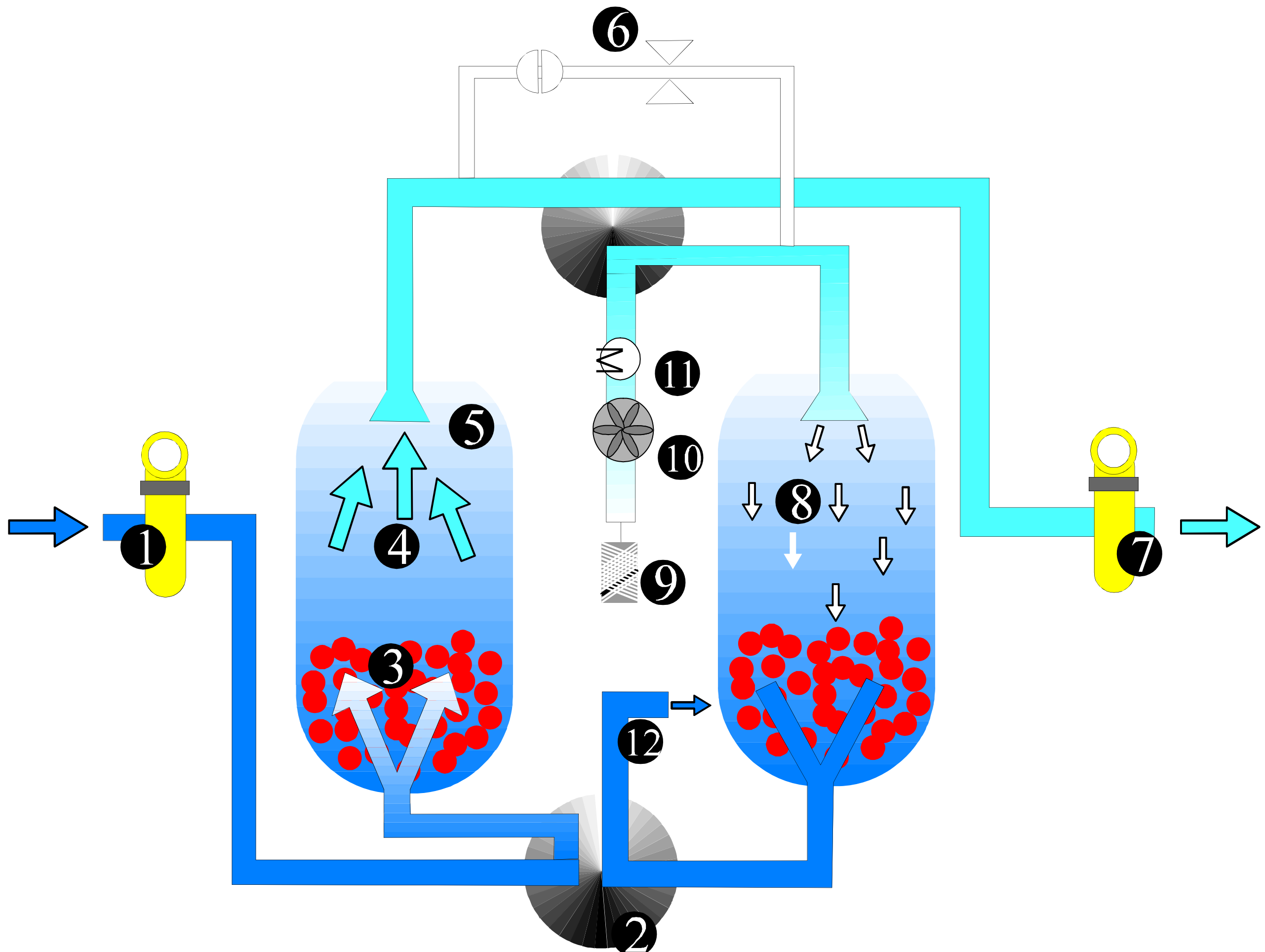
$$\frac{24\% \times 2.5\ \text{min}}{2.25\ \text{min}} \approx 27\ \%$$

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



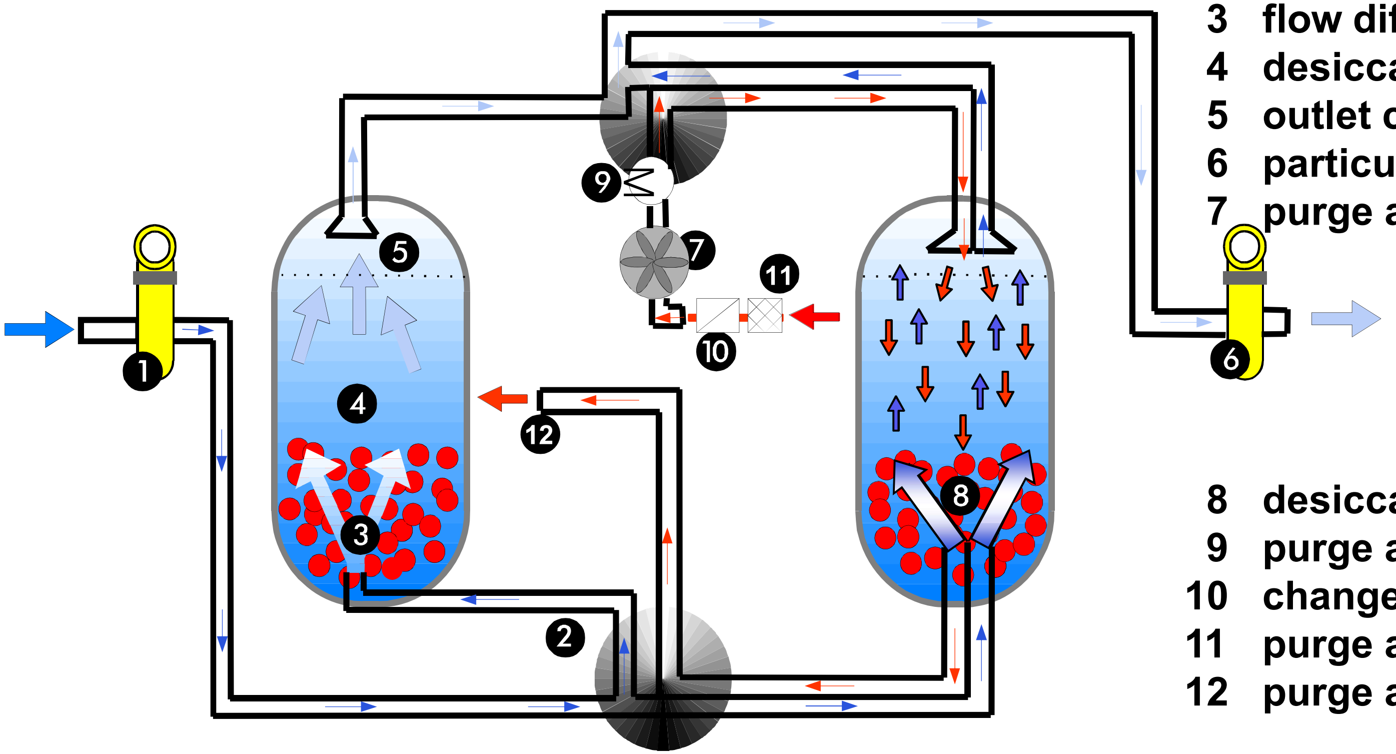
Desiccant drying - externally heated



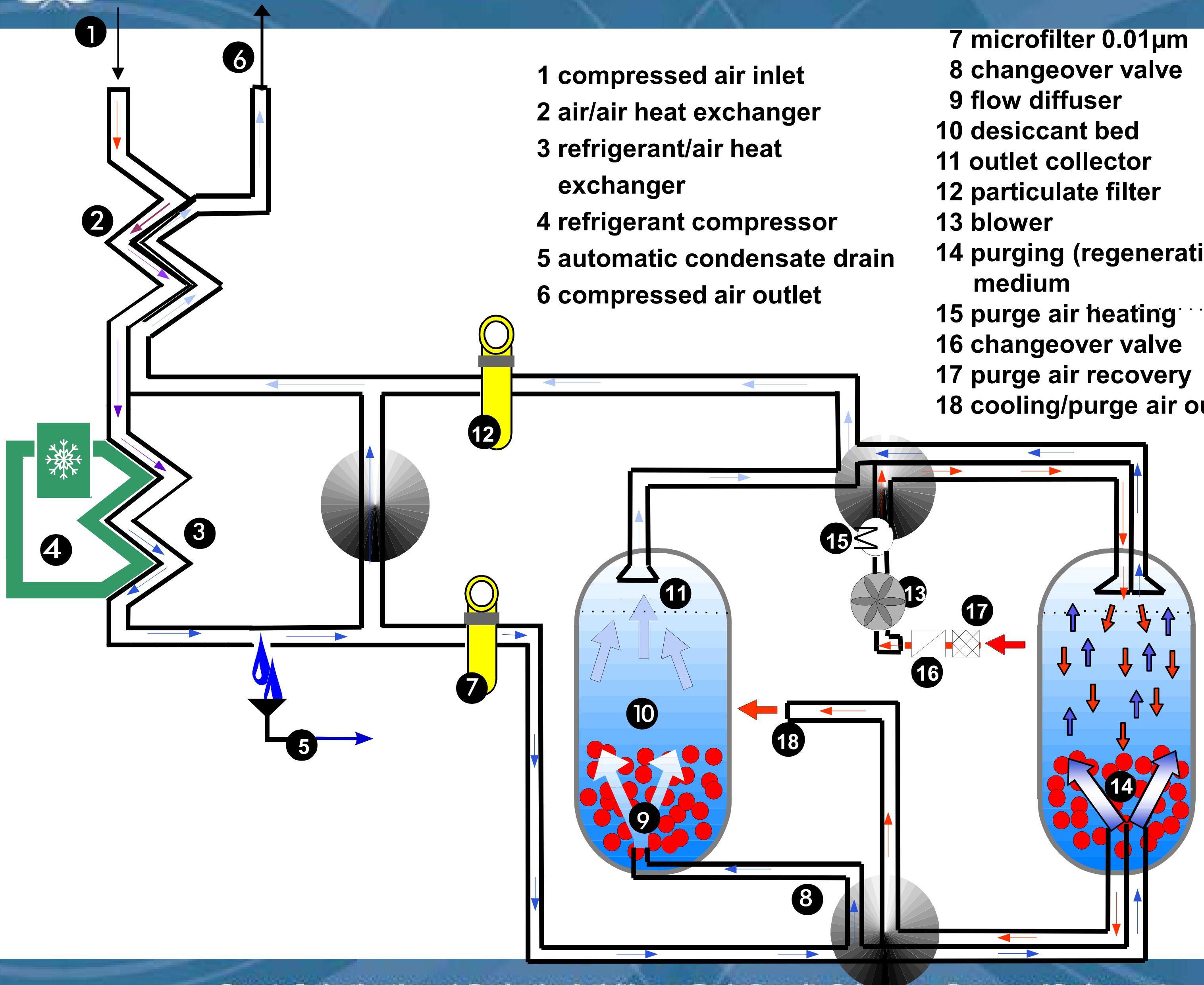
1 microfilter (0.01 µm, 0.01ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: adsorption
5 outlet collector
6 regeneration (purge) valve
7 particulate filter
8 desiccant bed: regeneration
9 purge air inlet
10 purge air blower
11 purge air heating
12 purge air outlet

Desiccant drying, externally heat regenerated

Principle of no compressed air loss:

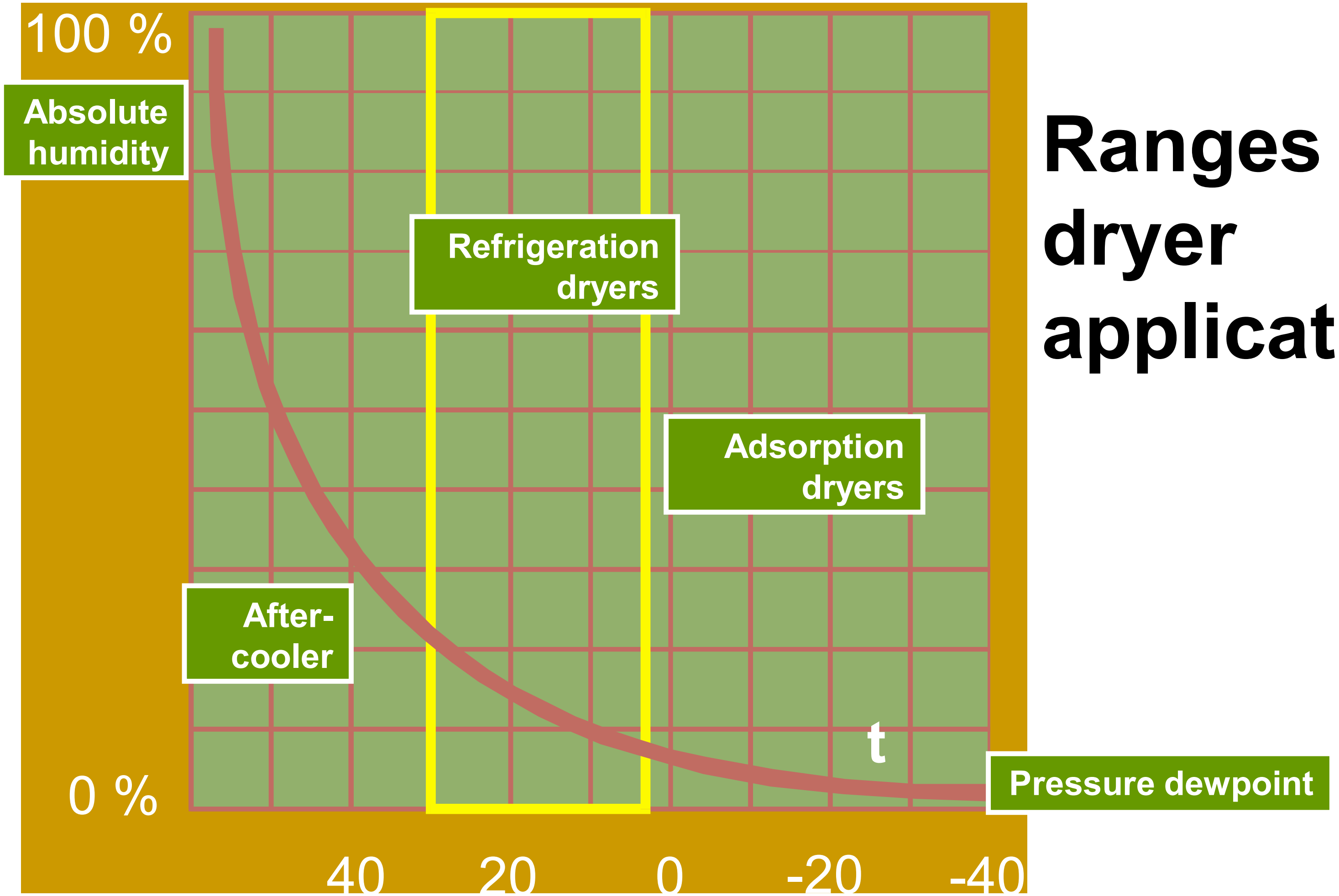


1 microfilter (0.01 µm, 0.01ppm)
2 changeover valve
3 flow diffuser
4 desiccant bed: adsorption
5 outlet collector
6 particulate filter
7 purge air blower
8 desiccant bed: regeneration
9 purge air heating
10 changeover valve
11 purge air inlet
12 purge air outlet



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

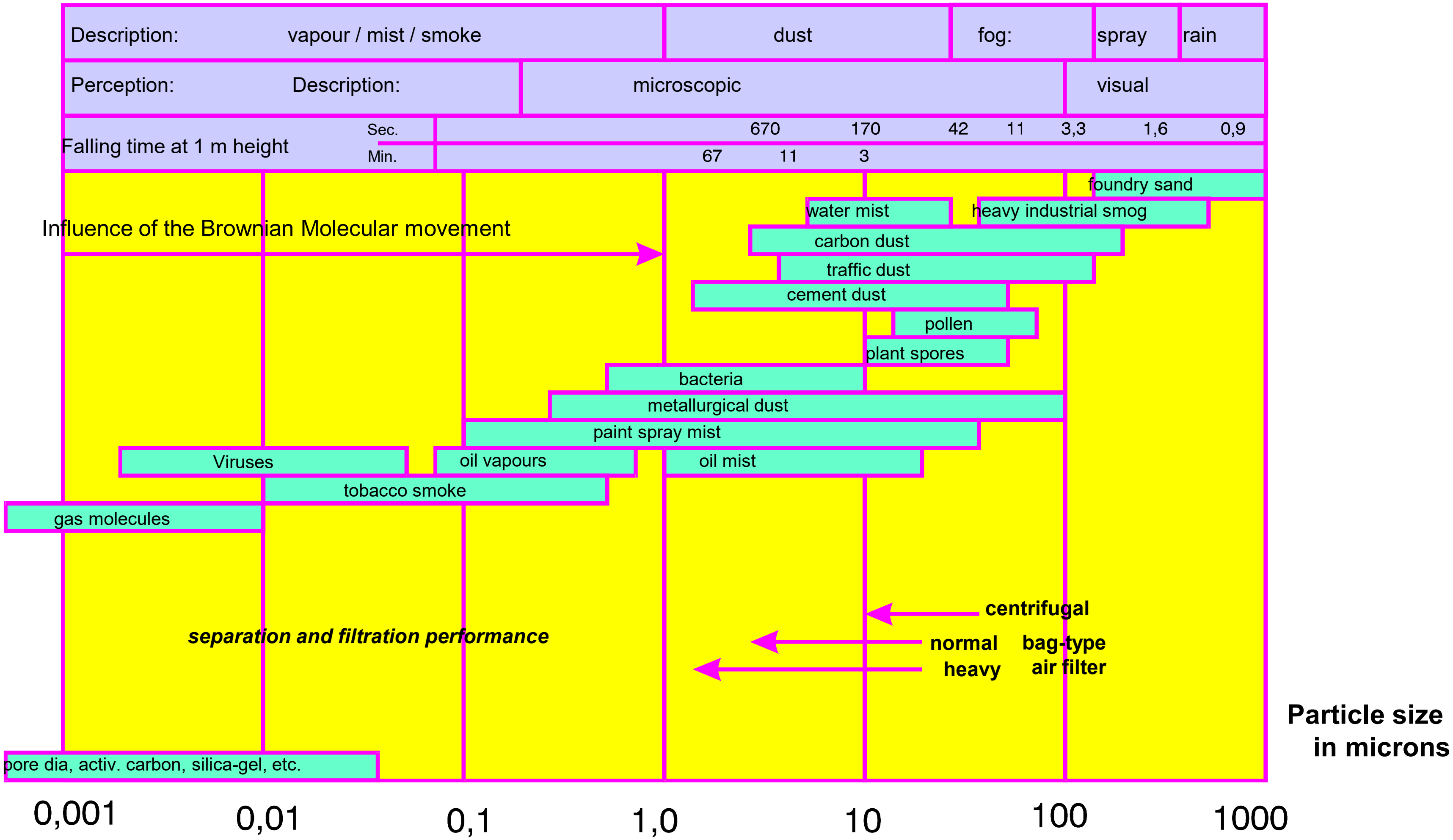
Ranges of dryer application



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

How large are the impurities in the air?

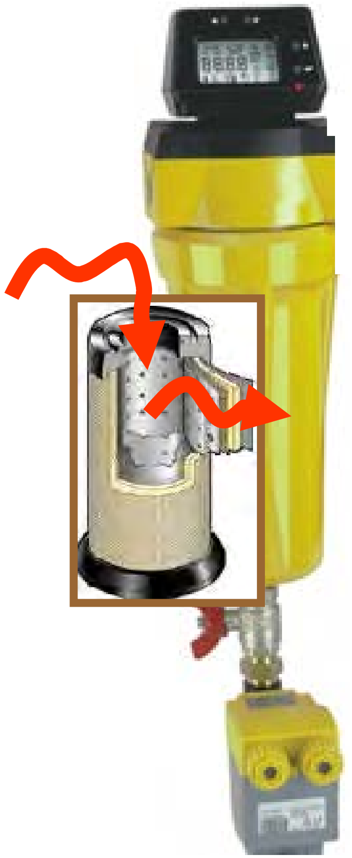


Permissible particle sizes

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

Current hydro carbon carry-over limits for various applications

Application	Max. hydro carbon carry-over in compressed air in mg/m^3
Working air Normal breathing air	< 5
Testing air	< 1
Pure breathing air	< 0.5
Oil-free air	< 0.003



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

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

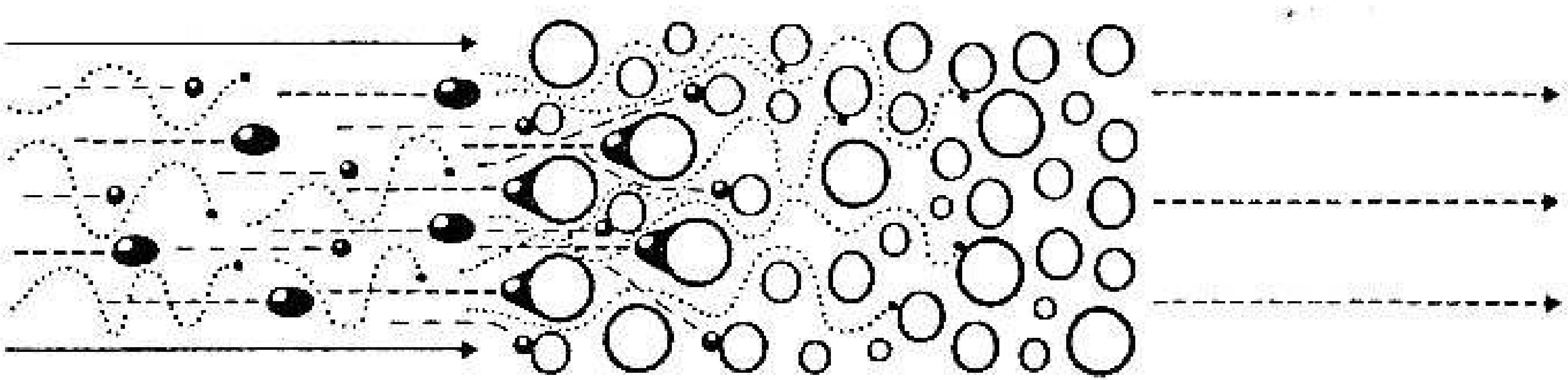
Microfilter

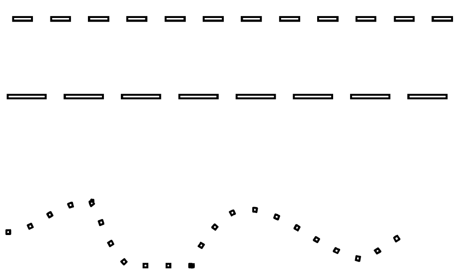
0.01 to 0.001 micron
for liquids
(aerosols) and particles

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

How does the microfilter work?

contaminated air | filter medium (deep-bed filter) | technically oil-free clean air



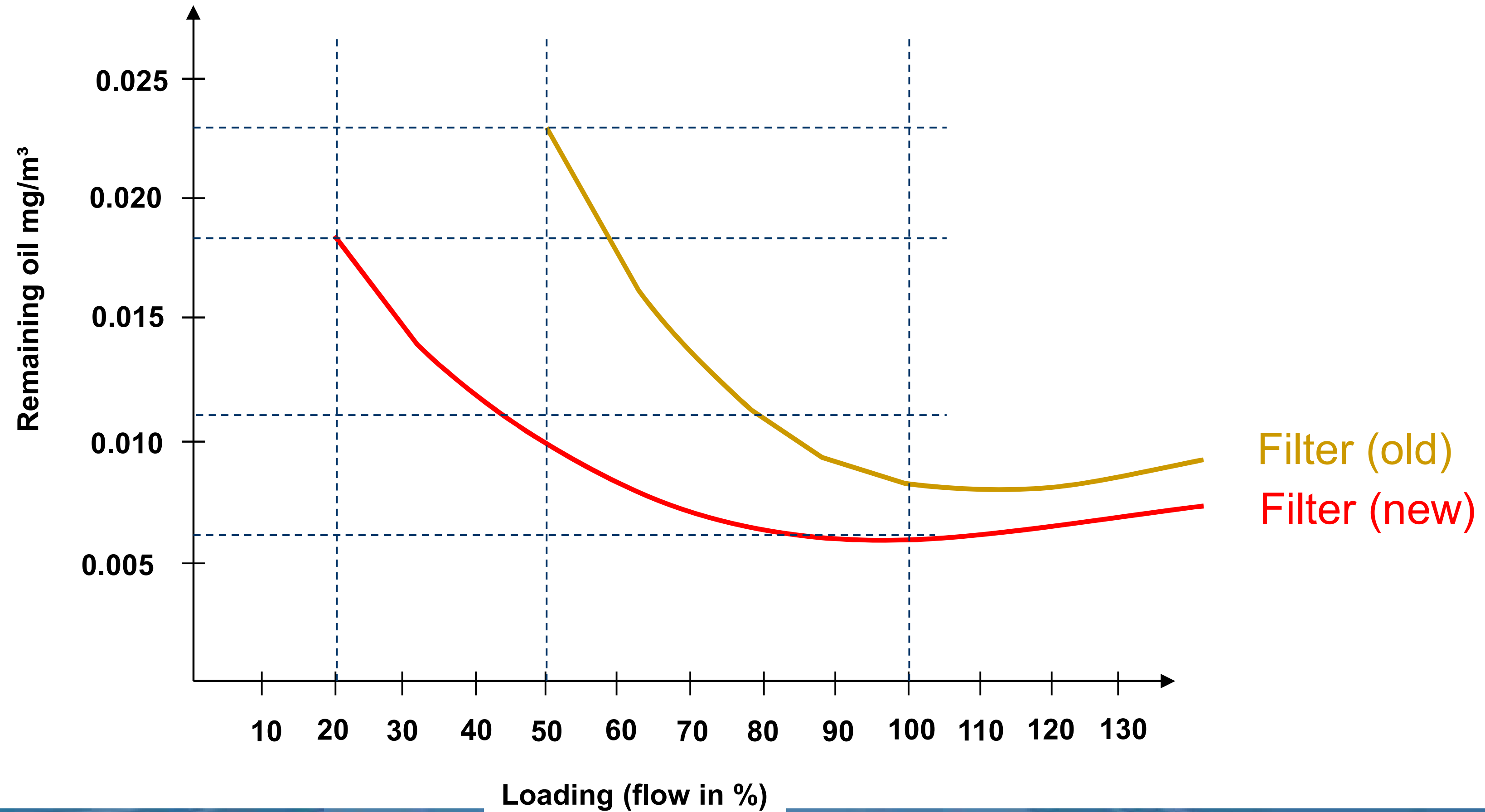


Direct interception

Impact

Diffusion /Coalescence

Coalescing filter behaviour in the partial load range



Activated carbon adsorber

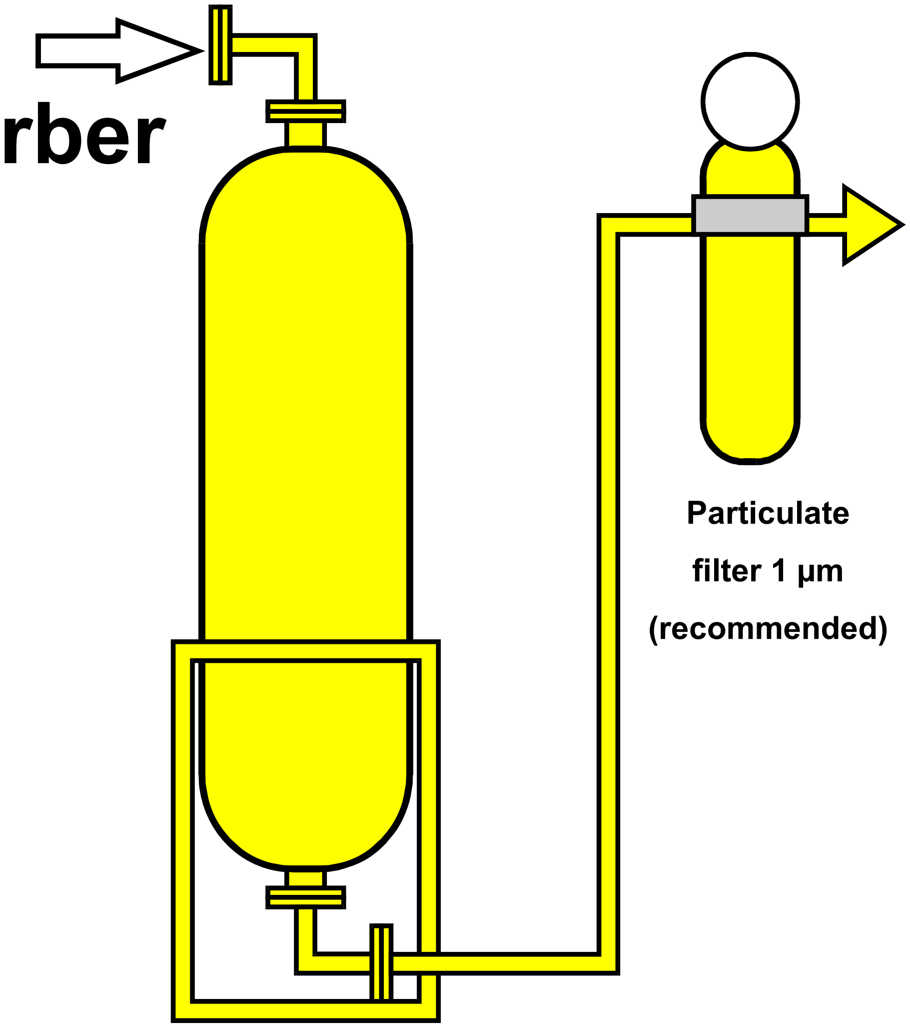
Quality of inlet air:

hydro carbon content <0.01 mg/m^3
free of particles > 0.01 µm

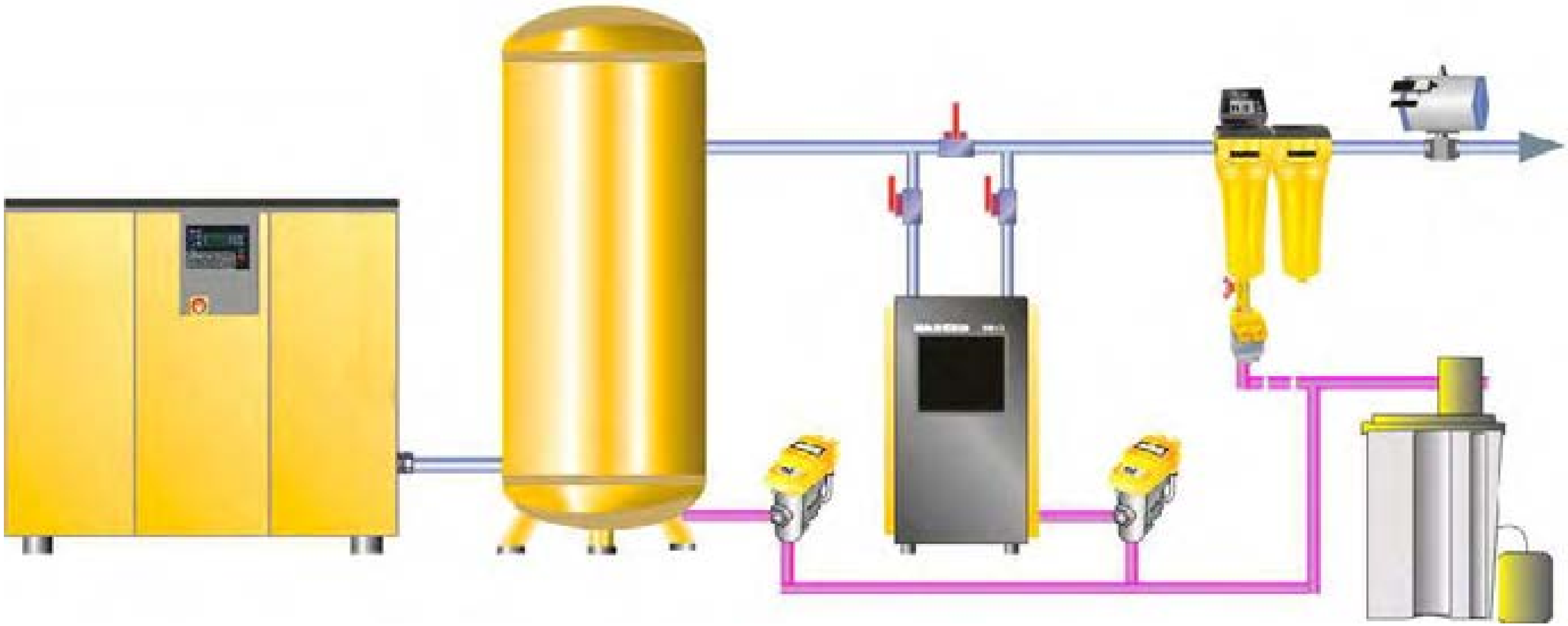
- **long contact time of the air and activated carbon bed**
- **long and reliable life**
- **hydro carbon indicator for continuous quality control**

Quality of outlet air:

hydro carbon content 0.003 mg/m^3

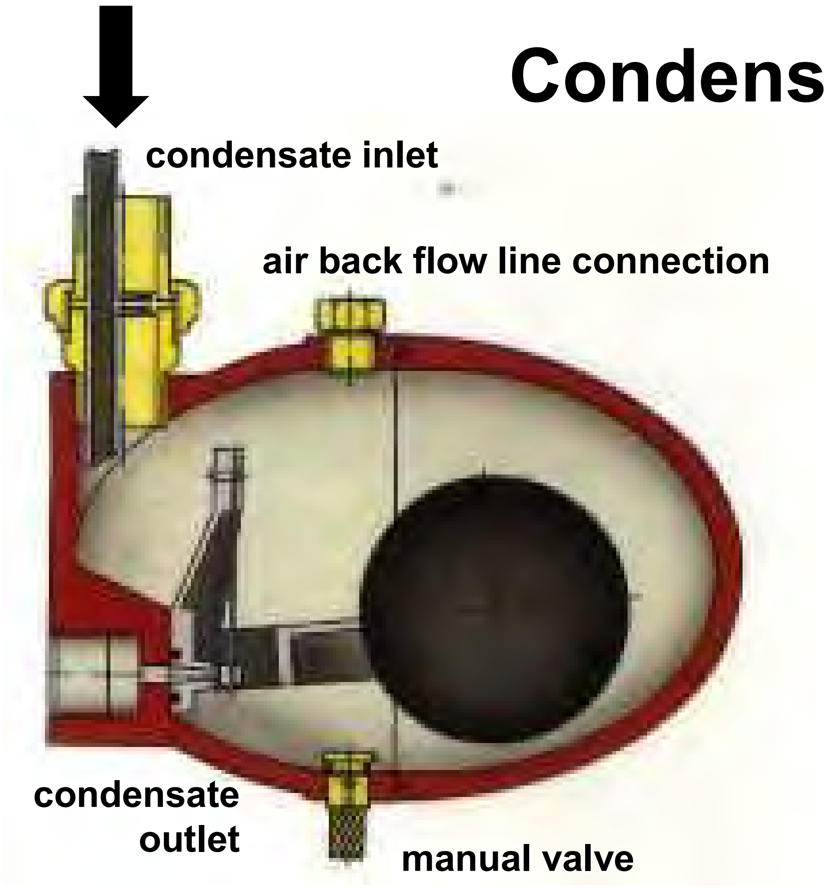


Condensate drainage



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

Condensate drains: float type



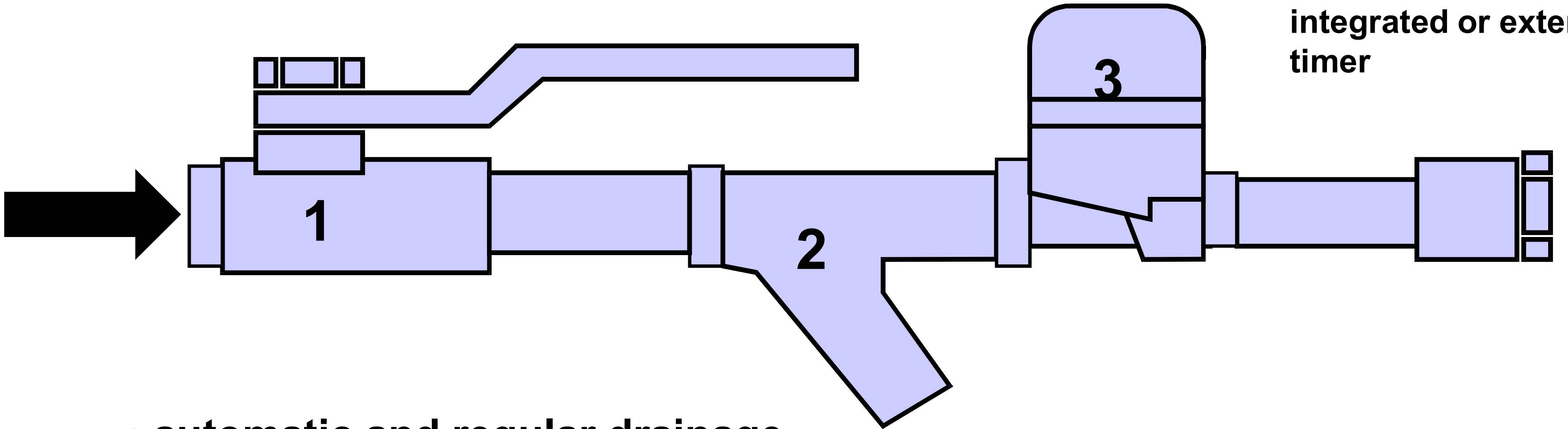
Drainage occurs only when sufficient condensate has collected

No compressed air blowoff

Regular maintenance required

Condensate drains: solenoid valve, timer controlled

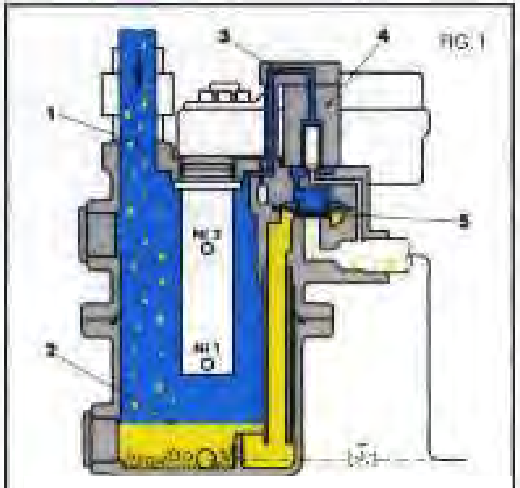
1 ball valve
2 dirt trap
3 solenoid valve with integrated or external timer



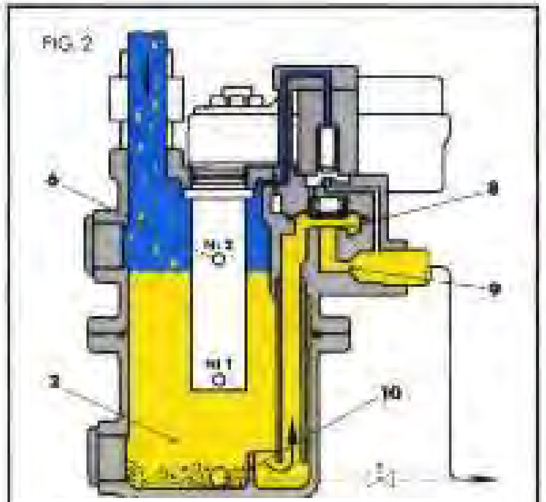
- automatic and regular drainage
- interval 1.5 to 30 min
- opening period 0.4 to 10 sec
- condensate can be directed into a disposal canister

Condensate drains: Electronic level-sensing type

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

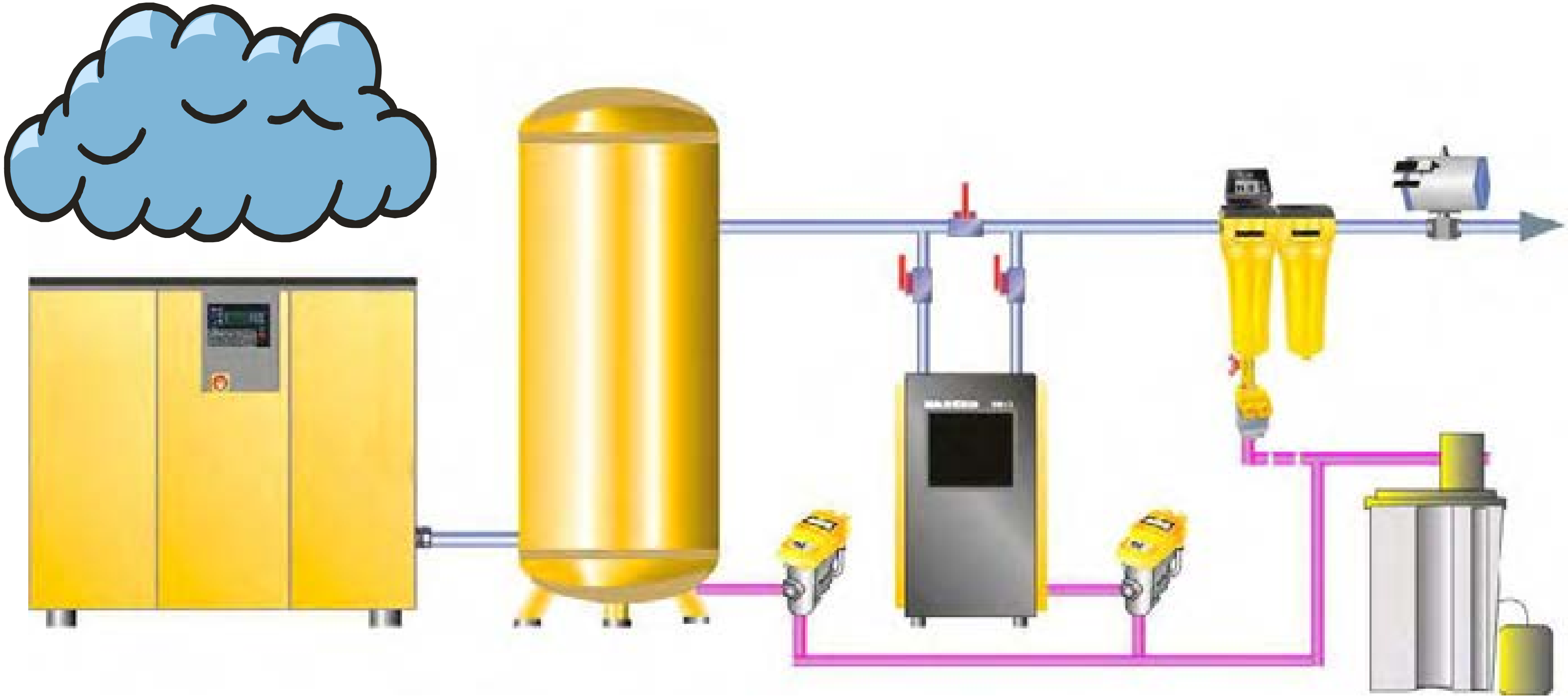


1 condensate inlet 4 solenoid valve
2 collection chamber 5 valve diaphragm
3 pressure balance line



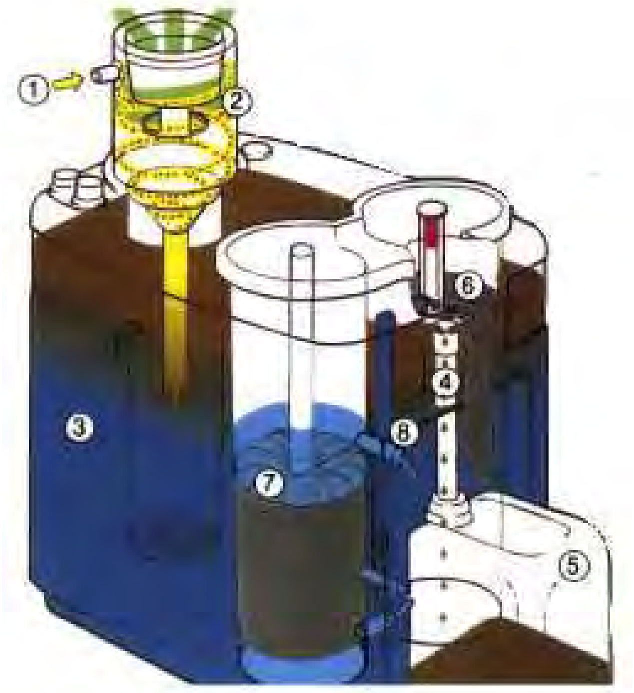
2 collection chamber 9 discharge pipe
6 level sensor
8 valve seat

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

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

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

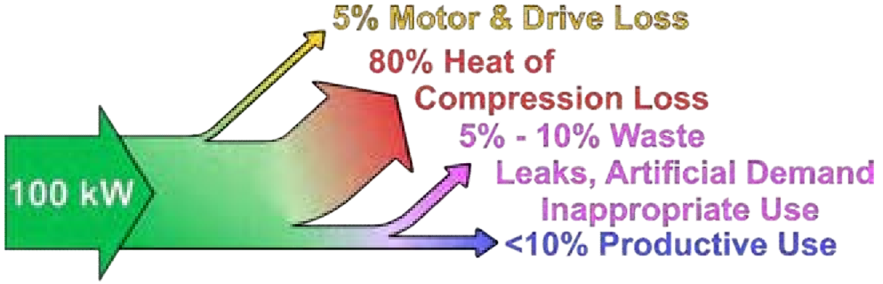
Sample	HC mg/l	Ph	Cu mg/l	Zn mg/l	Cl mg/l	Pb mg/l	Fe mg/l	Na mg/l
oil-free	4.2	4.7	2.5	0.75	1.3	0.2	0.2	1.6
fluid-injected	7.1	6.6	1.1	1	1	0.2	0.2	0.12
oil-free	7	5.5	1.7	0.22	2.4	0.2	0.2	0.45
fluid-injected	0.1	7.1	0.11	0.04	1	0.2	0.2	0.64
oil-free		4.2	16	2	6.4	2.1	4	1.5
oil-free	5.3	6.2	0.11	2.2	1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

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

5. Demand Side: Eliminate Compressed Air Waste

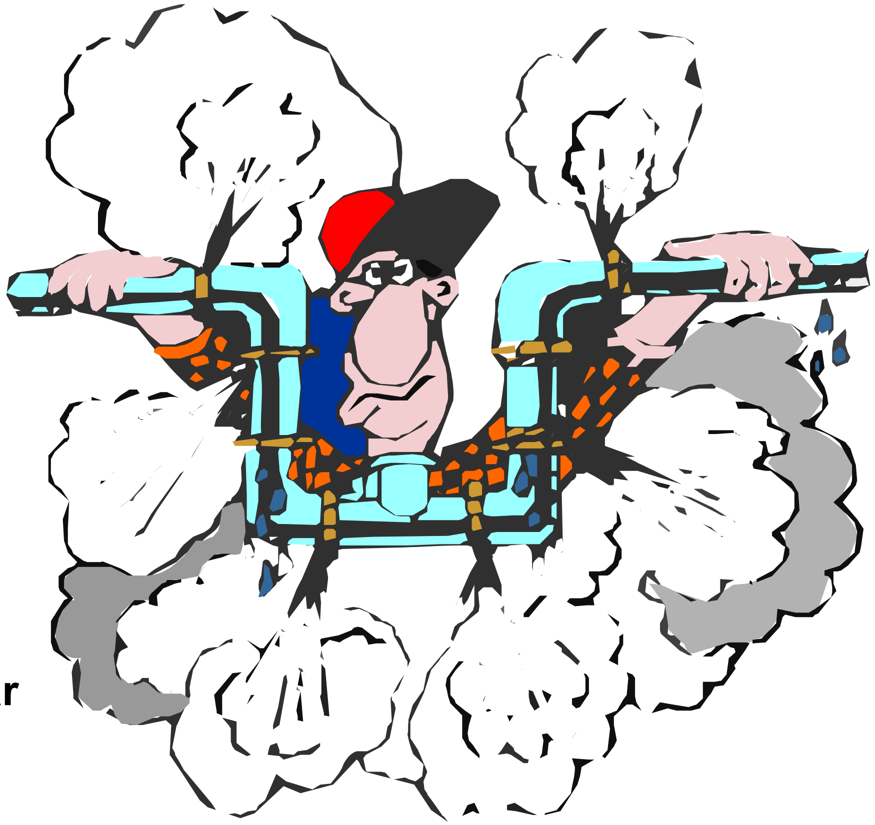
Compressed Air Energy Waste

- Leakage, including open drip legs and condensate drains,
- Operating the system at excessively high pressure, Artificial Demand
- Inappropriate use of compressed air
- Inadequate and / or uncontrolled compressed air energy storage
- Irrecoverable pressure loss in restrictive piping, filters, and other components
- Inefficient compressor control strategy



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 = ????

Leakage losses

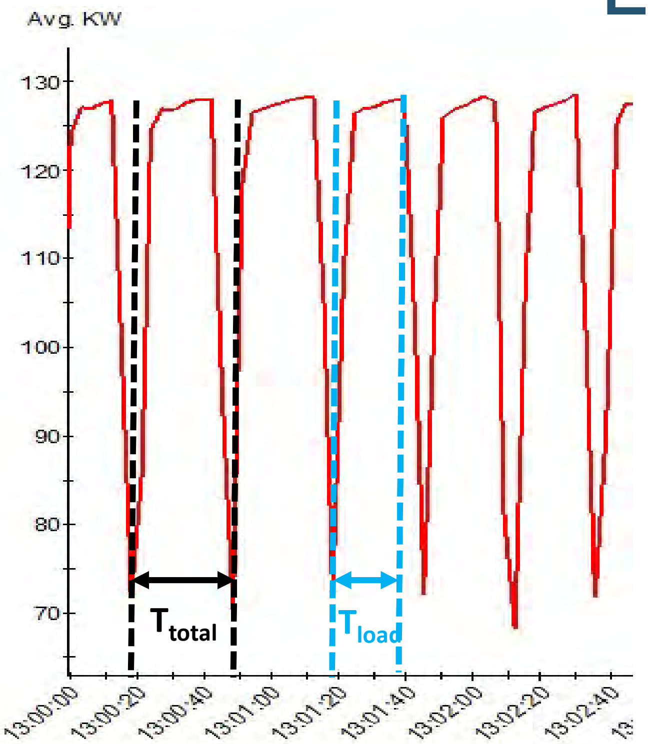
	Air Consumption at 6 bar (g) (m3/min)		Power Loss (kW)	
Hole Diameter	sharp orifice 0.61 coefficient	rounded orifice 0.97 coefficient	Shaft Power 6.2 kW / m^3/min.	Package Power 7.1 kW / m^3/min.
1mm	0,040	0,064	0,25 to 0,40	0,28 to 0,45
2mm	0,16	0,25	0,62 to 1,5	1,1 to 1,8
3mm	0,35	0,56	2,2 to 3,1	2,5 to 4,0
4mm	0,63	1,00	3,9 to 6,2	4,5 to 7,1
6mm	1,42	2,26	8,8 to 14,0	10,0 to 16,0

At EGP 0.80/kWh, a 6mm leak costs over
90,000 Rbl
/year in power plus additional service on the compressed air equipment.

One audible leak (±3mm) will cost EGP20,000 per year!

Gauge pressure before orifice, bar	Diameter of Orifice, mm (note: calculated flow rate assumes orifice coefficient of 0.61)											
	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

Measuring Leak Losses by Measuring Load/Unload Time



$$Q_{leaks} = \frac{Q_{gen} \times Tlo_{ad}}{T_{load} + Tunload}$$

Q_{leaks} = Leak rate (Nm^3/min)
Q_{gen} = Generated flow rate from compressors (m^3/min)
T_{load} = Time that compressor runs on load (minutes)
T_{total} = Time it runs on load, plus the time to unload (minutes)

Example:
Loading time ≈ 18 seconds (0.3min), and total time to load plus unload ≈ 30 seconds (0.5min). Compressor generates $10m^3/min$ flow

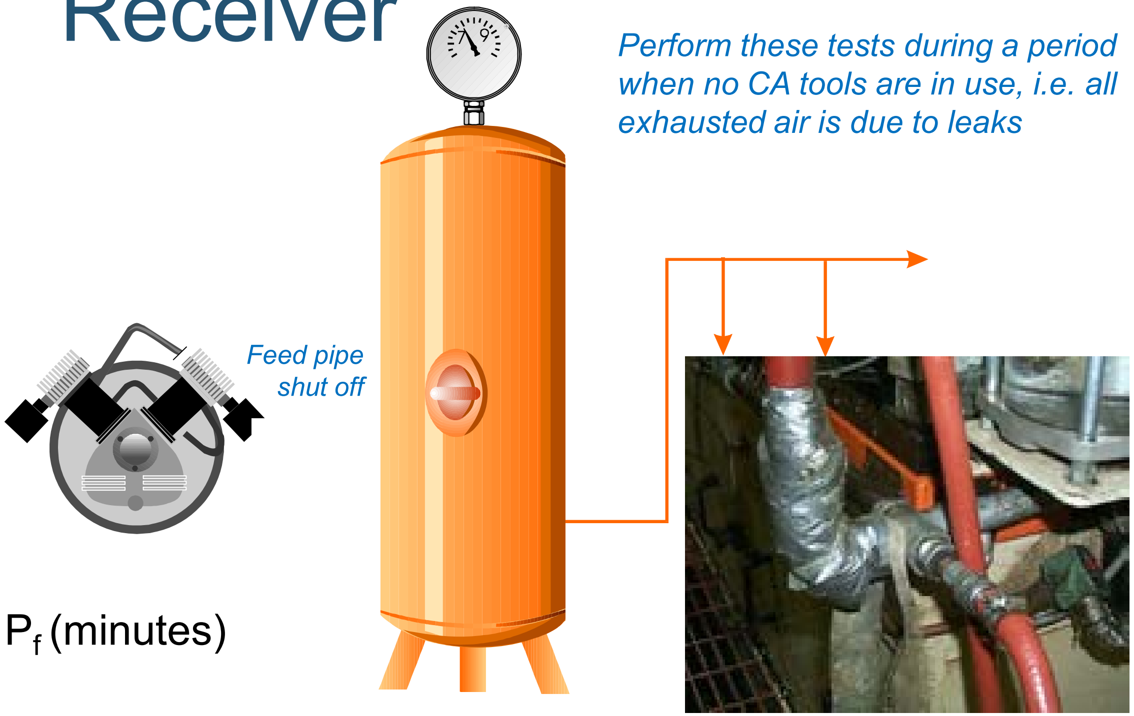
$$Q_{leaks} = \frac{10\frac{m^3}{min} \times 0.3min}{0.5min}$$

$$Q_{leaks} = 6\, m^3/min = 60\%$$

Measuring Leak Losses by Exhausting an Air Receiver

$$Q_{leaks} = \frac{V_{sys} \times (Pi - Pf)}{\Delta T \times Patm}$$

Perform these tests during a period when no CA tools are in use, i.e. all exhausted air is due to leaks



Q_{leaks} = Leak Rate (Nm^3/min)
V_{sys} = Volume of System (m^3)
P_i = Initial Pressure (bar_g)
P_f = Final Pressure (bar_g)
P_{atm}= Atmospheric pressure
ΔT = Time Interval between P_i and P_f (minutes)

Sample Calculation – System Bleed Down Test

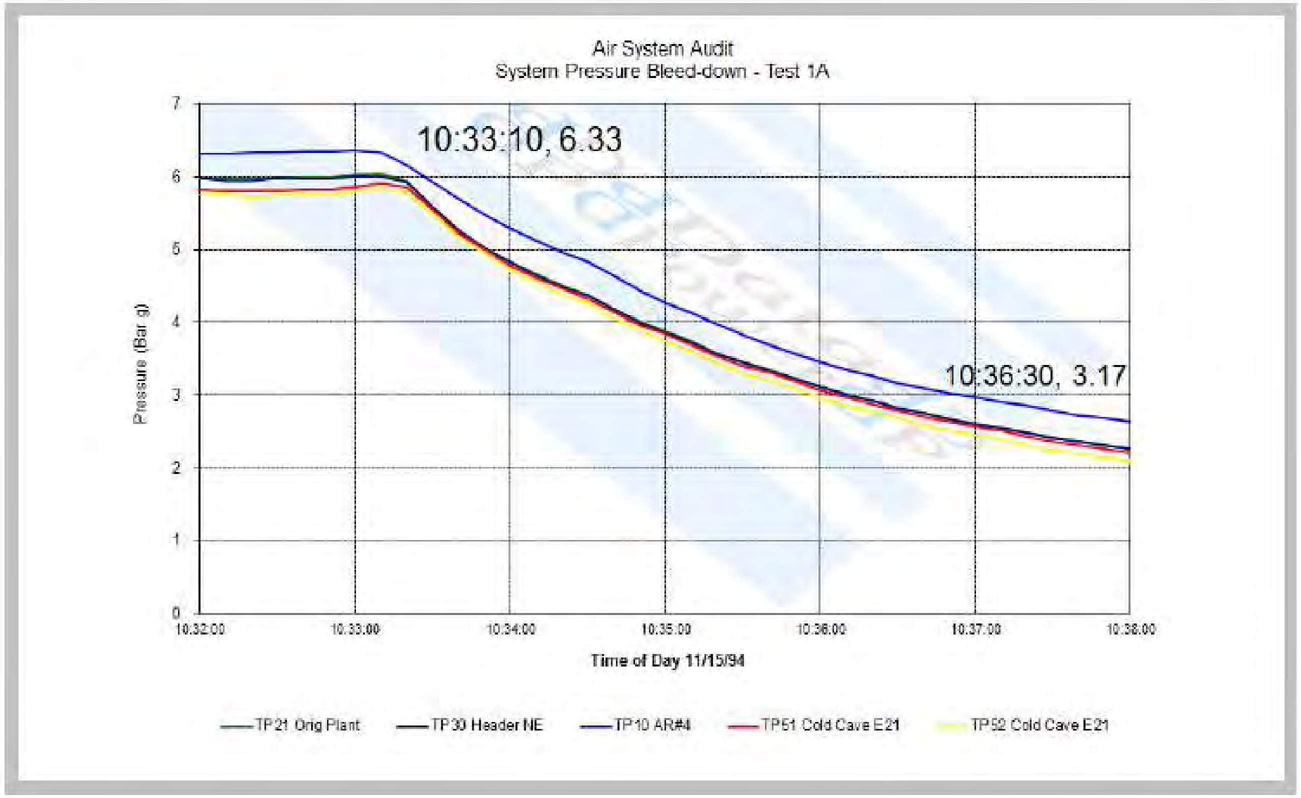
For example, a compressed air system with 25 m^3/ minute of total air compressor capacity has a total volume (including air receivers and piping) of 7.63 m^3.

A bleed down test is performed which resulted in the pressure decay curve shown in the next slide

The normal system pressure (P_I) was 6.33 bar at the time when all compressors were unloaded (or stopped). The system pressure was allowed to decay to 3.17 bar (P_F) (50% of the normal working pressure) and the time measured was 3 minutes 20 seconds (T = 3.33 minutes).

The compressed air non-production system flow rate is calculated to be 7.23 m^3 / minute.

$$Q = \frac{7.63\ \mathrm{m}^3 \times (6.33\ \mathrm{bar} - 3.17\ \mathrm{bar})}{3.33\ \mathrm{minutes} \times 1\ \mathrm{bar}} = 7.23\ \mathrm{m}^3/\mathrm{min}$$



$$Q = \frac{V_R \times (P_I - P_F)}{T \times P_A} \times 1.25$$

Where:

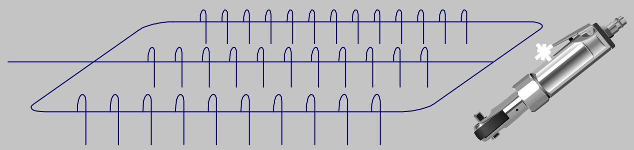
Q	=	Flow rate	P_F	=	Final pressure
V_R	=	Receiver & piping volume	T	=	Measuring period (time)
P_I	=	Initial pressure	P_A	=	Atmospheric pressure

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.

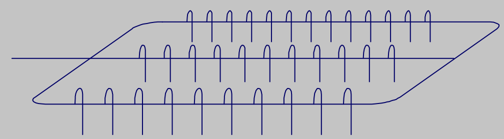
Using the two methods described previously, two measurements are carried out:

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.

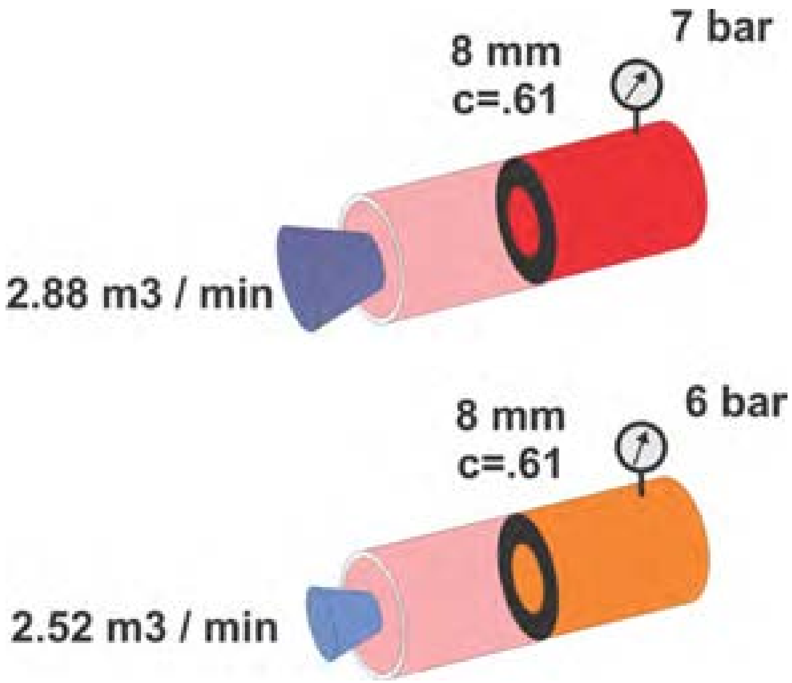
Artificial Demand

Artificial Demand

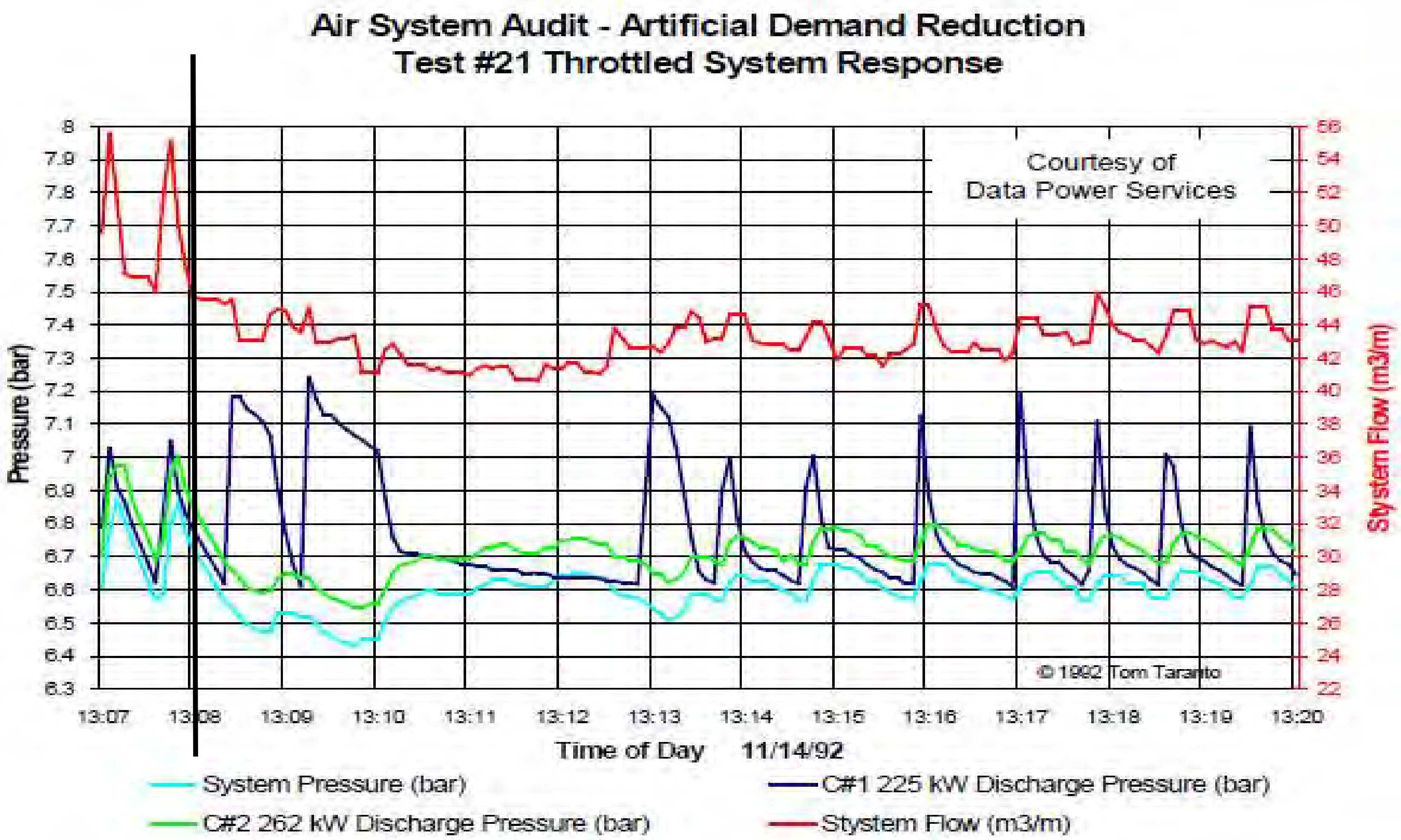
Artificial Demand is the increased compressed air flow consumed by a compressed air system when the applied demand side pressure is increased above the lowest optimum pressure necessary to support productive air use. All unregulated compressed air use and unregulated leakages contribute to the system's total artificial demand.

Artificial Demand

- If the required pressure is 6 bar
- Operating at 7 bar creates 2.88 m^3/min of artificial demand
- 12% of the air that is supplied to the system is wasted.



Artificial Demand Reduction



Inappropriate Use of Compressed Air

Inappropriate Use of Compressed Air
Inappropriate Use of Compressed Air is any productive work powered by compressed air energy that can be replaced with an alternative energy technology representing a more efficient conversion of energy to productive work.

Inappropriate Use of Compressed Air

- What are some examples of Inappropriate Use of Compressed Air?
- What alternative methods or energy technologies might be considered to replace the use of compressed air?

Inappropriate uses of compressed air

Open Blowing	Processes such as cooling, bearing cooling, drying, clean-up, draining compressed air lines, and clearing jams on conveyors.
Sparging	Sparging is aerating, agitating, oxygenating, or percolating liquid with compressed air.
Aspirating	Aspirating is using compressed air to induce the flow of another gas (such as flue gas) with compressed air.
Atomizing	Atomizing is where compressed air is used to disperse or deliver a liquid to a process as an aerosol.
Padding	Padding is using compressed air to transport liquids and light solids.
Dilute Phase Transport	Dilute Phase Transport is used in transporting solids such as powdery material in a diluted format with compressed air.
Dense Phase Transport	Dense Phase Transport used to transport solids in a batch format.

Inappropriate uses of compressed air (cont'd)

Personnel Cooling	Personnel cooling is operators directing compressed air on themselves to provide ventilation. (always inappropriate)
Open hand held blowguns or lances	Open hand held blowguns or lances are any unregulated hand held blowing and are a violation of most health and safety codes, and very dangerous. (always inappropriate)
Diaphragm pumps	Diaphragm pumps are commonly found installed without regulators and speed control valves. Those diaphragm pumps that are installed with regulators are found with the regulators adjusted higher than necessary.
Vacuum Generation	Vacuum generators are used throughout industry. Some applications for vacuum generators are shop vacuums, drum pumps, palletizers, depalletizers, box makers, packaging equipment, and automatic die cutting equipment.
Vacuum Venturi	Applications where compressed air is used with a venturi, eductor, or ejector to generate a negative pressure mass flow. When compressed air is forced through a conical nozzle, the velocity increases and a decrease in pressure occurs. Vacuum generators are used throughout industry. Some applications for vacuum generators are shop vacuums, drum pumps, palletizers, depalletizers, box makers, packaging equipment, and automatic die cutting equipment
Cabinet cooling	When first cost is the driving factor, open tubes, air bars (copper tube with holes drilled along the length of the tube) and vortex tube coolers are used to cool cabinets. Cabinet cooling should not be confused with panel purging (an explosion proof panel having an inert gas passed through it at positive pressure). Cabinet cooling should not be confused with panel purging (an explosion proof panel having an inert gas passed through it at positive pressure).

Alternatives to compressed air energy use

Inappropriate Use	Alternative	Inappropriate Use	Alternative
Open Blowing	Fan, Blower, Broom, Electrically powered vacuum	Personnel Cooling	Electric Fan
Sparging	Blower, Mechanical Agitation	Open hand held blowguns or lances	Blower (low or medium pressure), Low pressure compressor, Electrically powered vacuum, Brush, broom or other mechanical device
Aspirating	Blower, Fan	Diaphragm pumps	Electrically driven pump
Atomizing	Blower, High Pressure Nozzle	Vacuum Generation	Electrically Driven Vacuum Pump, Centralized Vacuum System
Padding	Blower (low or medium pressure), Low Pressure Compressor	Vacuum Venturi	Low pressure venturi designed to be powered by a blower.
Dilute Phase Transport	Blower (low or medium pressure), Low Pressure Compressor	Cabinet cooling	Ventilation fan, heat pipes, liquid cooling, refrigerated cooler
Dense Phase Transport	Blower (low or medium pressure), Low Pressure Compressor Mechanical Conveyor	Vacuum Generation	Electrically Driven Vacuum Pump, Centralized Vacuum System

Irrecoverable Pressure Loss

Irrecoverable Pressure Loss
Irrecoverable Pressure Loss in a compressed air system is the difference in pressure at two points in the system resulting from the interaction between compressed airflow and the fixed frictional resistance of components that compressed air is flowing through.

Key Learning Points

1. Use compressed air only when other alternatives are not available.
2. Compressed air systems should be operated at the lowest practical pressure.
3. Optimize compressor control with a properly implemented control strategy.

Key Energy Points

4. Eliminating inappropriate use reduces air demand and saves energy.
5. Reducing system pressure eliminates Artificial Demand and saves energy.
6. Reducing leakage loss in the system eliminates waste and saves energy.
7. Minimize irrecoverable pressure loss and reduce compressor discharge pressure to save energy.
8. Greatest energy savings occur when the compressor control strategy optimizes the balance between supply and demand.

6. Distribution

Pneumatic Power

Air Flow > Mass or Weight of Air

Pressure > Potential Energy

Increasing – or – Decreasing

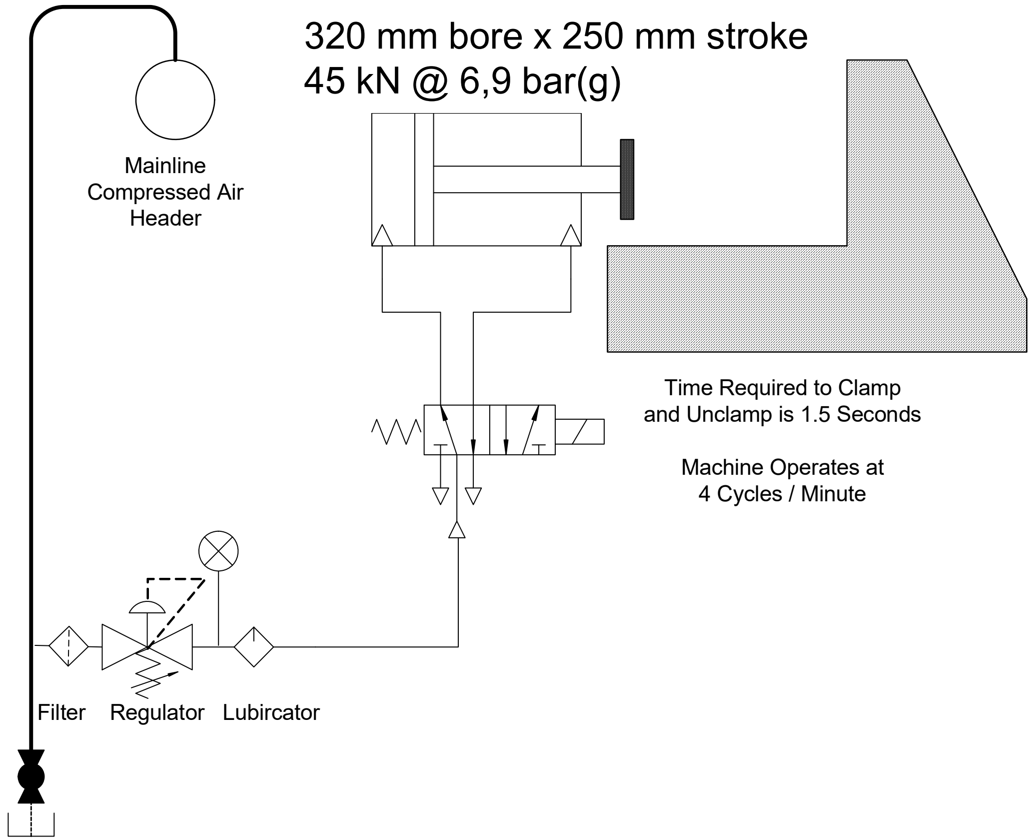
Flow – or – Pressure

Increase – or – Decrease

Power Delivered & Power Consumed

Clamping Cylinder

- 1,5 seconds
- 4 cycles per minute
- 320mm Bore (45 000 Newtons @ 6,9 bar)
- 250mm Stroke Length



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

$$m^3 = V \times \frac{\Delta P}{P_{atm}} = 0{,}02\ m^3 \times \frac{6{,}9\, bar(g) + 1\, bar}{1\, bar} = 0{,}158\, m^3$$

Cylinder Average Air Demand (1 minute)

$$Average\ Air\ Flow\ \ (m^3) = 8\,\frac{Strokes}{Minute} \times 0{,}158\,\frac{m^3}{Stroke} = 1{,}246\ m^3$$

What Size Components?

Air Line Size ___________________________

Filter, Regulator, Lubricator _____________

Valve Size _______________________________

Cylinder Peak Dynamic Flow Rate

$$Dynamic\ Airflow\ Rate = \frac{1,264\ m^3}{1,5\ seconds} \times \frac{60\ seconds}{1\ Minute} = 6,32\ m^3 / \min$$

What Size Components Now?

Air Line Size ______________________

Filter, Regulator, Lubricator ___________

Valve Size ________________________

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

- 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.

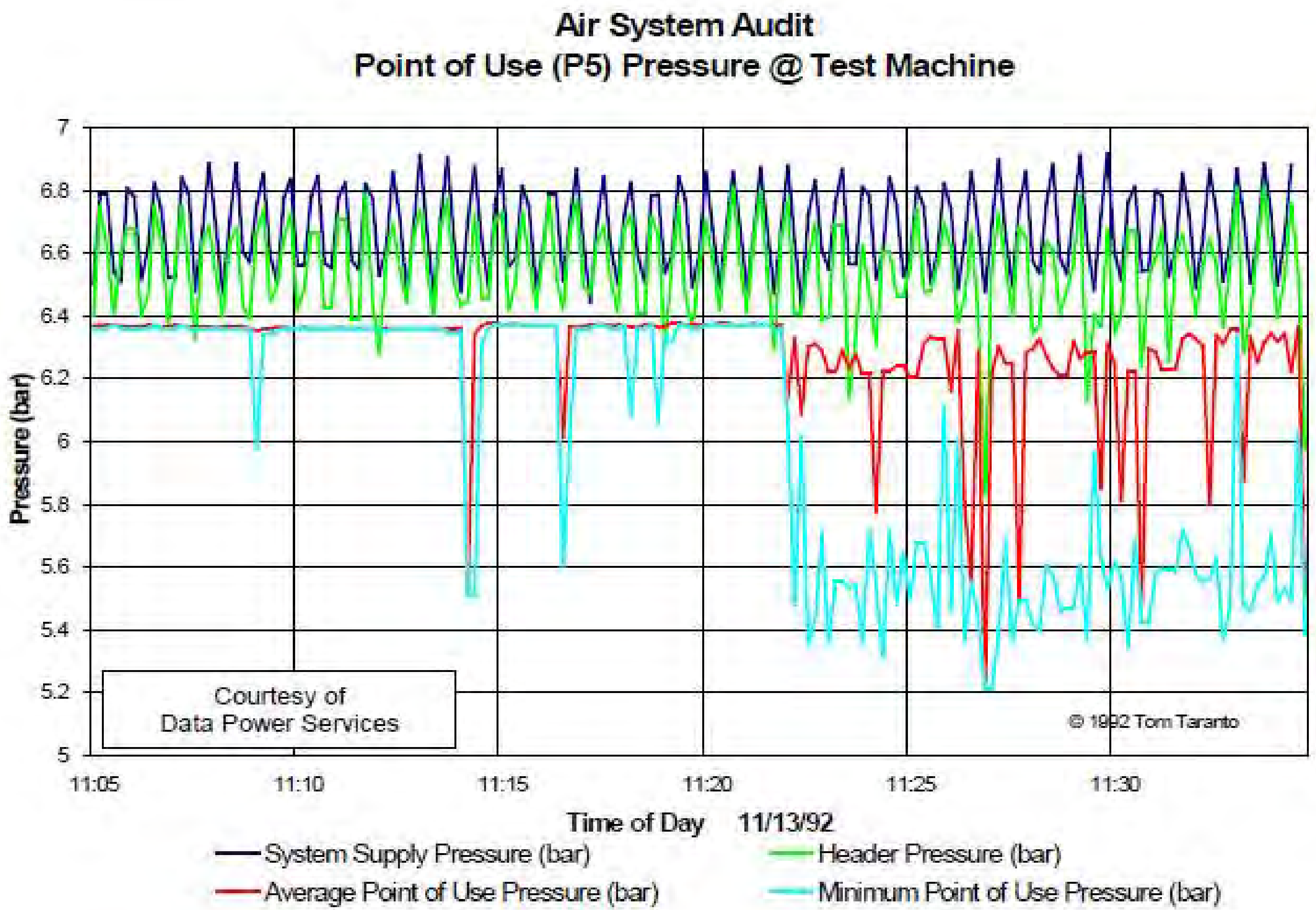
Perceived High Pressure Demands

- 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

Validate Perceived High Pressure

Pressure Gauges – Mechanical Damping



Test Machine Flow Dynamic Demand

What's Wrong With This Picture?

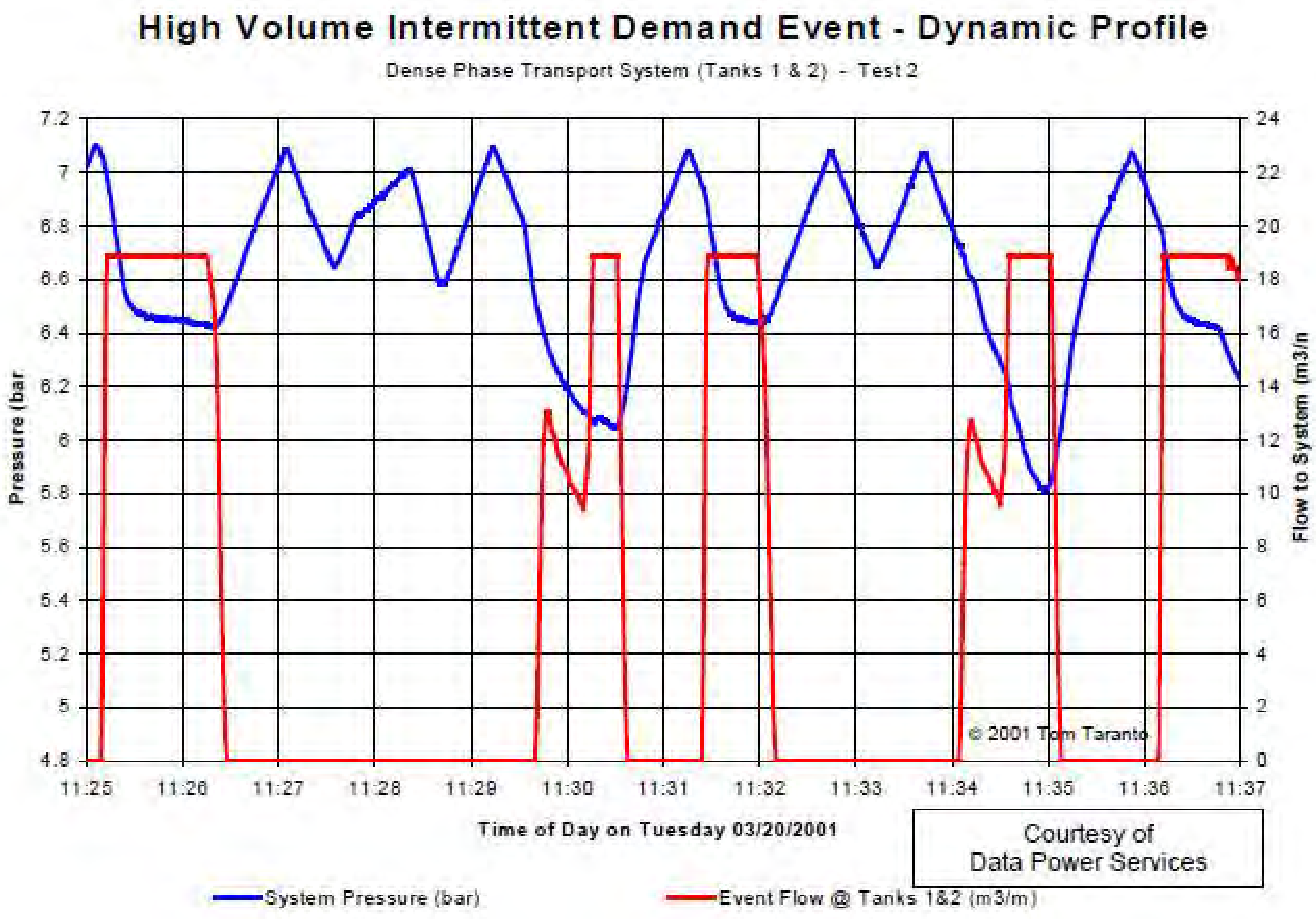
- High Volume Intermittent Demand
  - Consume Large Airflow for Short Periods
  - High Peak Airflow Rate and Low Average Demand
  - Affects the System Pressure Profile

    Control Signals — Supply Pressure

    Distribution Gradient — Use Point Pressure

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**


High Volume Intermittent Demand Event - Dynamic Profile
Dense Phase Transport System (Tanks 1 & 2) - Test 2
Pressure (bar
7.2
7
6.8
6.6
6.4
6.2
6
5.8
5.6
5.4
5.2
5
4.8
Flow to System (m3/n
24
22
20
18
16
14
12
10
8
6
4
2
0
11:25
11:26
11:27
11:28
11:29
11:30
11:31
11:32
11:33
11:34
11:35
11:36
11:37
Time of Day on Tuesday 03/20/2001
© 2001 Tom Taranto
Courtesy of
Data Power Services
System Pressure (bar)
Event Flow @ Tanks 1&2 (m3/m)

- 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**

- Which Piping Configuration Performs Best?

Key Learning Points

1. Identify dynamic airflow conditions of average –vs- peak airflow.

2. Classify air demands as Flow Static and Flow Dynamic.

3. Point of use connection practice has a significant effect on applications performance.

4. Review perceived high pressure air demands to validate their pressure requirements.

5. Pressure gauges have slow response to pressure changes. Pressure transducers and high-speed sampling may be required to capture pressure dynamics.

Key Energy Points

6. Supplying higher end use pressure requiring higher discharge at the compressor(s) increases compressor power (kW) by 6% per bar.

7. Poor piping design with excessive flow restriction can create a perception that the end use air demand requires higher pressure than is actually necessary.

8. Minimize the use of hose for connections. Hose has much smaller ID size (higher pressure drop) than similar diameter pipe.

9. Where hose must be used select the hose size based on the inside diameter and peak airflow rate. Avoid the use of hose, hose barbs and pipe clamps. They are very restrictive and frequently develop leaks.

Key Energy Points

10. Do not use redundant point of use dryers, filters, etc. as each component represents additional pressure drop.

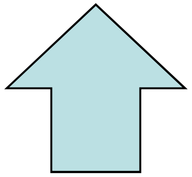
11. Avoid over filtration, maintain an appropriate compressed air cleanliness class for the application requirements.

12. When components are improperly sized for average airflow rate rather than peak airflow requirements, system is pressure is often increased to accommodate the improperly sized components.

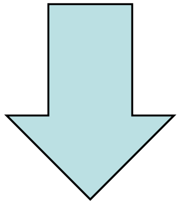
13. Size all connection equipment to the actual dynamic conditions associated with the application. Account for the peak airflow rate that must be supported, do not size equipment based on average airflow rate.

Balancing the Supply to Demand

- Supply > Demand ~ Pressure



- Demand > Supply ~ Pressure

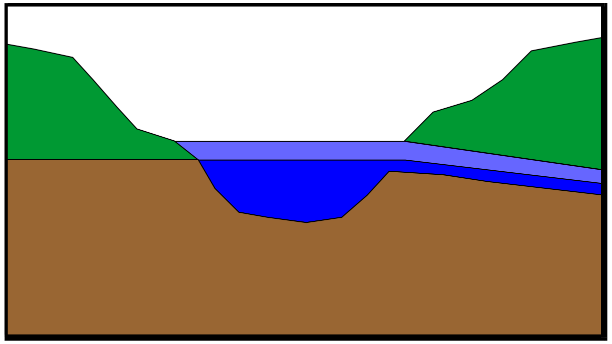


- Air System Minimum Pressure
  - What is the correct pressure?
  - What is the Cost?

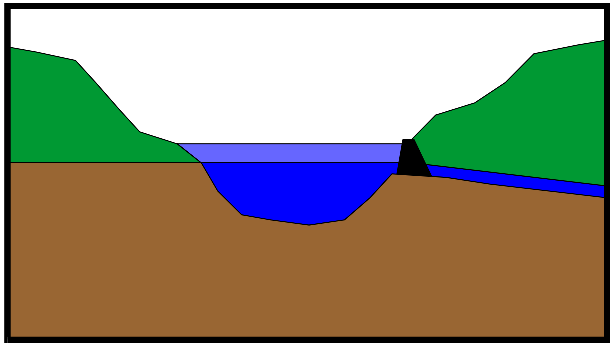
- Increased Air Pressure = Waste
  - Artificial Demand
  - Increasing Pressure Increases Airflow

Engineer Primary Storage Systems

Storage; A Lake – vs – A Reservoir

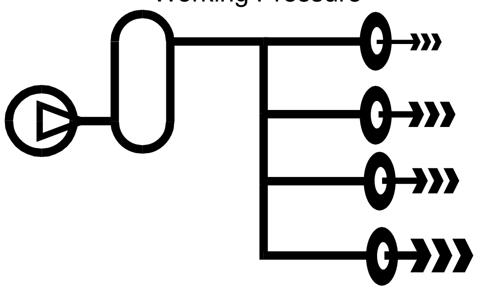


LAKE

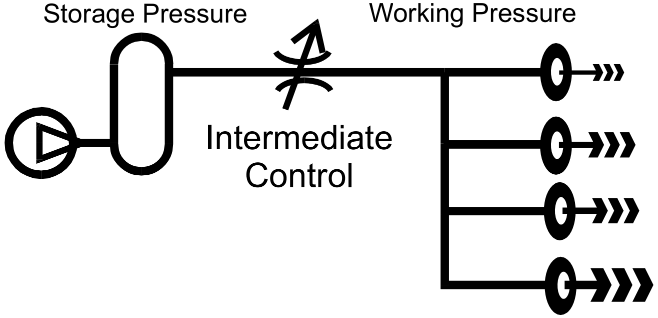


RESERVOIR

AIR RECEIVER



AIR STORAGE

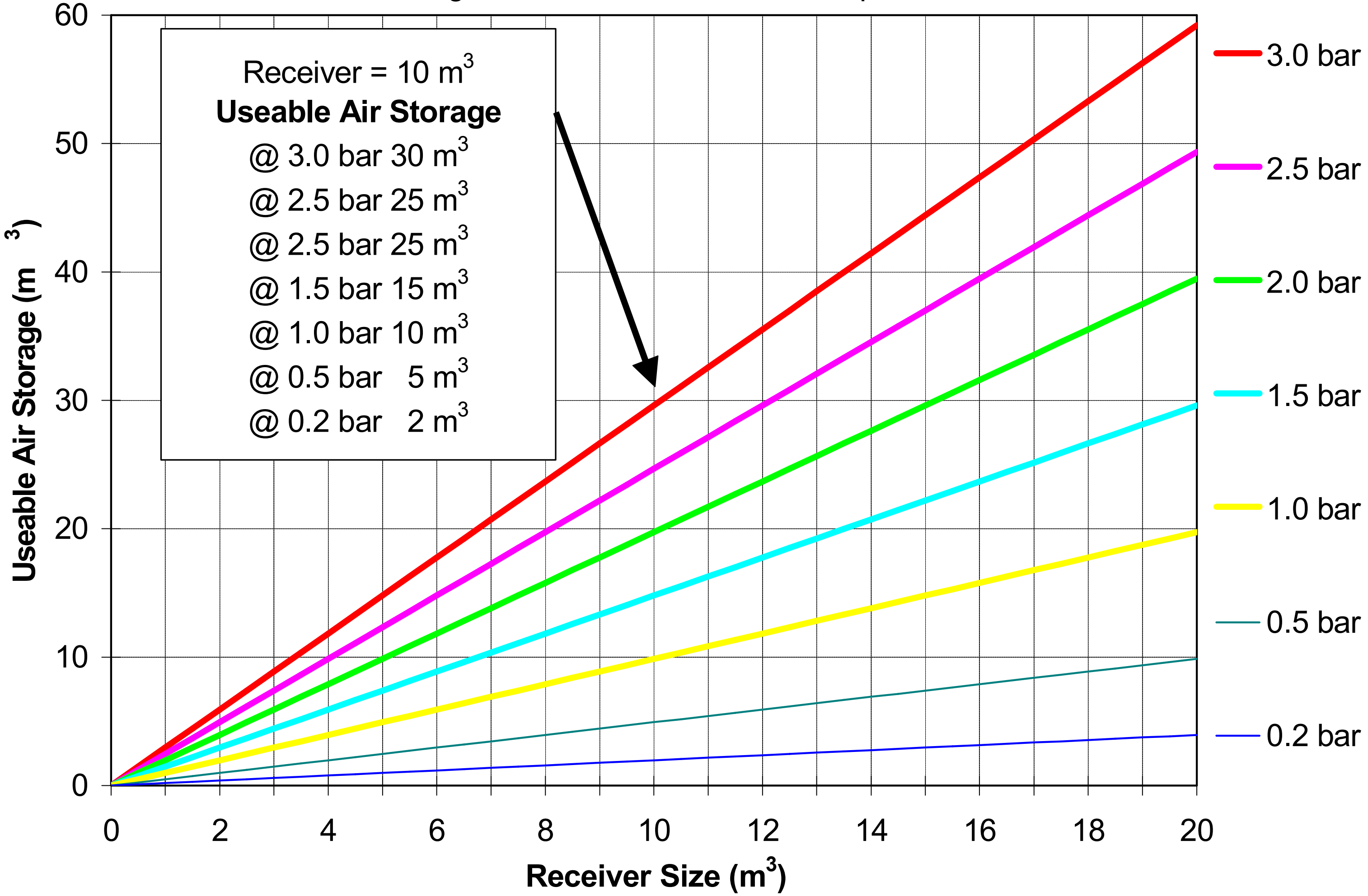


- Stabilize System Operation
  - Minimize the cost of generating compressed air.
  - Control air demand and reduce artificial demand.
  - Create controlled air storage to supply peak demand

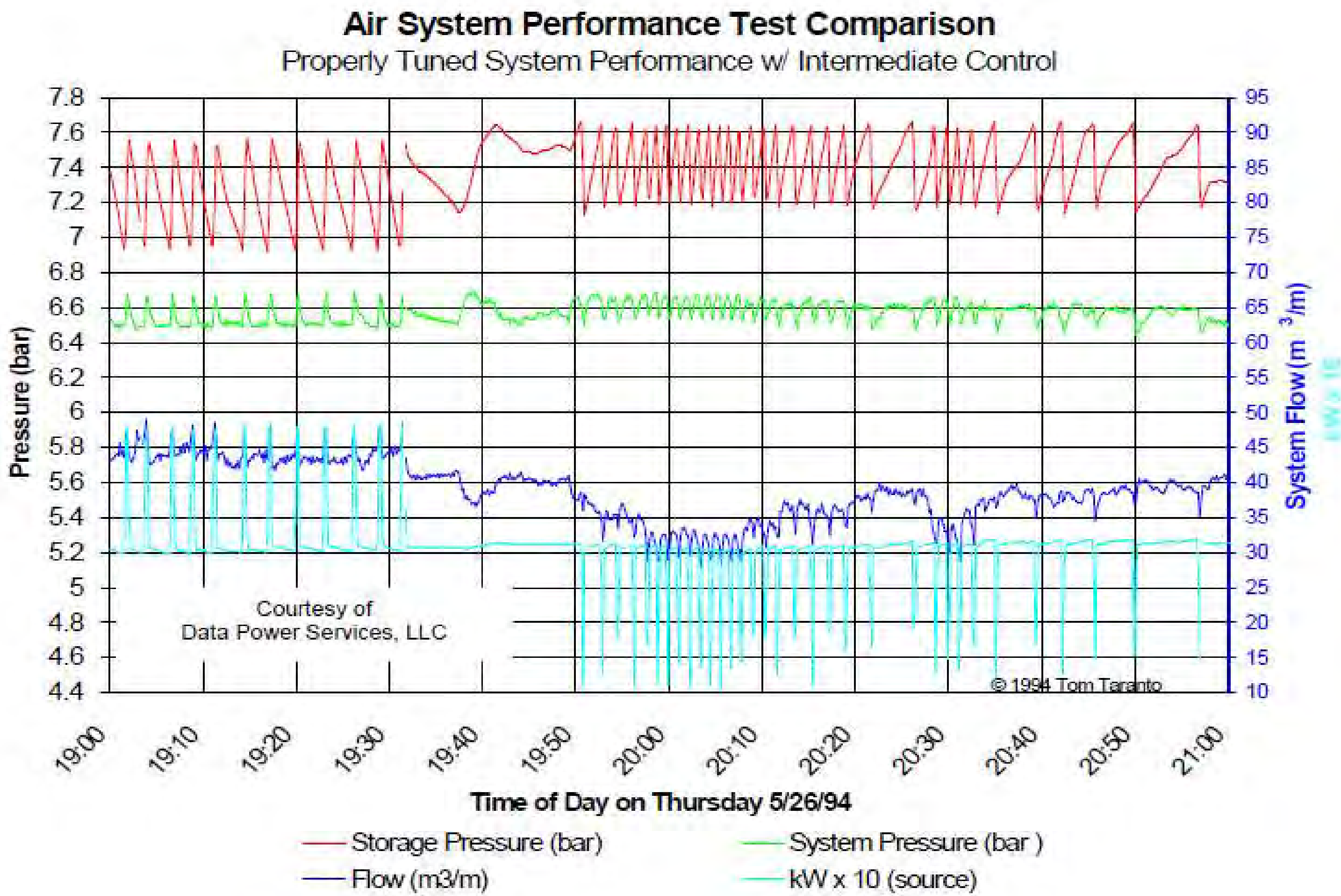
- Evaluating Controlled Storage
  - Meet surge demands
  - Satisfy events as defined in the demand profile
  - Improve compressor control response

Compressed Air Storage - for Stable System Operation

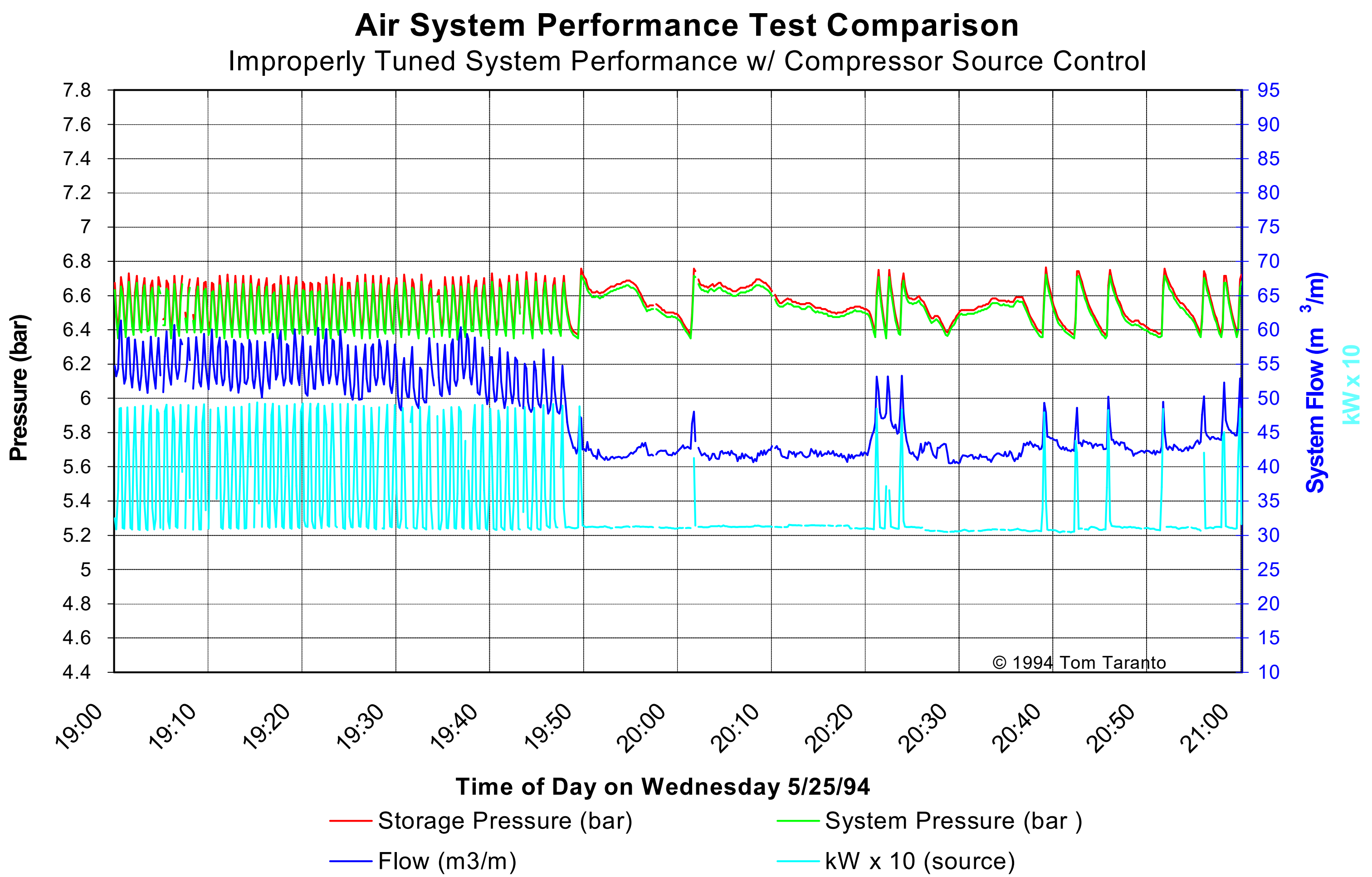
Useable air in storage based on receiver size and pressure differential



Tuning Compressor & System Controls



Tuning Compressor & System Controls



Key Learning Points

1. Stabilize system operating pressure.

2. The amount of energy in storage depends on storage volume and controlled pressure differential.

Key Energy Points

3. Elevated air pressure increases compressed air demand at leaks and unregulated air demands.

4. Leakage can be reduced by controlling to a lower system pressure.

5. Artificial demand is a component of any unregulated leak or air demand.

6. Target pressure should be the lowest optimal pressure to supply productive air demands.

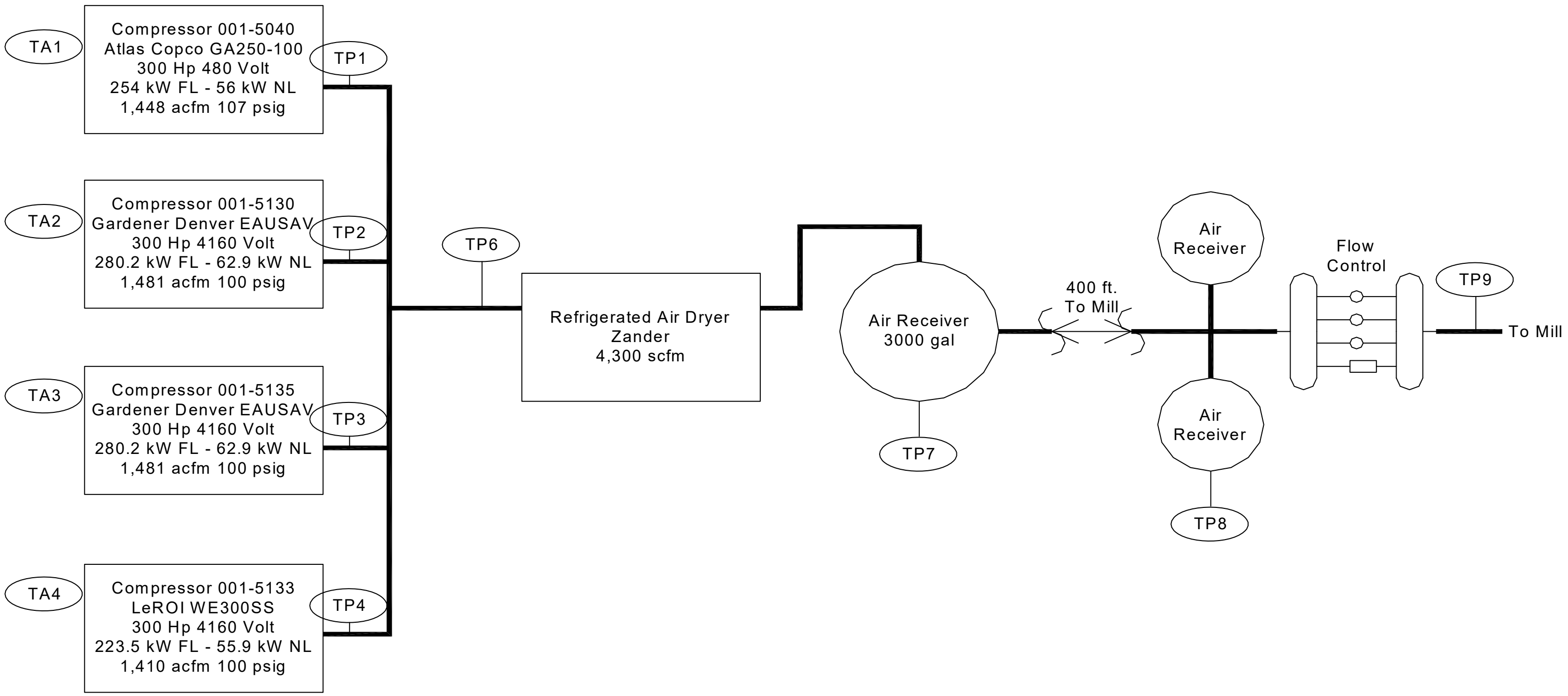
7. Air storage should be designed to supply surge demands, satisfy events defined in the demand profile, and improve compressor control response.

7. Pressure Profile

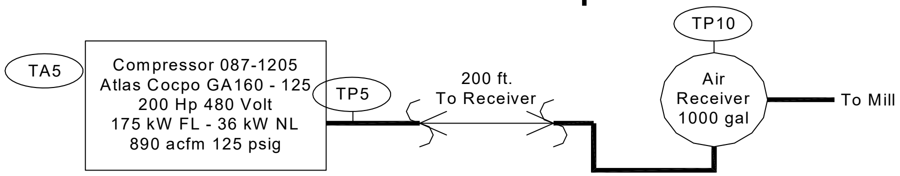
Typical pressure measurement locations

- 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

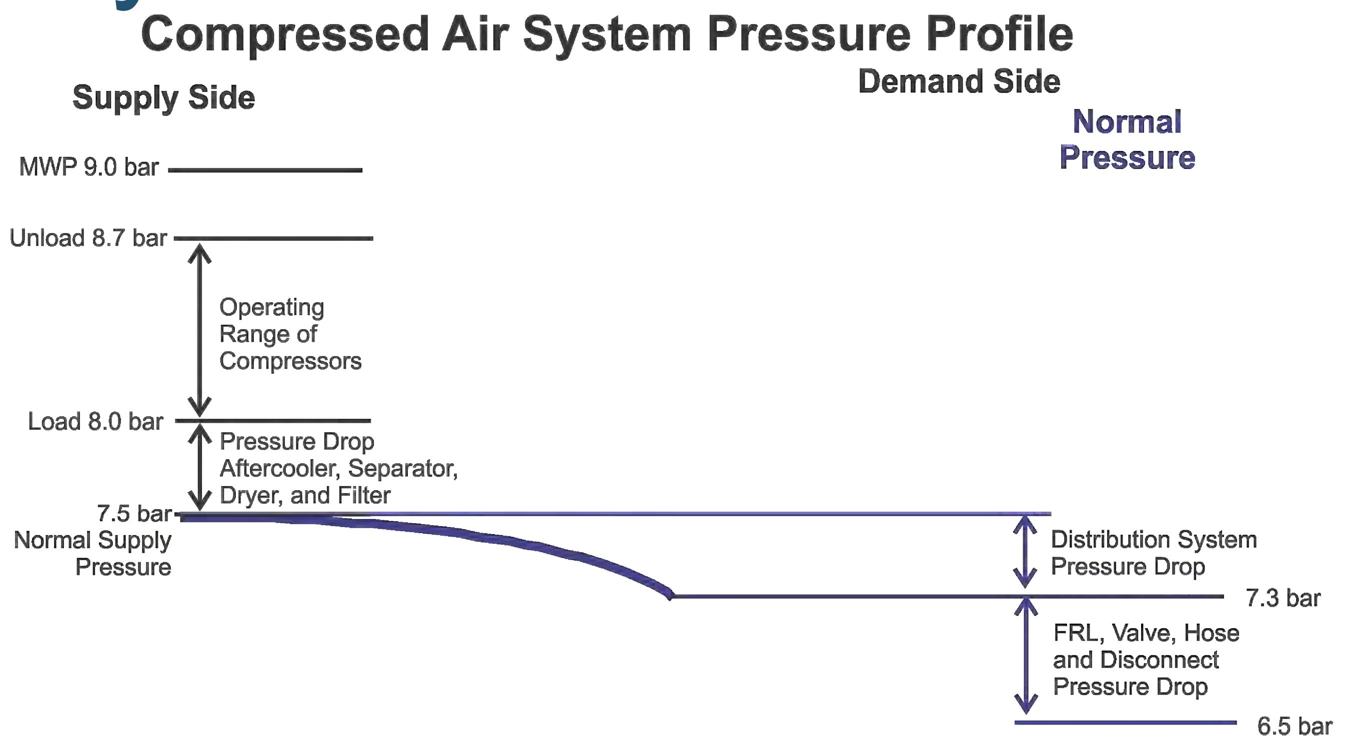
Plant Air Compressors



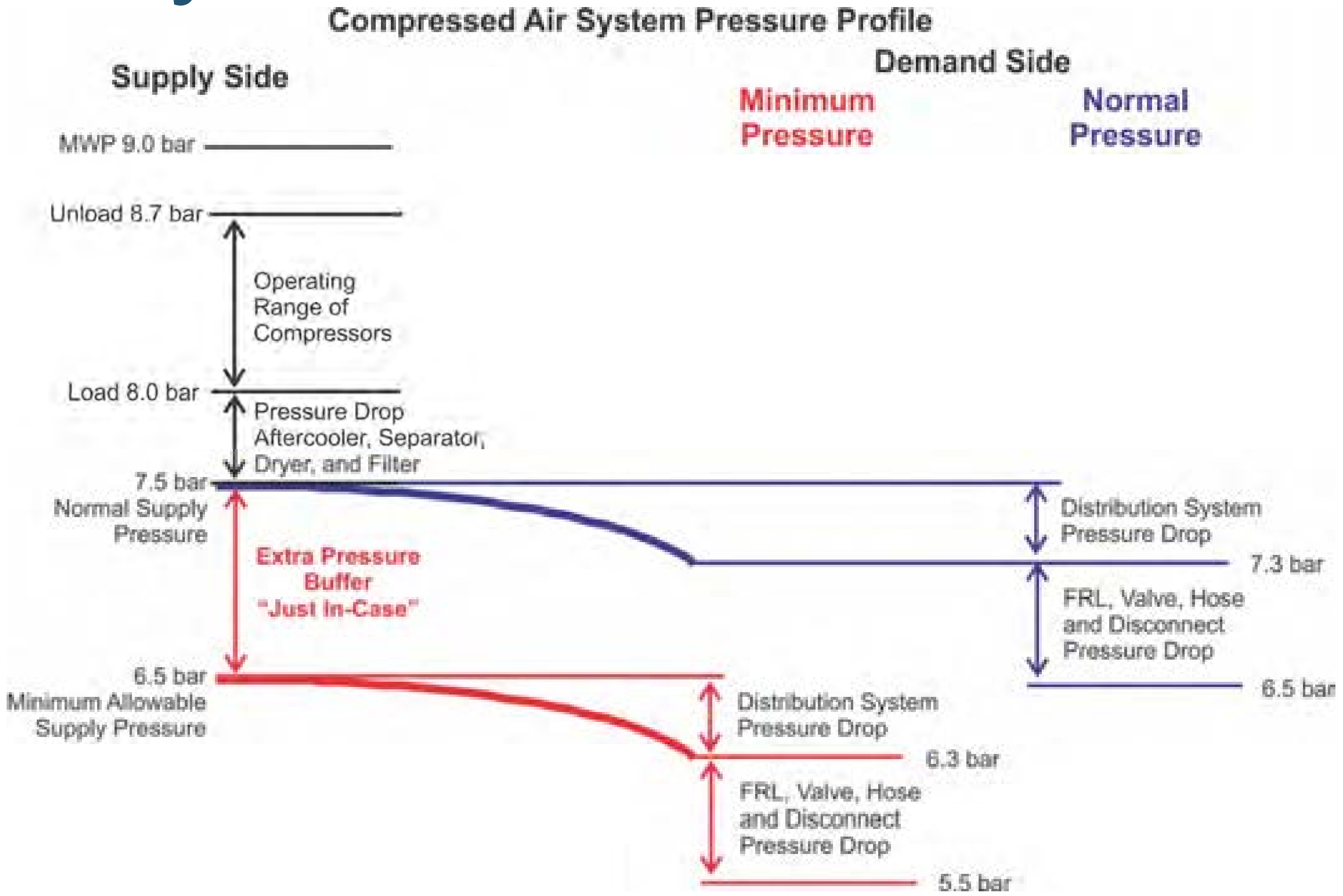
Pack House Compressor



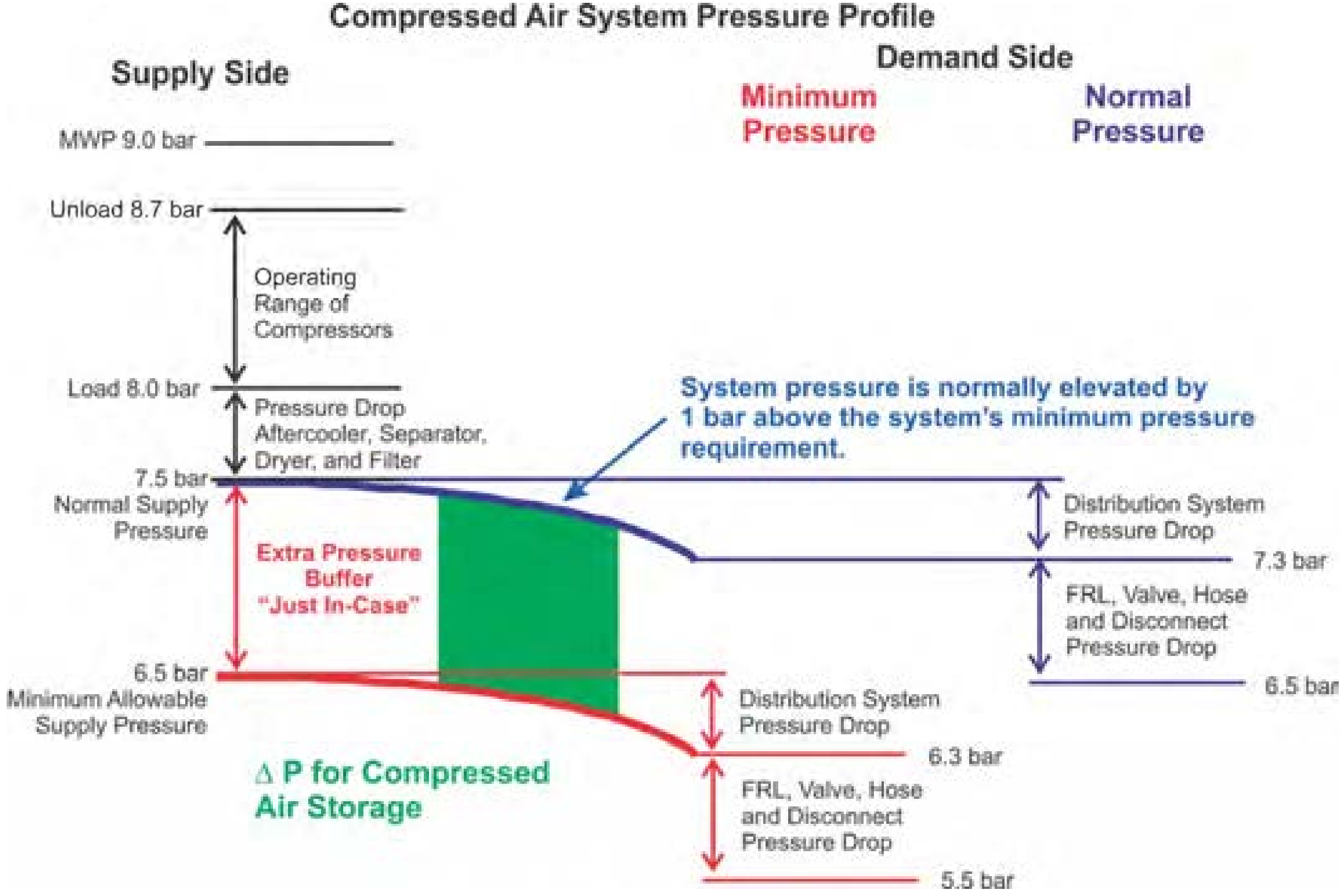
System Pressure Profile



System Pressure Profile



System Pressure Profile



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

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).

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

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.

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

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.

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.

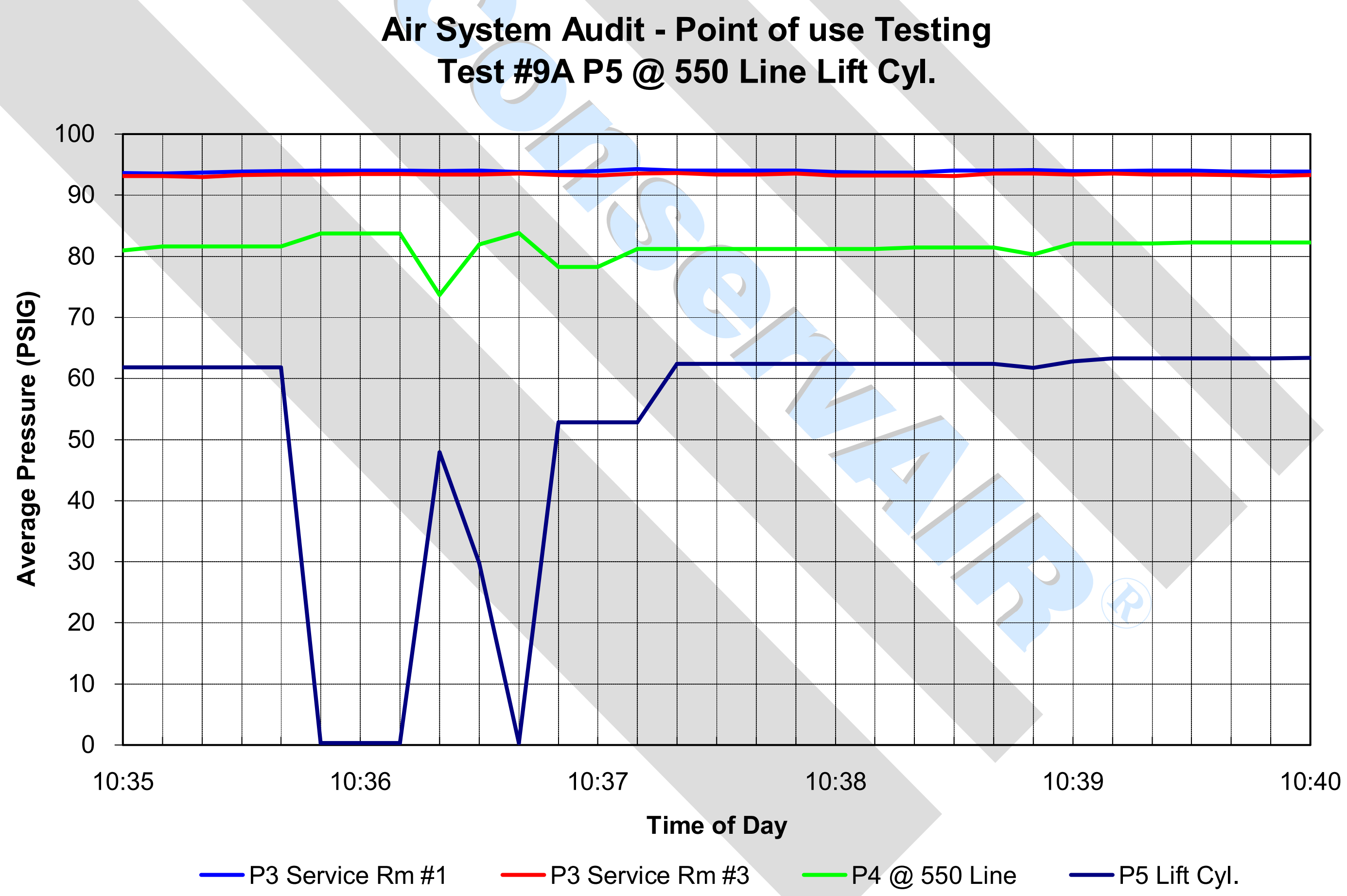
Pressure Profile Design Criteria

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

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

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



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.

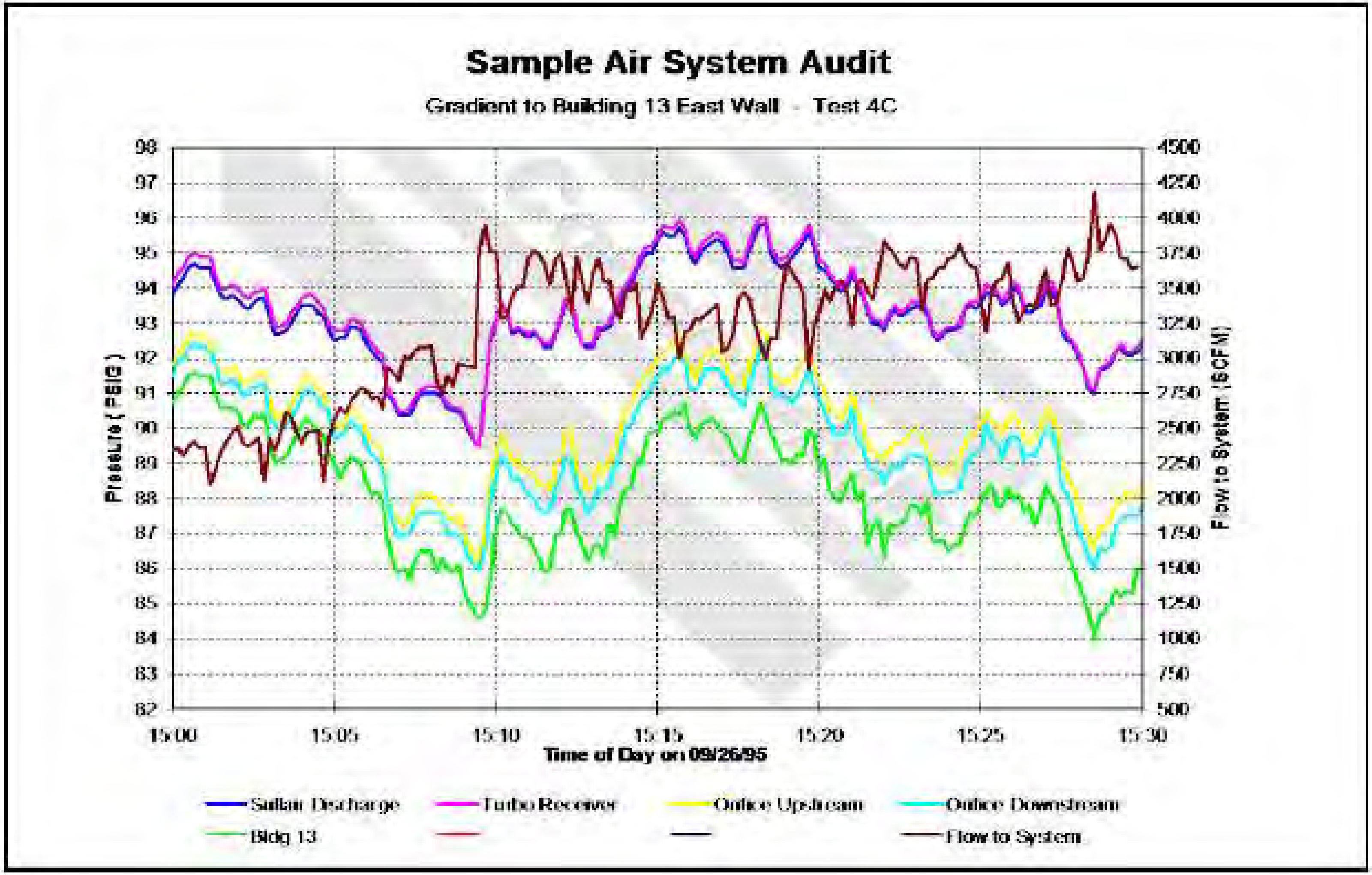
Key Points – Point of Use Pressure

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.

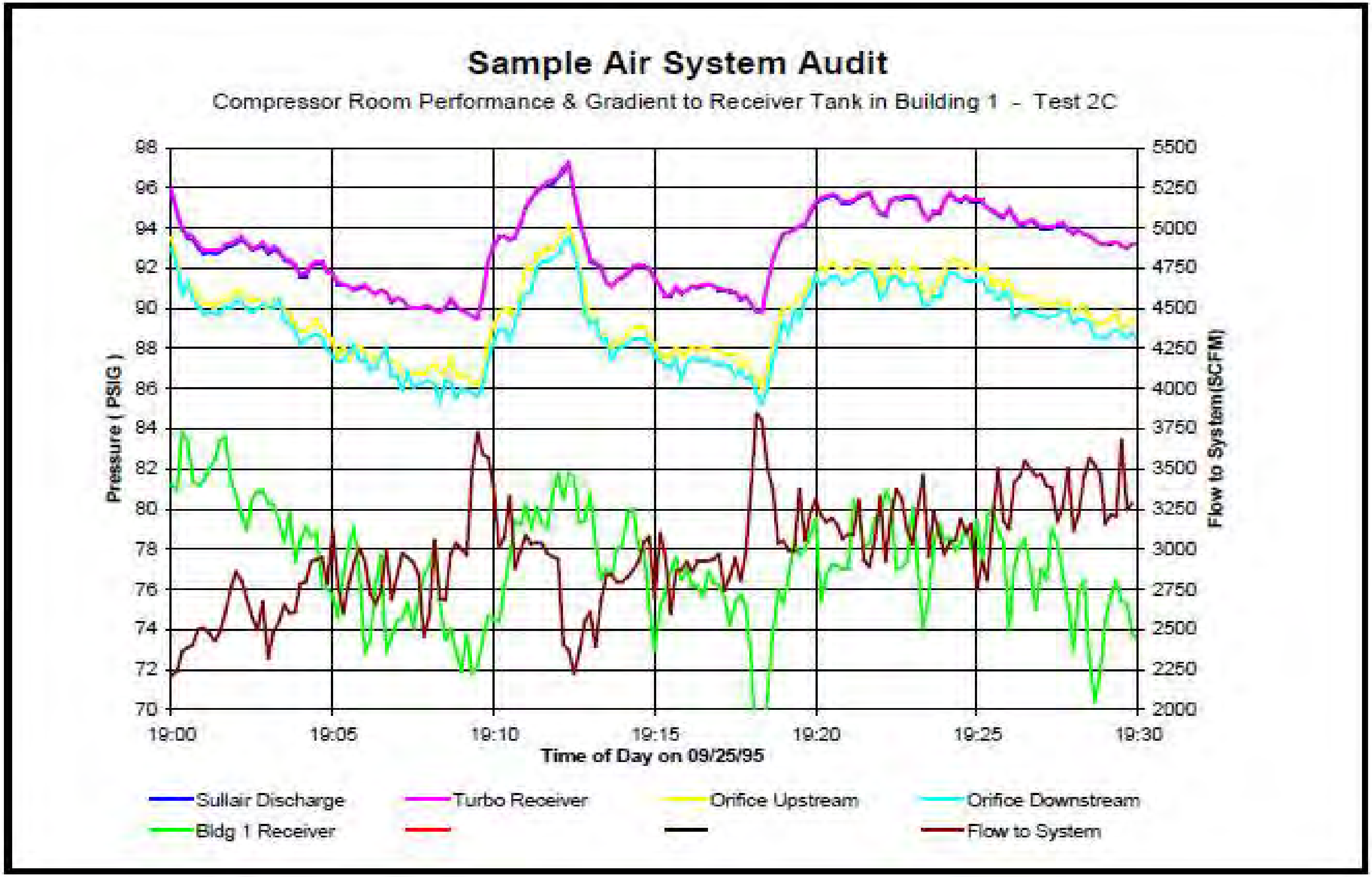
Pressure Profile Distribution Pressure Gradient

- 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 *d*P / *d*X.
- 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.

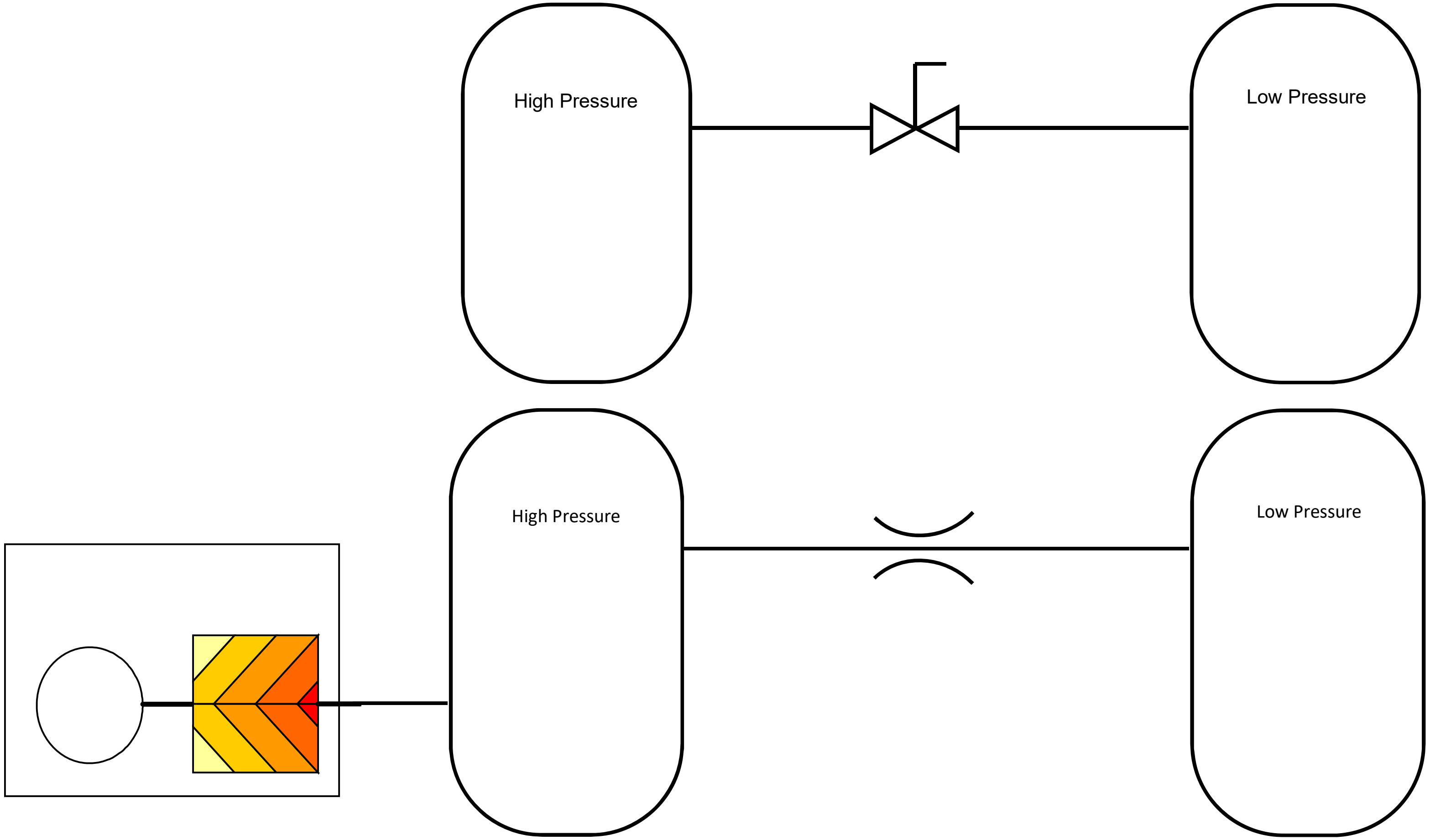
Distribution System Performance



Distribution System Performance

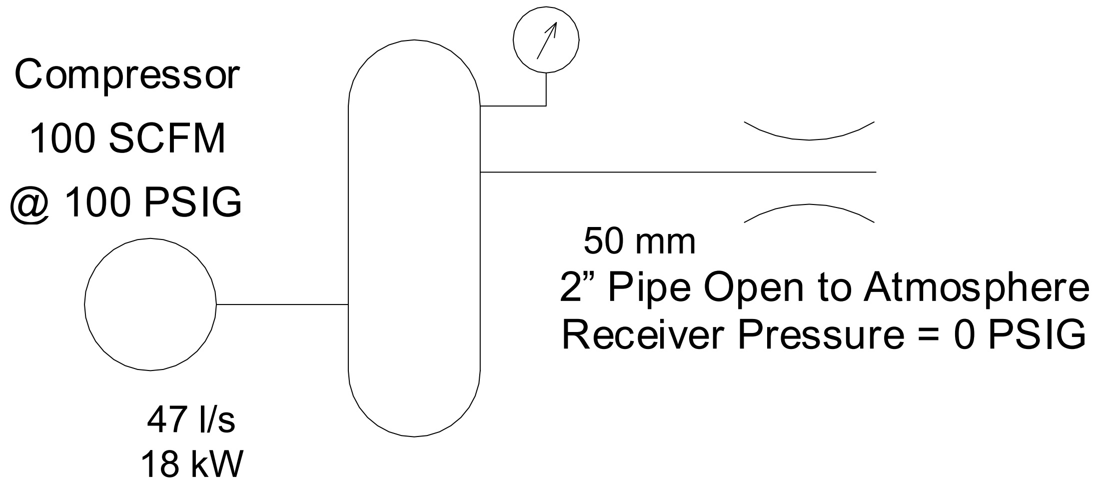


Sustained Pressure Gradient

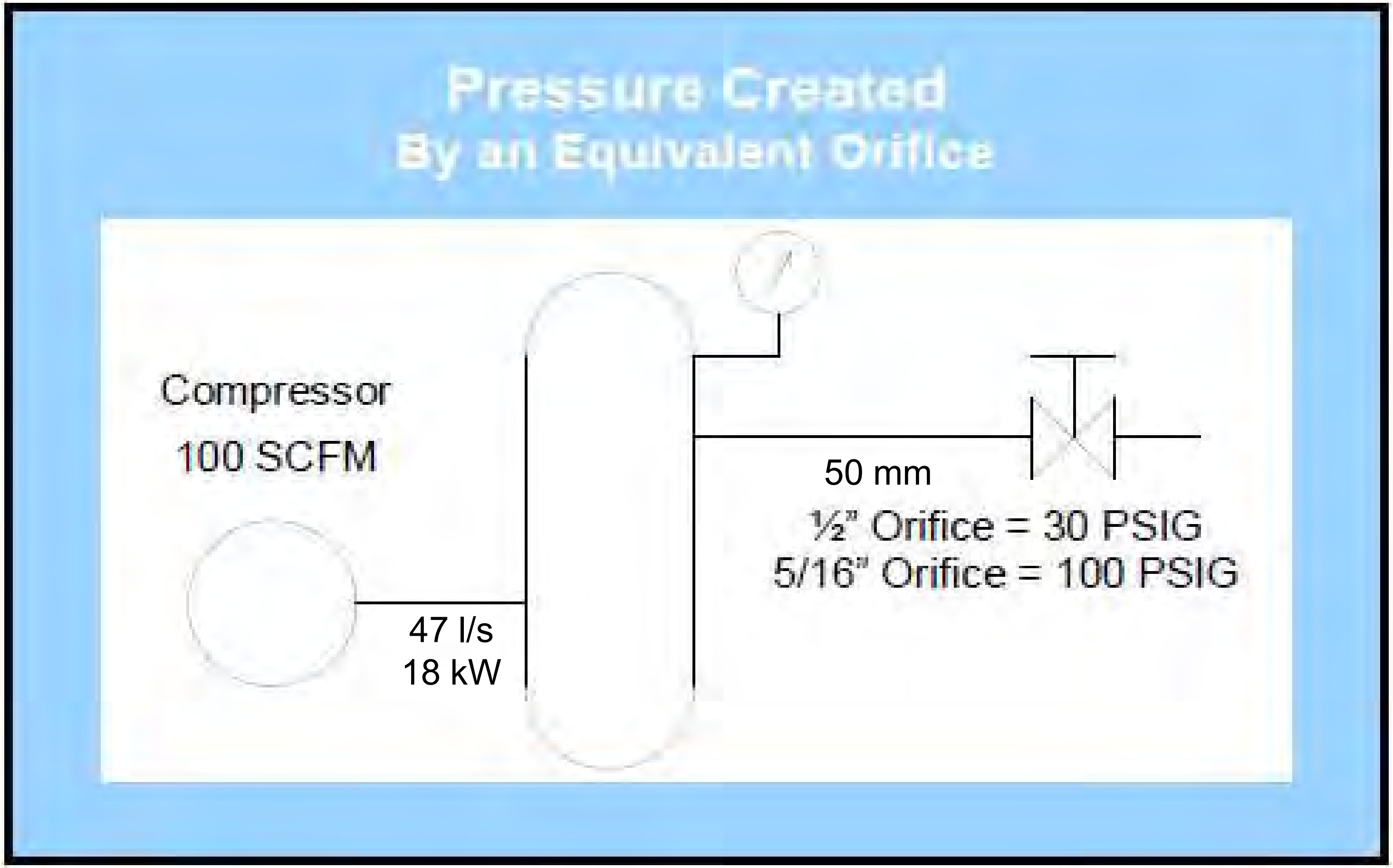


System Resistance Creates Pressure

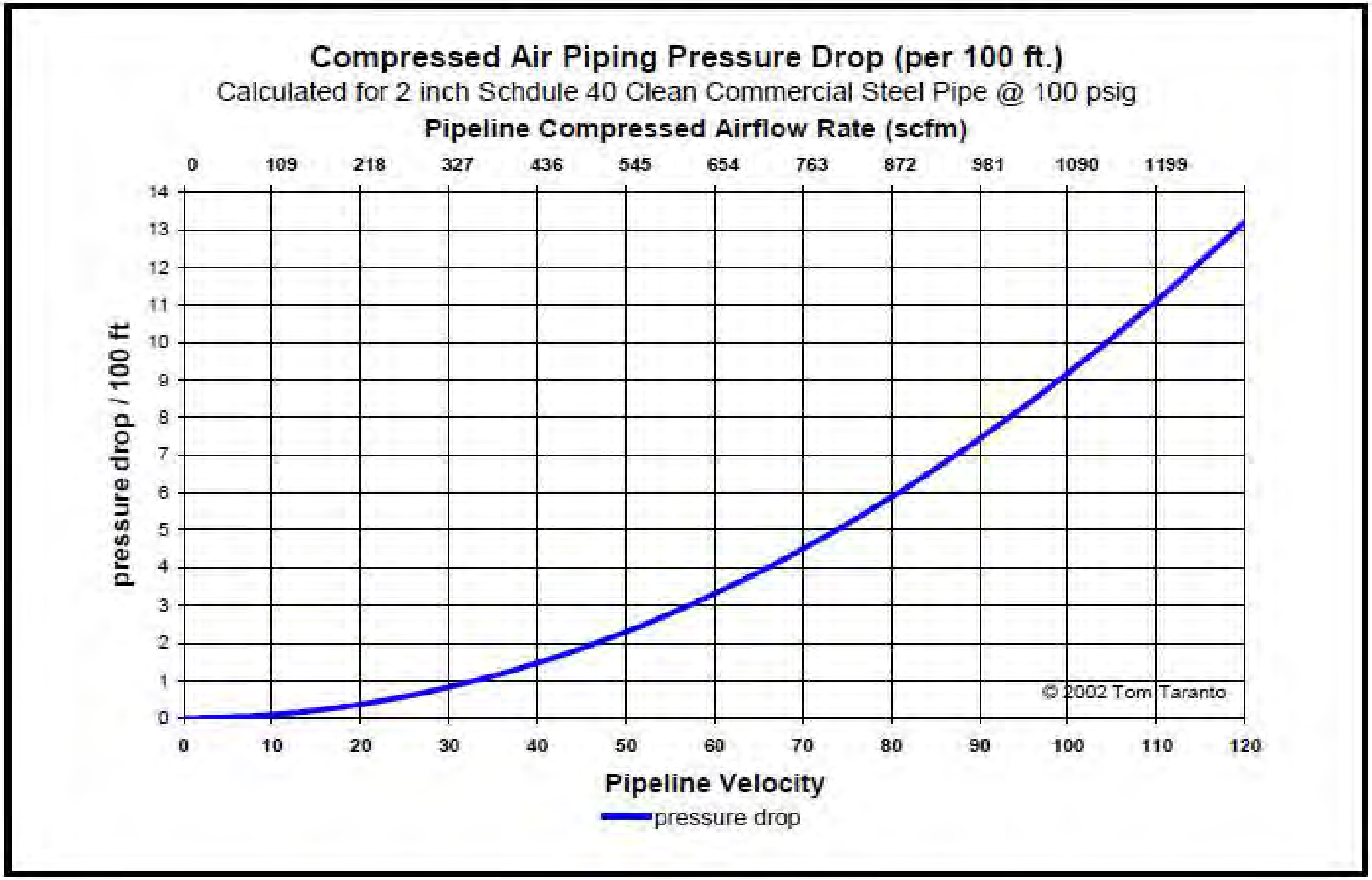
Flow, Pressure & System Resistance
Compressors Pump Flow
Resistance Creates Pressure



System Resistance Creates Pressure



Pressure Loss in Fluid Flow



Key Learning Points - Distribution

1. Check pressure gradient at peak airflow rate.
2. Normally pressure should track supply at < 0.15 bar (< 2 psig) pressure differential.
3. High pressure gradient leads to unstable performance.
4. High pressure gradients in distribution piping must be corrected.
5. Compressors create airflow, system resistance creates pressure.

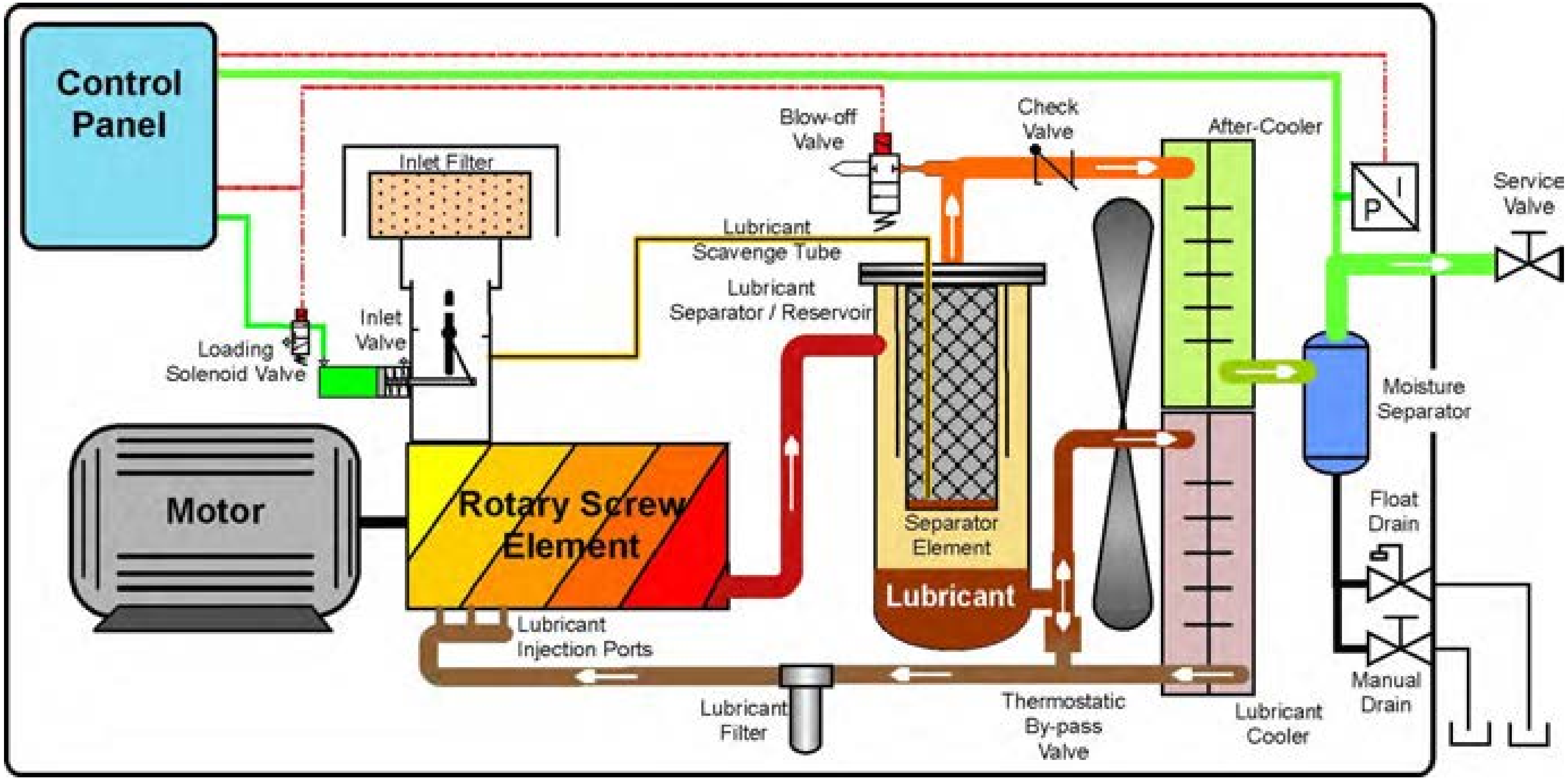
Key Energy Points - Distribution

6. Sustained pressure gradient will drive inefficient compressor load cycles.

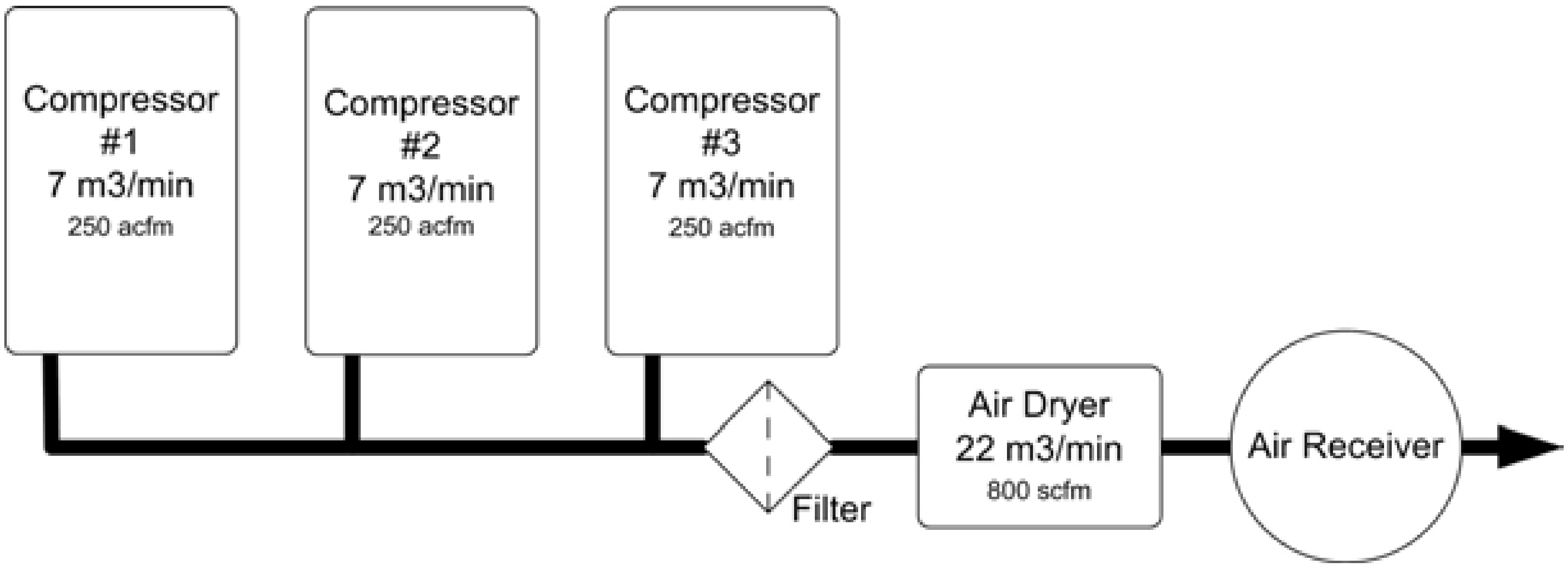
7. Pressure drop increases as a function of airflow change squared.

8. Mainline distribution headers design velocity should be less than 10 m/s (30 ft/sec).

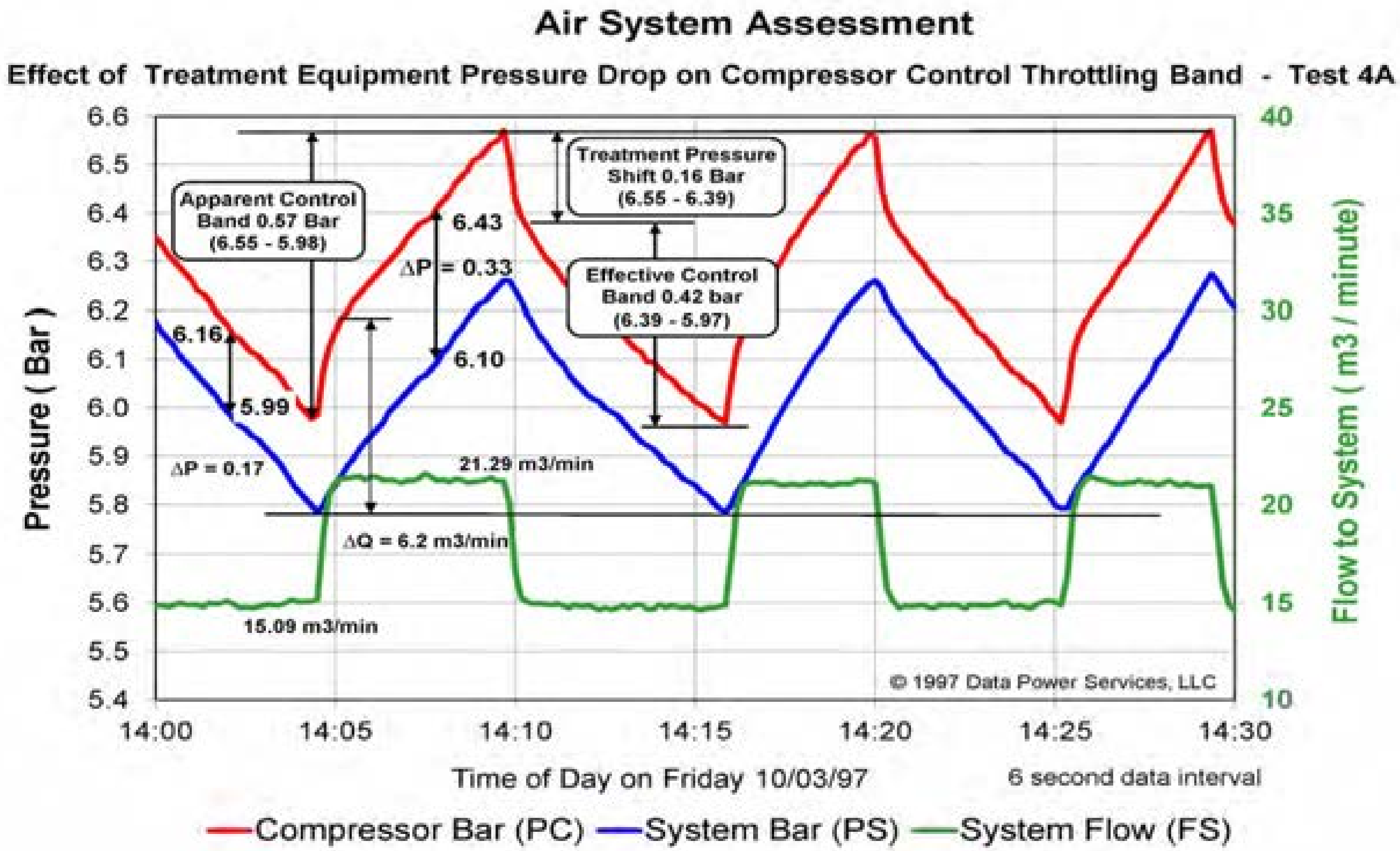
Pressure Profile
Air Compressor Control Signal



Pressure Profile
Control Shift as Flow Changes



Control Shift as Flow Changes



Pressure Profile
Pressure Drop Changes w/ Flow

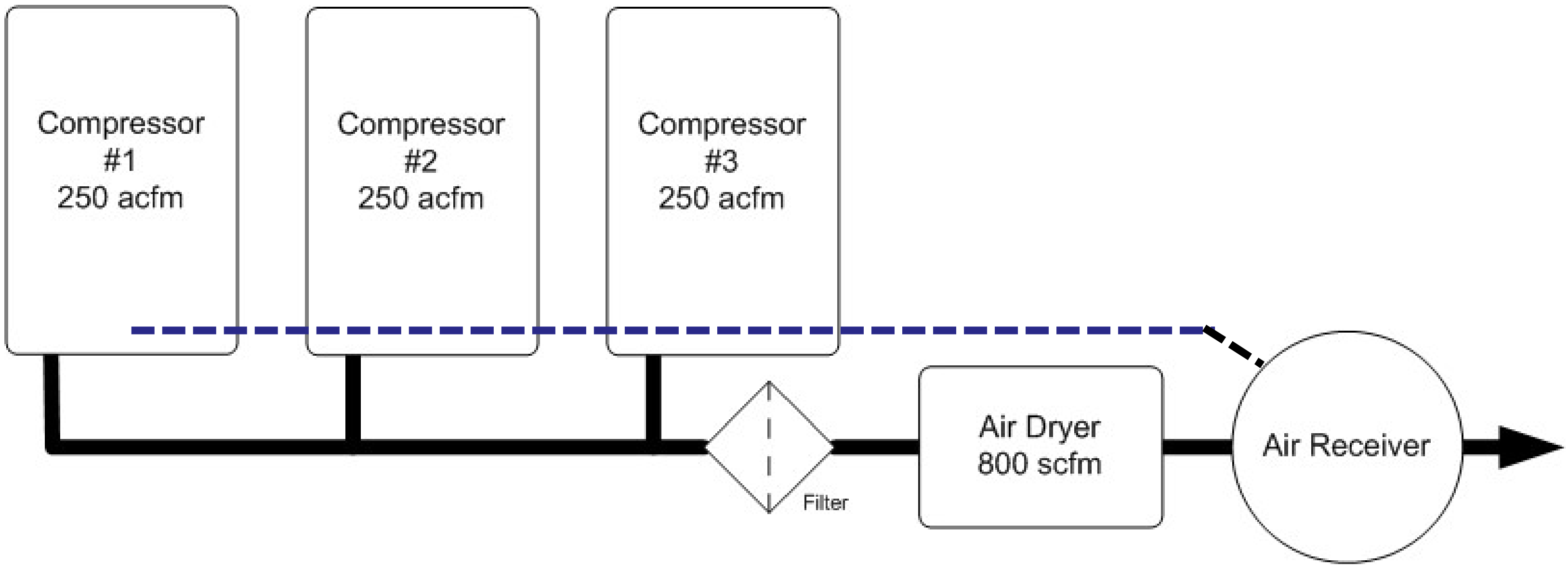
- In a Fluid System, pressure drop changes as the square of the change in velocity.

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

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

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

Pressure Profile
Remote Control Pressure Sensing



Key Learning Points – 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.

Key Energy Points – Control Signals

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. If remote sensing is used, over-pressure protection should sense pressure within the compressor package.

8. Air Storage and System Energy Balance

Balancing Supply and Demand

- 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 (Nm^3 / min) consumed by the use as considered during the time duration of one or more full cycles of operation.

Balancing Supply and Demand

- 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.

Balancing Supply and Demand

- 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.

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.

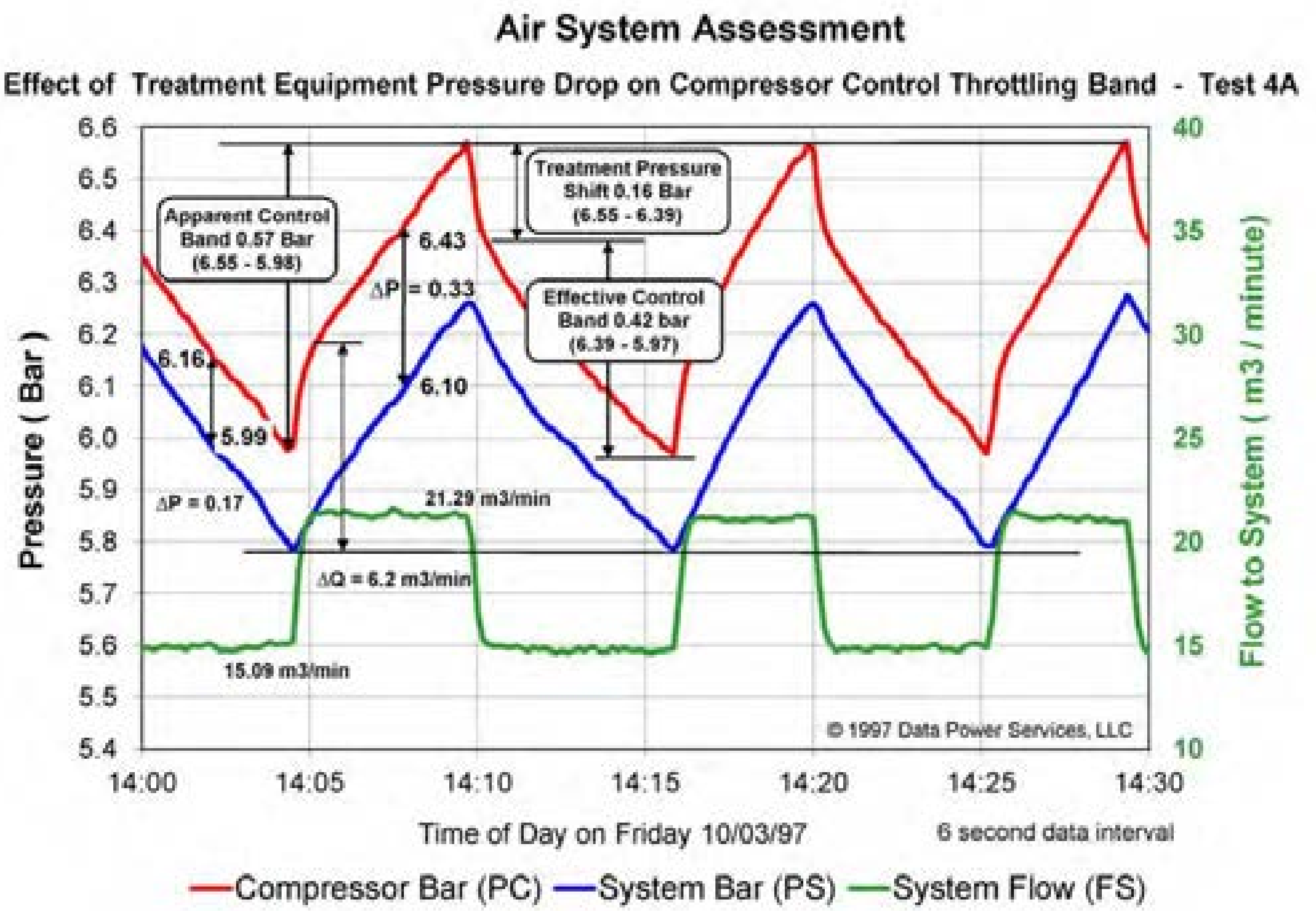
Storage Capacity Calculation

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

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

Looking back at Figure 7.13
If Pmin = 5.4 bar, what is the value of Pmax?



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.

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

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

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

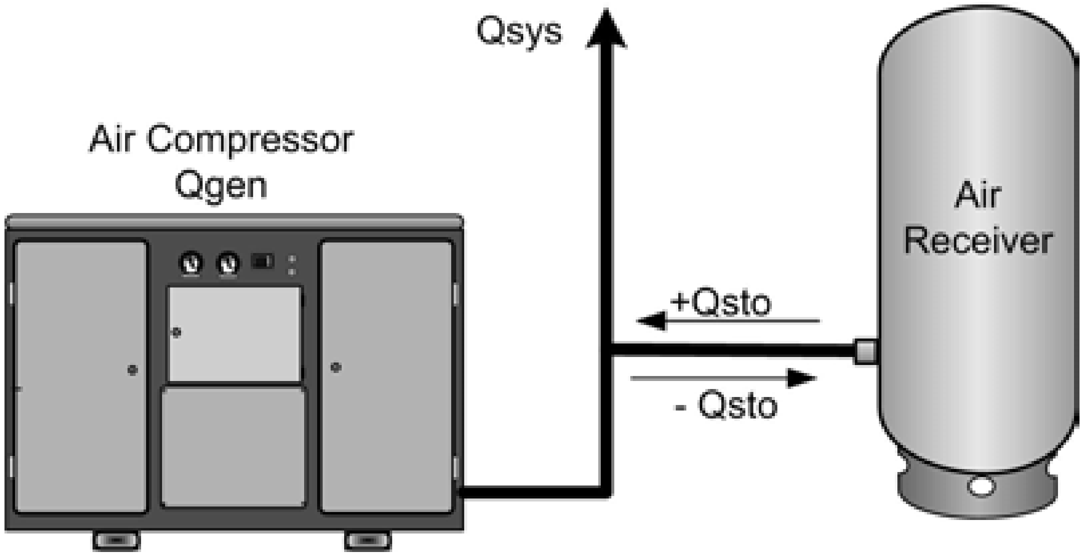
Air Storage and System Energy Balance

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

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

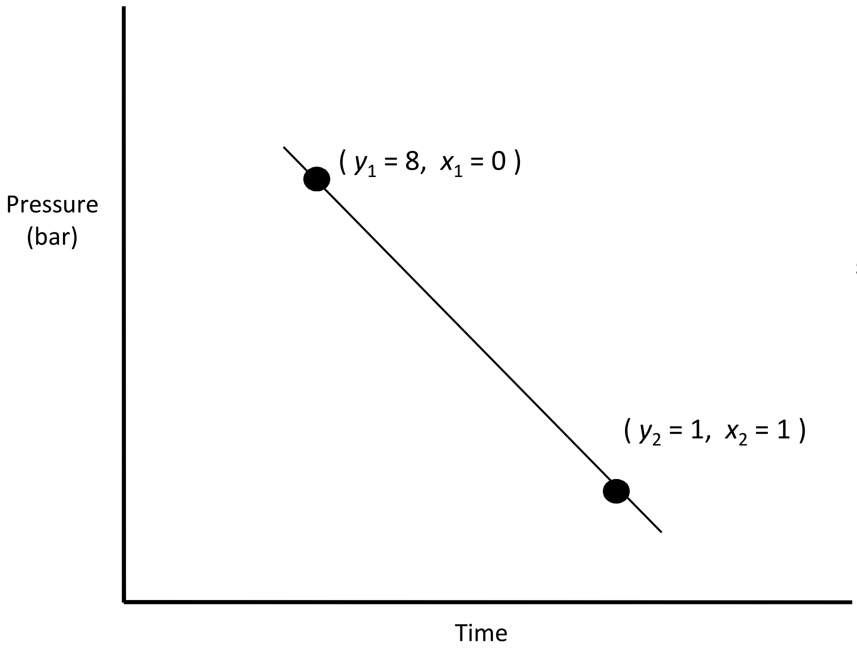
($-\ Q_{sto}$) for increasing pressure

($+\ Q_{sto}$) 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.

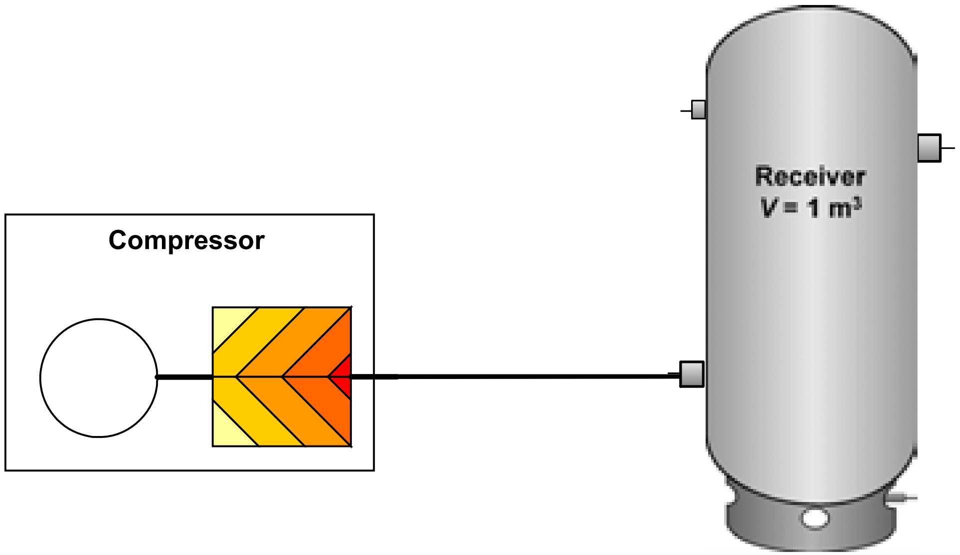
$$V_{gas} = V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}$$

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

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.

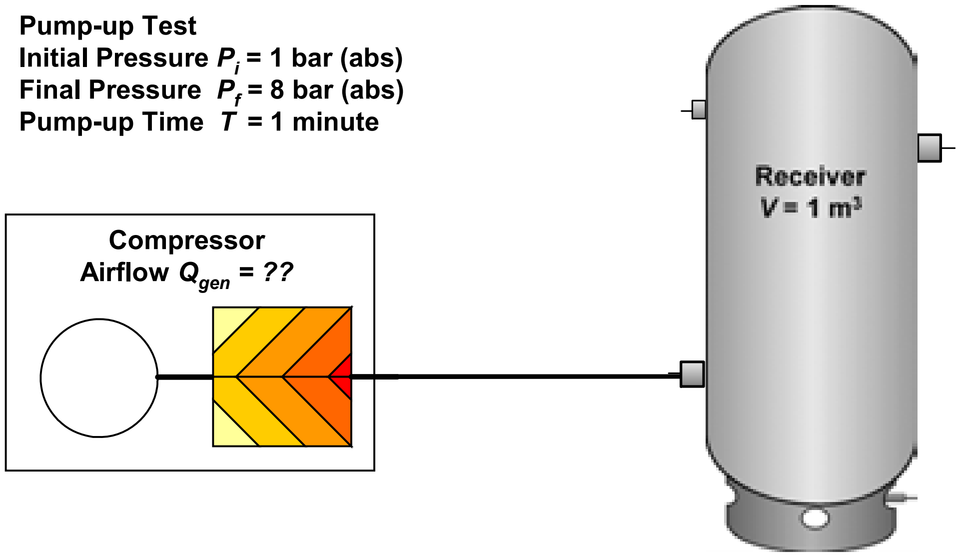
$$V_{gas} = V_{rec} \times \frac{(P_f - P_i)}{P_{atm}}$$

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

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

Air Receiver Pump-up Test

Pump-up Test
Initial Pressure P_i = 1 bar (abs)
Final Pressure P_f = 8 bar (abs)
Pump-up Time T = 1 minute

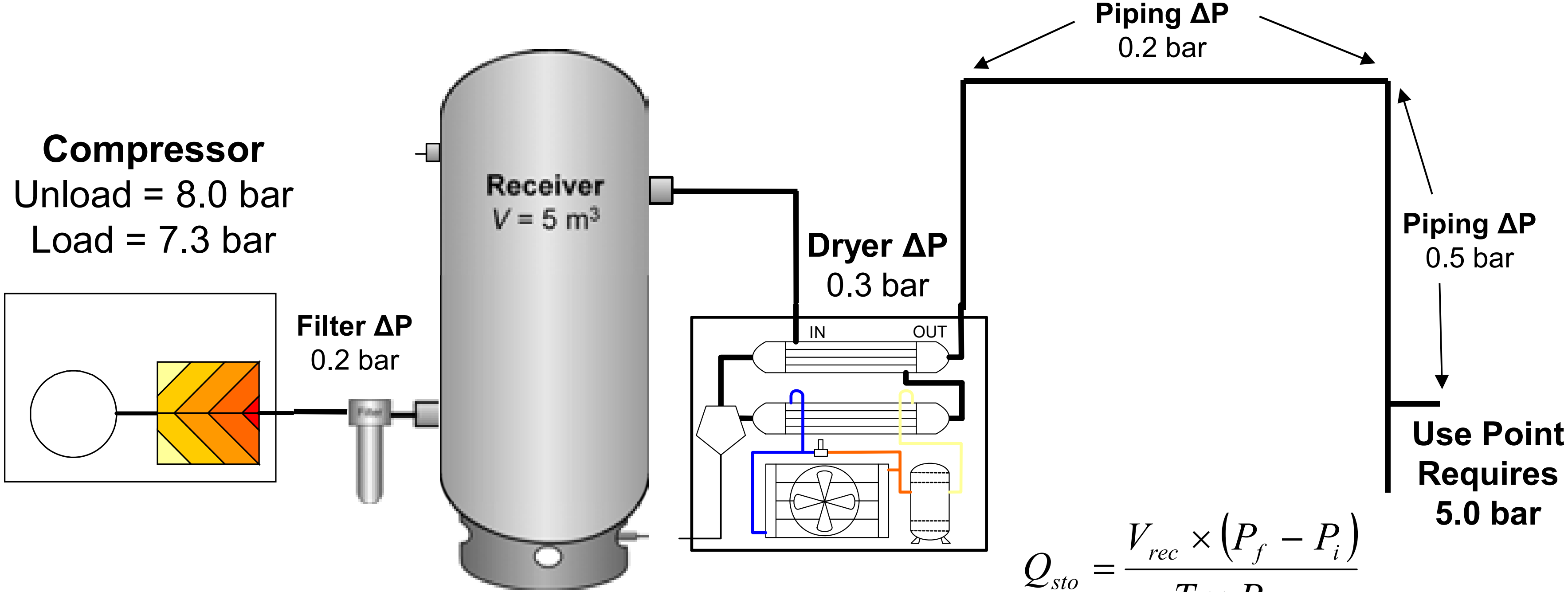


$$Q_{gen} = \frac{V_{rec} \times (P_f - P_i)}{T \times P_{atm}}$$

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

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

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*).

Definition of Variables and Units of Measure

C_{pn} = *Pneumatic Capacitance (m^3 / kPa)*

V_{rec} = *Receiver Volume (m^3)*

V_{pipe} = *Piping Volume (m^3)*

V_{sys} = *System Volume (m^3)*

P_a = *Atmospheric Pressure (kPa)*

P_i = *Initial Receiver Pressure (kPa)*

P_f = *Final Receiver Pressure (kPa)*

ΔP = *Storage Pressure Delta ($P_f - P_i$)*

rs = *Storage Pressure Ratio (Pf – Pi) / Pa*

V_{gas} = *Compressed Air Volume (Nm^3) Normal cubic meters*

P_{load} = *Compressor Load Pressure (kPa)*

P_{unload} = *Compressor Unload Pressure (kPa)*

Q_{sys} = *Airflow rate for the system (kPa)*

Q_{gen} = *Airflow rate from Generation compressor(s) (m^3/min)*

Q_{sto} = *Airflow rate of storage (m^3/min)*

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

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

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

Example: Using System Capacitance to Calculate Dynamic Airflow Rate

- A system has a total volume (receivers plus piping) of 4 m^3, the compressor's capacity is 4 m^3/min and there is an event load which causes a drawdown of system pressure. Data logging of system performance shows that the system pressure falls from (P_i) 655 kPa to (P_f) 600 kPa during the event which lasts for 1 minute. What is the peak dynamic airflow rate for the system which occurs during the demand event?

System Capacitance:

$$C_{pn} = \frac{V_{sys}}{P_a}$$

$$C_{pn} = \frac{4\ m^3}{100\ kpa} = 0.40\, m^3/kPa$$

Air Released from Storage:

$$V_{gas} = C_{pn} \times \Delta P = C_{pn} \times (P_f - P_i)$$

$$V_{gas} = 0.04\, m^3/kpa \times (600 - 655) = -2.2\ Nm^3$$

Peak Dynamic Demand: $Q_{sys} = Q_{gen} + Q_{sto} = 4 + 2.2 = 6.2\ Nm^3/min$

Suppose in the previous example, the drawdown event lasted only 25 seconds instead of one minute. What is the peak dynamic airflow rate?

$$Q_{sys} = Q_{gen} + \left(-1 \times Q_{sto}\right)$$

$$Q_{sto} = C_{pn} \times \frac{dP}{dt}$$

$$substituting:$$

$$Q_{sys} = Q_{gen} + \left(-1 \times C_{pn} \times \frac{dP}{dt}\right)$$

$$Q_{sys} = 4\frac{Nm^3}{\min} + \left[-1 \times \left(0.04\frac{Nm^3}{kpa} \times \frac{(600-655)}{25}\frac{kpa}{\sec} \times 60\frac{\sec}{\min}\right)\right]$$

$$Q_{sys} = 9.28\, Nm^3/\min$$

When the demand event ends, the system pressure is observed to increase from 600 kPa back to 655 kPa in the same 25 seconds of time. Assuming the compressor remains fully loaded, what is the air system demand during this time?

$$Q_{sys} = Q_{gen} + Q_{sto}$$

$$Q_{sto} = C_{pn} \times \frac{dP}{dt}$$

$$Q_{sys} = 4\frac{Nm^3}{\min} + \left[-1 \times \left(0.04\frac{Nm^3}{kpa} \times \frac{(655-600)}{25}\frac{kpa}{\sec} \times 60\frac{\sec}{\min}\right)\right]$$

$$Q_{sys} = 4\frac{Nm^3}{\min} + \left(-5.28\frac{Nm^3}{\min}\right) = -1.28\,Nm^3 / \min$$

Key Learning Points

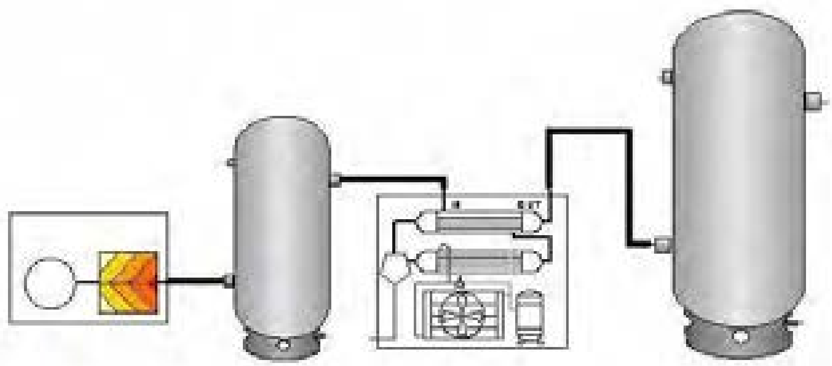
1. System dynamics and the types of compressed air end use applications will determine the nature of the compressed air demand profile.
2. There can be a significant difference between average air demand (what compressors supply) and peak airflow rate driven by real air demand.
3. There are 4 sources of compressed air, rotating on-line capacity, rotating reserve capacity, storage capacity, and stand-by capacity.
4. The amount of useable energy in storage depends on receiver volume and available pressure differential.

Using Pneumatic Capacitance to Evaluate Compressor Load Cycles

Use the Pneumatic Capacitance approach to calculate the System Airflow rate (Q_{sys}).

Given:

- V_{sys} = 6.1 m^3
- C_{pn} = 0.061 m^3 / kPa
- Pa = 100 kPa
- P_{load} = 600 kPa
- P_{unload} = 655 kPa
- Q_{sys} = ?? m^3 / minute
- Q_{gen} = 15 m^3 / minute
- T_L = 29 seconds (Compressor Load Time)
- T_{NL} = 25 seconds (Compressor Unload Time)



Using Pneumatic Capacitance to Evaluate Compressor Load Cycles

- Method #1: Load / unload cycle operating period

$$Q_{sys} = Q_{gen} \times \%load = Q_{gen} \times \left(\frac{T_L}{T_L + T_{NL}} \times 100 \right)$$

$$\%\,load = \left(\frac{T_L}{T_L + T_{NL}} \times 100 \right) = \left(\frac{29}{25+29} x\,100 \right) = 53.7\,\%$$

$$Q_{sys} = 15\,Nm^3\ /minute \times 53.7\% \ = 8.06\,Nm^3\ /minute$$

Using Pneumatic Capacitance to Evaluate Compressor Load Cycles

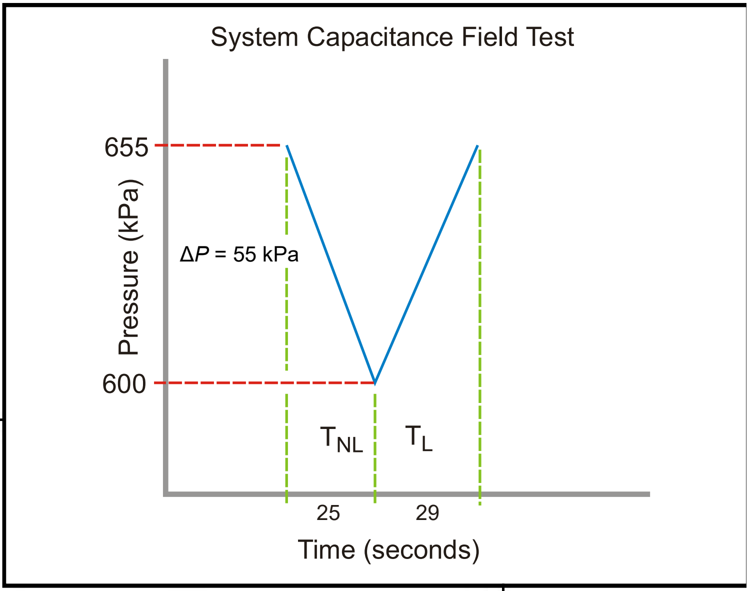
- Method #2: System capacitance method

$$Q_{sys} = Q_{gen} + Q_{sto} = Q_{gen} + \left[-1 \times \left(C_{pn} \times \frac{dP}{dt} \right) \right]$$

$$Q_{sys} = 15\frac{Nm^3}{min} + \left[-1 \times \left(0.061\frac{Nm^3}{kPa} \times \frac{(655-600)}{29}\frac{kPa}{sec} \times 60\frac{sec}{min} \right) \right]$$

$$Q_{sys} = 15\frac{Nm^3}{min} + \left[-6.94\frac{Nm^3}{min} \right] = 8.06 Nm^3 \,/minute$$

Calculating the Pneumatic Capacitance of a Compressed Air System



$$C_{pn} = Q_{test(L)} \times \frac{T_L}{T_L + T_{NL}} \times \frac{T_{NL}}{\Delta P}$$

$$C_{pn} = 15\frac{m^3}{min} \times \frac{29\ sec}{(29+25)\ sec} \times \frac{25 sec}{(600-655) kPa} \times \frac{1 min}{60 sec}$$

$$C_{pn} = 0.061\frac{m^3}{kPa}$$

To solve for the system's volume, multiply by atmospheric pressure:

$$V_{sys} = C_{pn} \times P_{atm} = 0.061\frac{m^3}{kPa} \times 100kPa = 6.1\ m^3$$

Key Learning Points

1. System dynamics and the types of compressed air end use applications will determine the nature of the compressed air demand profile.
2. There can be a significant difference between average air demand (what compressors supply) and peak airflow rate driven by real air demand.
3. There are 4 sources of compressed air, rotating on-line capacity, rotating reserve capacity, storage capacity, and stand-by capacity.
4. The amount of useable energy in storage depends on receiver volume and available pressure differential.

Key Energy Points

5. The key to consistent, stable, and efficient operation of a compressed air system is maintaining balance between supply and demand.
6. Rotating on-line capacity must be equal to or greater than average air demand.
7. Peak demand is best supplied from storage. However, when air is used from storage there needs to be time and extra compressed air capacity to refill storage before the next event occurs.
8. Compressor controls should shut off compressors that are not needed, operate all compressors at full load, and trim with only 1 compressor operating at part load capacity. (Positive displacement)

Key Energy Points

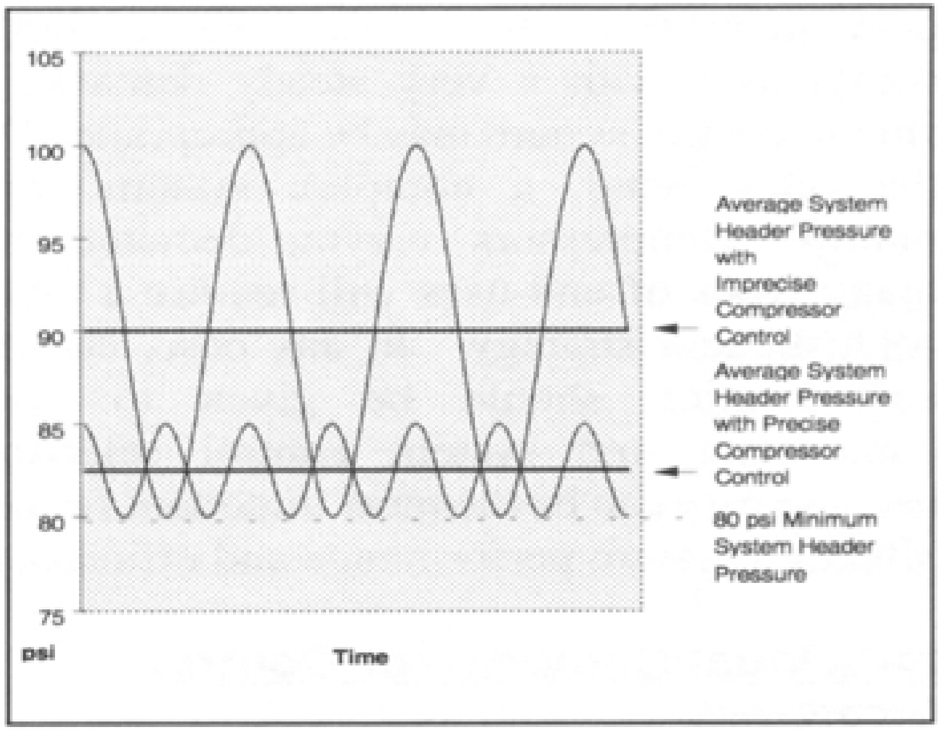
9. Select a trim compressor with efficient part load capacity control.
10. There are many different applications for compressed air storage, engineer storage based on system requirements.
11. In many systems the single largest event requiring storage is the unanticipated shutdown of an operating air compressor.

9. Compressed Air System Controls

Match the compressed air supply with system demand

- The objective of any control strategy is also to shut off unneeded compressors or delay bringing on additional compressors until needed.
- All units which are on should be run at full-load, except for one unit for trimming.
- Needed to orchestrate a reduction in the output of the individual compressor(s) during times of lower demand.

Precise control system is able to maintain a much lower average pressure



Impacts of Controls on System Pressure

Every 1 bar of pressure difference is equal to about a 6% change in energy consumption.

Controls and System Performance

- Type of control specified is determined by the type of compressor and the demand profile
- With a single compressor system with a very steady demand, a simple control system may be appropriate.
- A complex system with multiple compressors, varying demand, and many types of end-uses will require a more sophisticated strategy.

Individual Compressor Control Strategies

a. Start/Stop

- Simplest control available to reciprocating or rotary screw.
- Motor is turned on or off in response to the discharge pressure of the machine.
- Typically, using a simple pressure switch.
- Not be used in an applications that has frequent cycling

Individual Compressor Control Strategies

b. Load/Unload

- Also known as constant speed control
- Allows the motor to run continuously
- An unloaded rotary screw compressor will consume 15-35% of full-load power while delivering no useful work
- Some load/unload control schemes can be inefficient.

Individual Compressor Control Strategies

c. Modulating Controls

- Throttling inlet control
- Applied to centrifugal and rotary screws
  - With displacement: inefficient means of varying output.
  - With centrifugal:
    - More efficient results are obtained, particularly with the use of inlet guide vanes
    - Capacity reduction is limited by surge and minimum throttling capacity.

Individual Compressor Control Strategies

d. Multi-step (Part-load) Controls

- Designed to operate in two or more partially-loaded conditions.
- Output pressure can be closely controlled without requiring start/stop or load/unload.
- Reciprocating: two-step (start/stop or load/unload), three- step (0%, 50%, 100%) or five-step (0%, 25%, 50%, 75%, 100%) control.
- Rotary screw: sliding or turn valves. Generally applied in conjunction with modulating inlet valves

Individual Compressor Control Strategies

e. Variable Frequency Drives

- Cost is no longer a major issue
- VFDs have become more reliable and efficient at full-load.

System Controls

a. Single Master (Sequencing) Controls

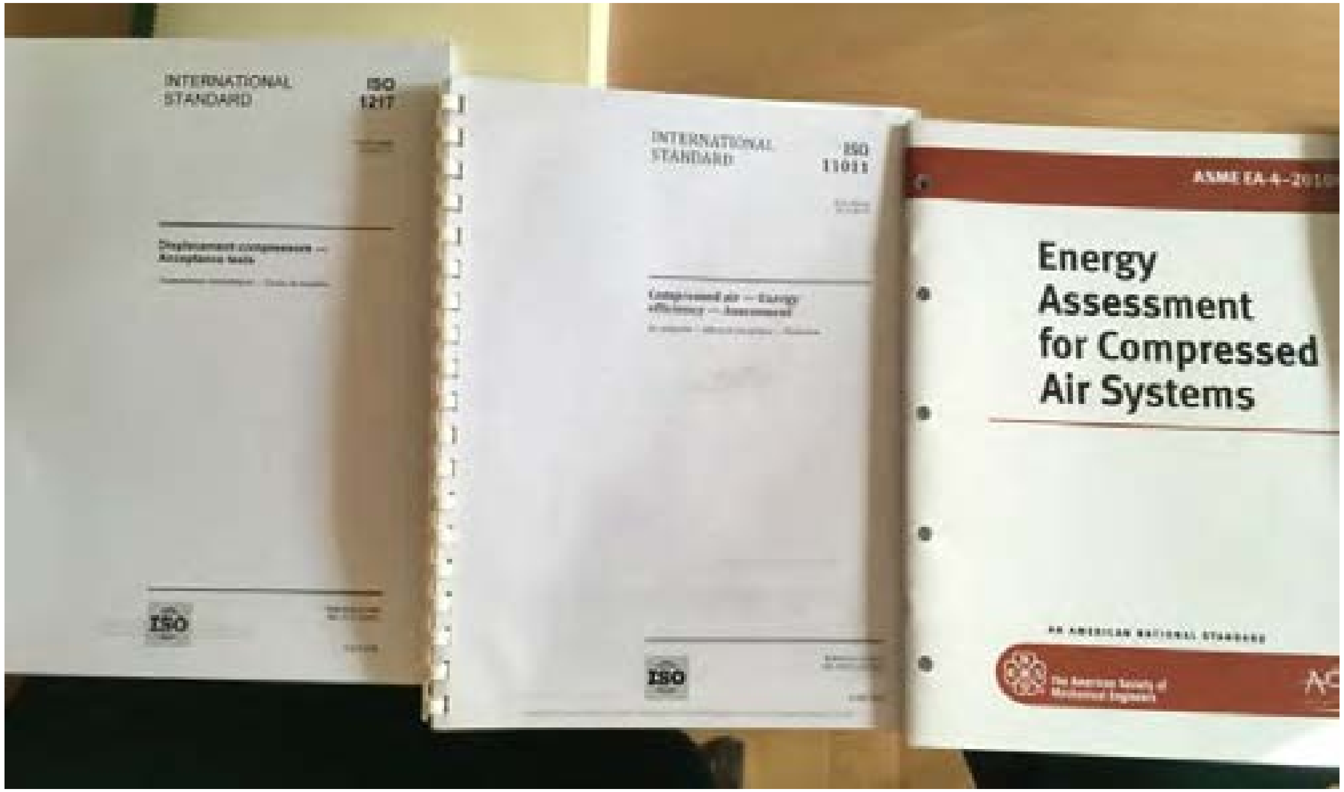
- Referred to as single master control units
- Higher efficiency because the control range around the system target pressure is tighter
- Careful matching of system controls and storage capacity

System Controls

b. Multi-Master (Network) Controls

- Network controls offer the latest in system control
- Individual controllers are linked or networked together, thereby sharing all operating information and status.
- Changing air demand can be met more quickly and accurately
- Tight pressure control range

10. 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

- 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.

- 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

Nameplate power calculation for annual energy cost:

$$\frac{kW\,(nameplate) \times load\ \ factor \times hours \times energy\ \text{cost}}{motor\ \ efficiency} = annual\ \ energy\ \text{cost}$$

- *Where:*
  - *kW (nameplate) = full load nameplate kW of the motor*
  - *load factor = % driven load operating power in relation to motor nameplate power*
  - *hours = annual running hours*
  - *energy cost = $ / kWh*
  - *motor efficiency = full load motor efficiency*

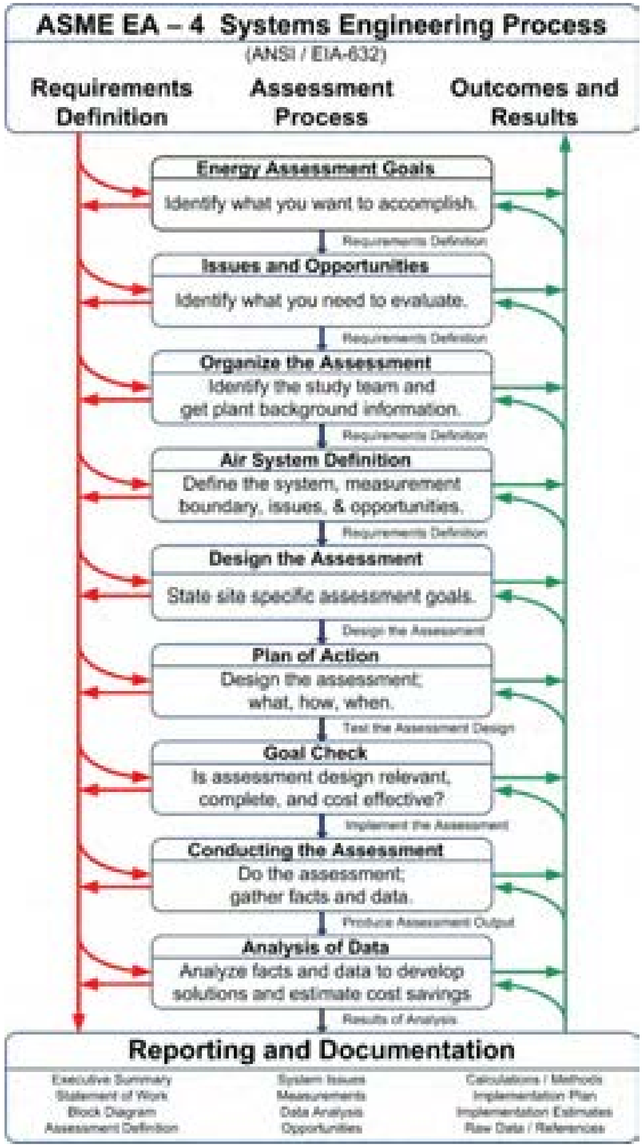
Measured Volts - Amps calculation for annual energy cost.

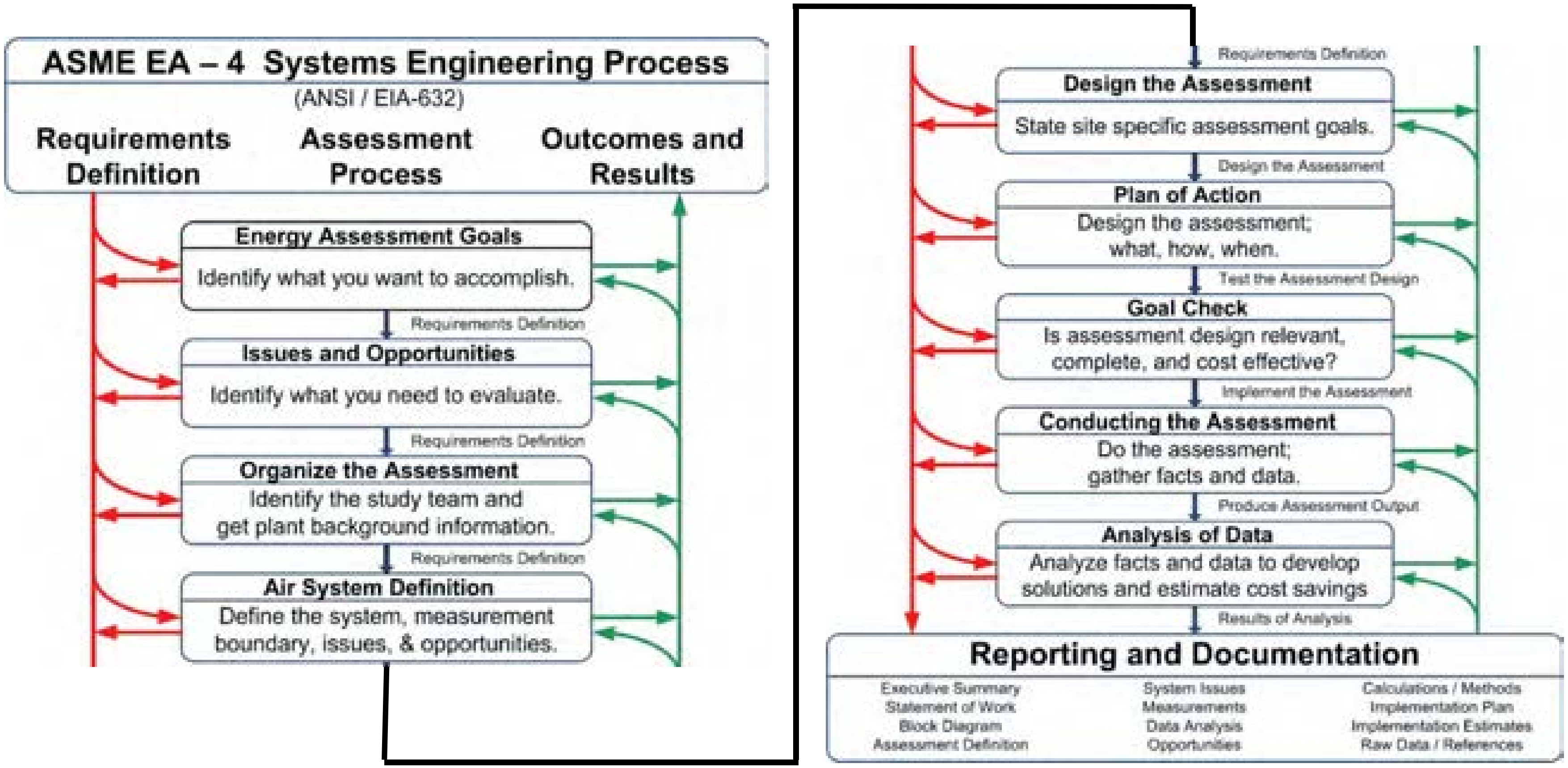
$$\frac{volts \times amps \times 1.732\ x\ \ pf\ \times hours \times energy\ \text{cost}}{1000} = annual\ energy\ \text{cost}$$

- *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*

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

(see chart in the workbook Figure 10-1)




ASME EA – 4 Systems Engineering Process
(ANSI / EIA-632)
Requirements Definition
Assessment Process
Outcomes and Results
Energy Assessment Goals
Identify what you want to accomplish.
Requirements Definition
Issues and Opportunities
Identify what you need to evaluate.
Requirements Definition
Organize the Assessment
Identify the study team and get plant background information.
Requirements Definition
Air System Definition
Define the system, measurement boundary, issues, & opportunities.
Requirements Definition
Design the Assessment
State site specific assessment goals.
Design the Assessment
Plan of Action
Design the assessment; what, how, when.
Test the Assessment Design
Goal Check
Is assessment design relevant, complete, and cost effective?
Implement the Assessment
Conducting the Assessment
Do the assessment; gather facts and data.
Produce Assessment Output
Analysis of Data
Analyze facts and data to develop solutions and estimate cost savings
Results of Analysis
Reporting and Documentation
Executive Summary
Statement of Work
Block Diagram
Assessment Definition
System Issues
Measurements
Data Analysis
Opportunities
Calculations / Methods
Implementation Plan
Implementation Estimates
Raw Data / References

- 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.

- **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.

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

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

- 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

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

- 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.

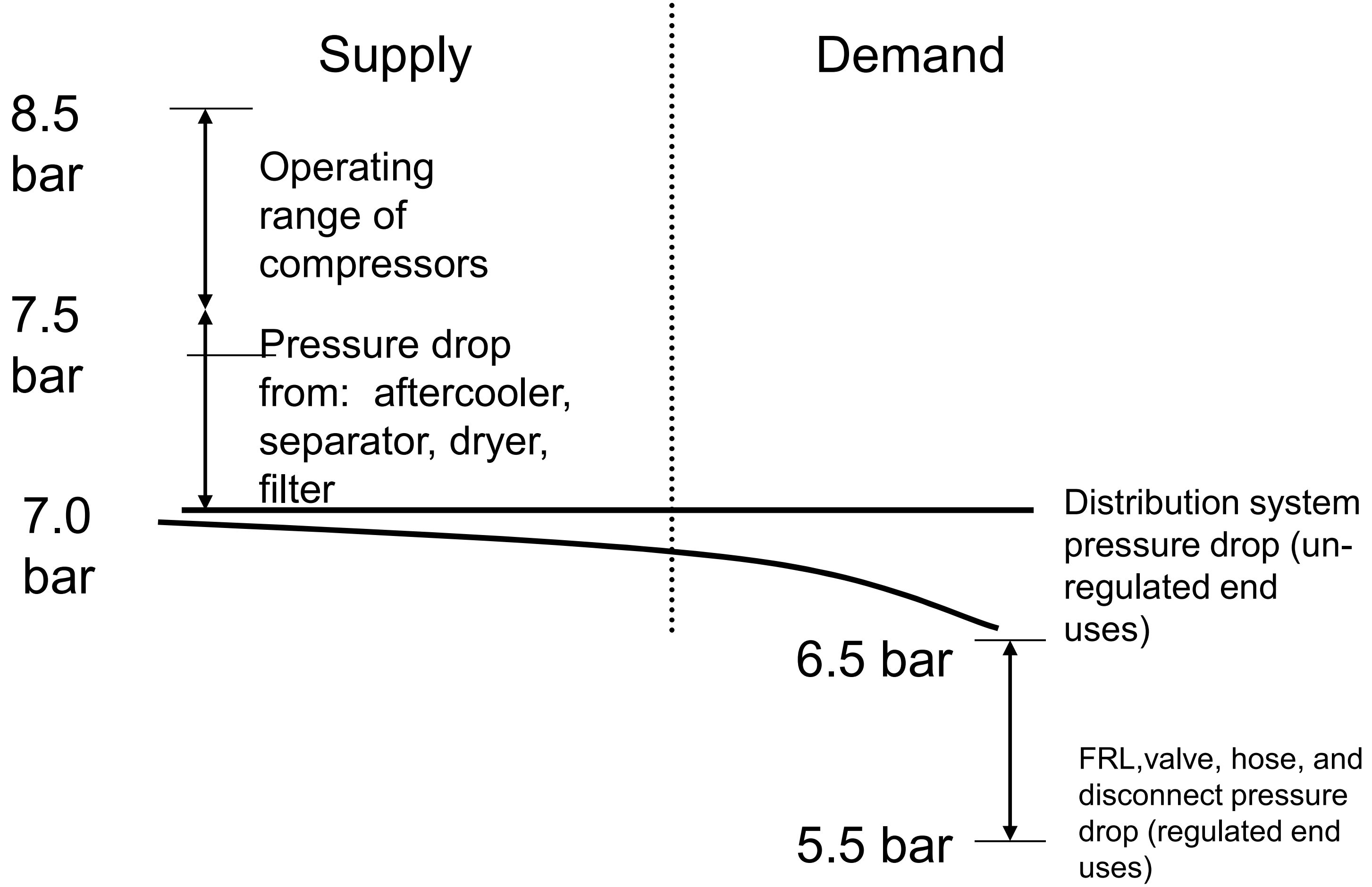
11. Data Collection & Analysis

- 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

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

- 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.

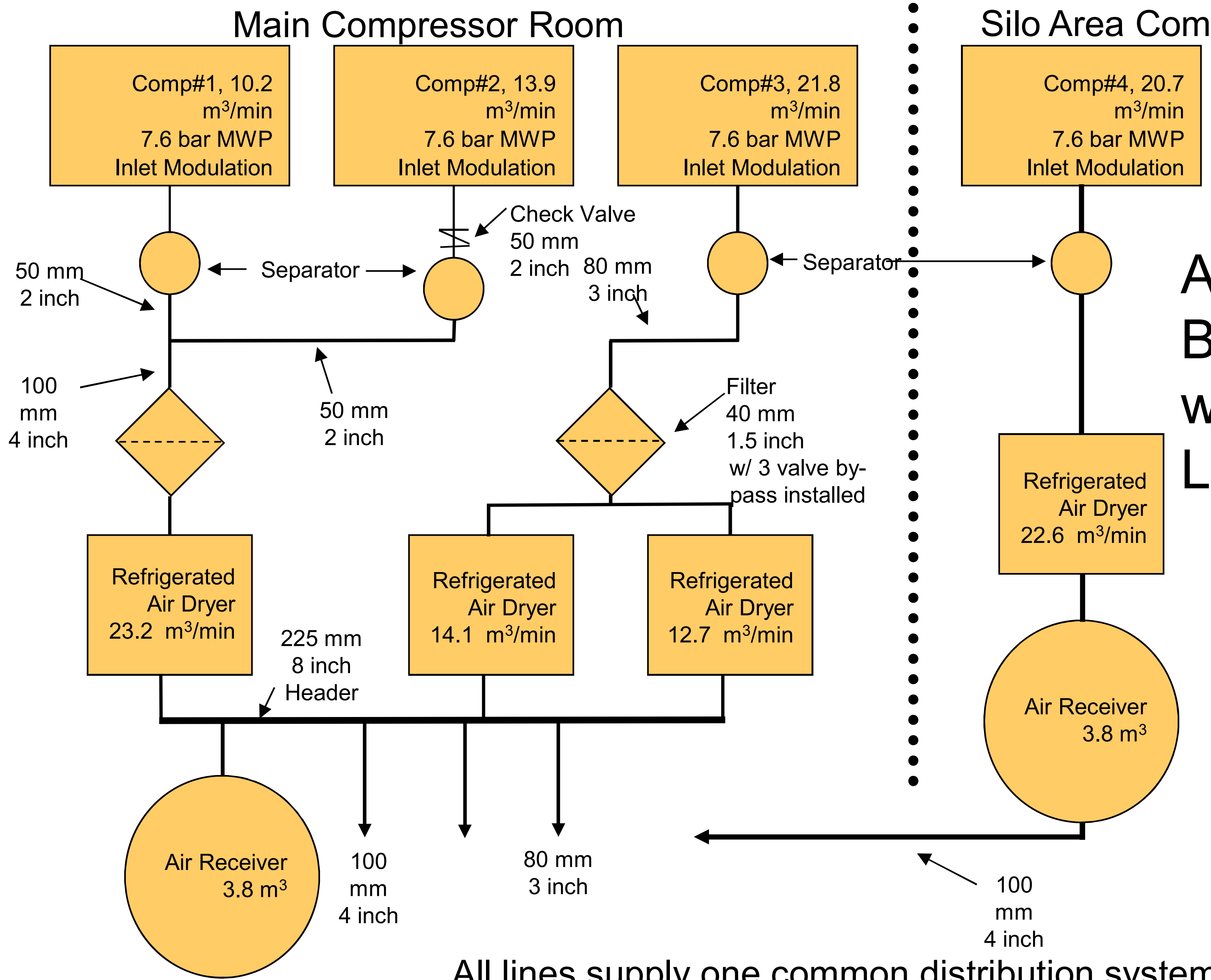
System Pressure Profile (typical)



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

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

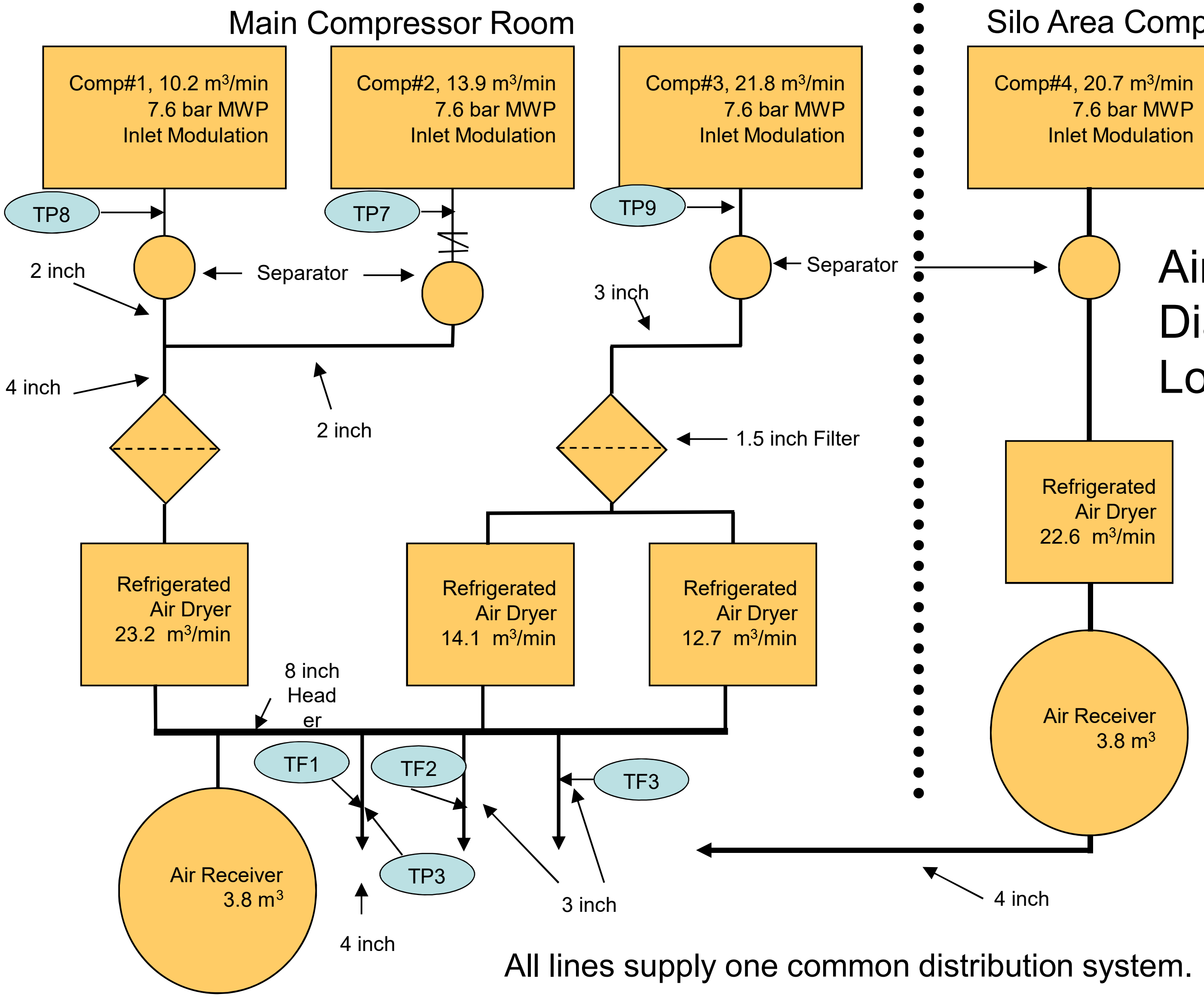
Air System Block Diagram with Test Locations



All lines supply one common distribution system.

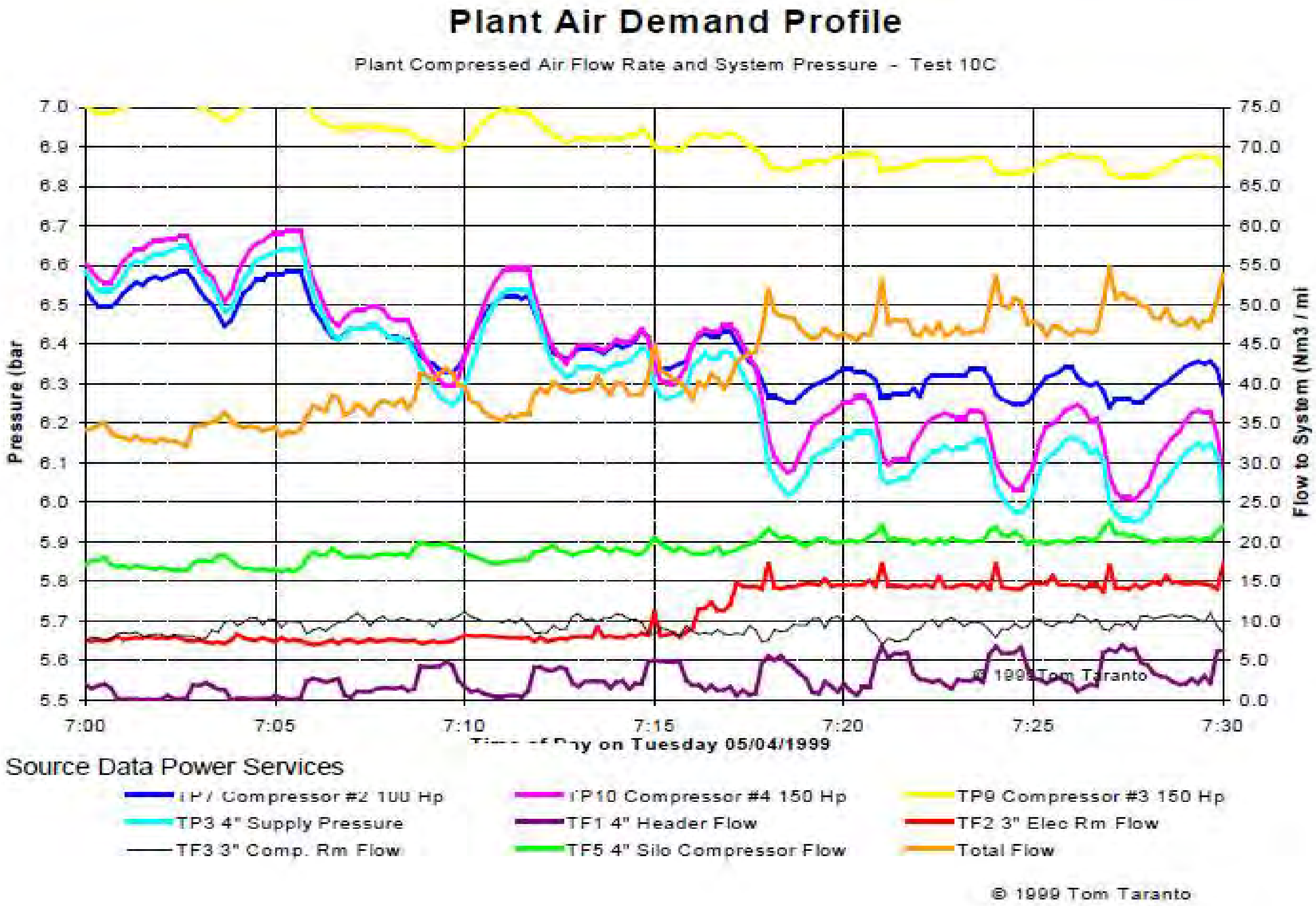
- Pressure & Flow Dynamic Profiles
  - Identify Characteristic Signatures
  - Characterize Drawdown Rates, magnitude and duration of events
  - Quantify Transient Supply Deficits, evaluate benefits of increased storage
  - Correlate Known Demand Events with demand side performance upsets and supply side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

Air System Block Diagram with Test Locations

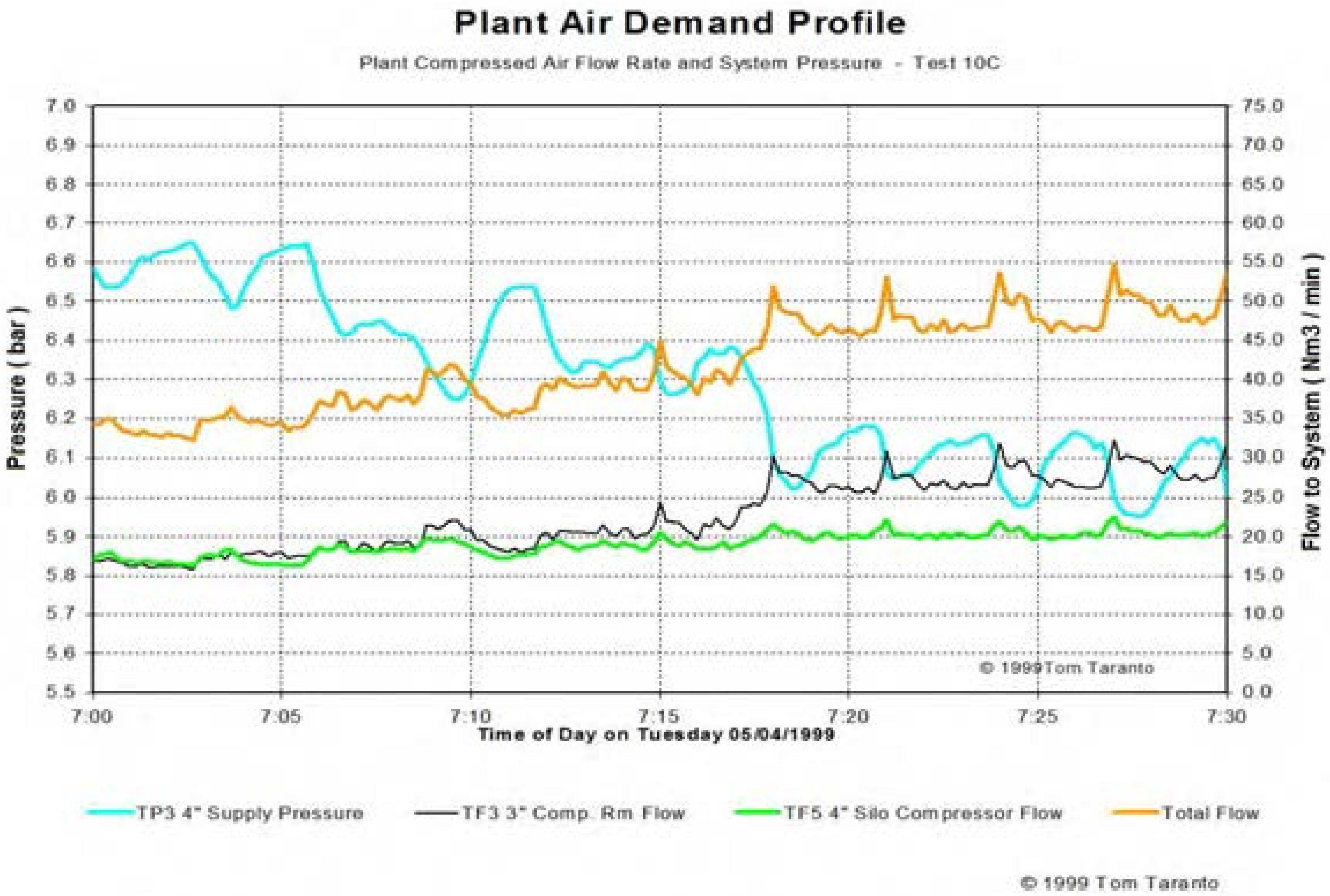


All lines supply one common distribution system.

Demand Profile & Characteristic Signature Demand Events



Supply Side Response to the Demand Events



Key Learning Points

1. Training and education must raise awareness of compressed air cost, opportunities to lower air pressure, and improve system performance.

2. Monitoring compressed air system performance provides necessary management information to keep the air system operating efficiently, and reliably.

3. In today's highly competitive global economy, timely compressed air system management information is essential.

Key Energy Points

4. Compressed air energy is a significant investment including capital, energy, maintenance, and productivity costs.

5. Multiple compressor systems can be very inefficient if not properly controlled.

6. Compressed air demand and pressure profile data can help identify potential areas for improvement.

7. Compressed air system assessment defines performance and current method operating costs.

Key Energy Points

8. Balancing system operation provides stable performance and reduces energy cost.

9. Inappropriate compressed air demands must be identified and replaced with more energy efficient alternatives.

10. Leak management, correctly sized distribution piping, and good point of use piping practice improves air application performance

11. Reducing system operating pressure to the lowest optimum pressure necessary to supply productive air demands, will reduce energy cost.

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?
  - ***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 setup
  - Scaling of engineering units

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.

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

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)

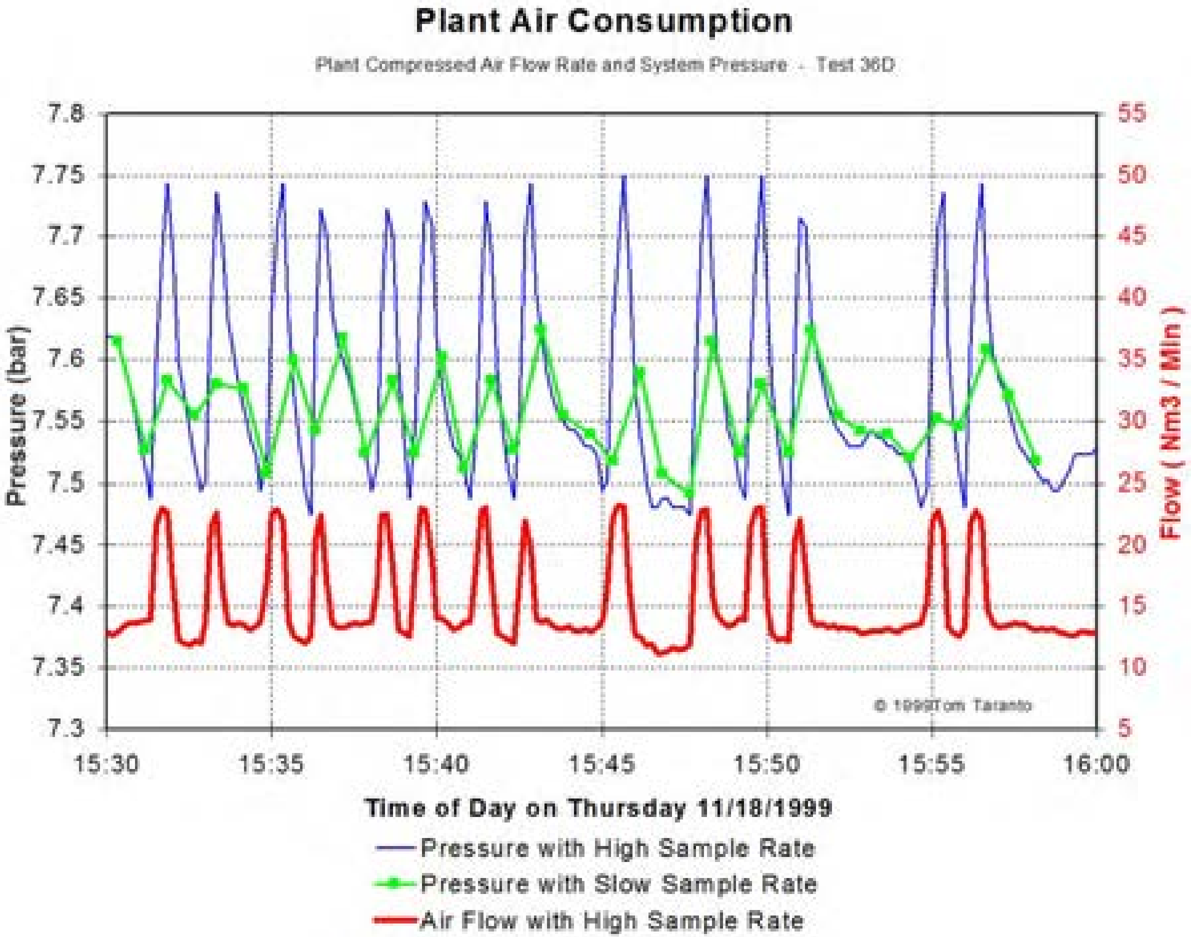
Dynamic Response

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

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 3s and averaging 15 samples.



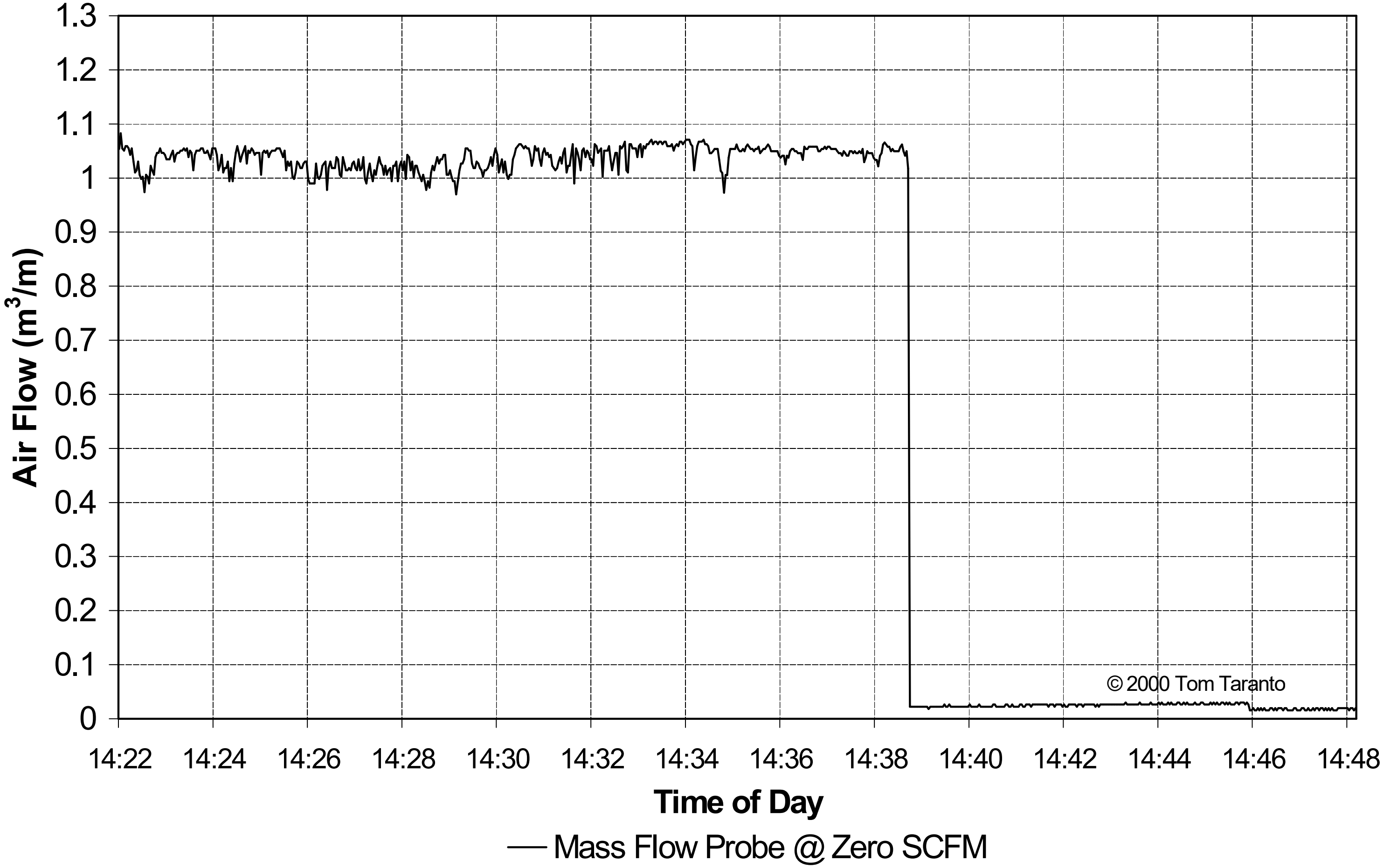
- Selecting Sensors to Support Informational Goals and the Measurement Plan
  - Physical parameters to be measured
    - pressure, power, energy, airflow, and others.
  - Sensor detects a physical parameter
    - Mechanical movement sensed by a strain gauge & output is changing resistance
  - Transmitter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

Flow Meter with Floating Power Source Interference

Compressed Air Mass Flow Probe Scaled for 0 - 49 m³/m

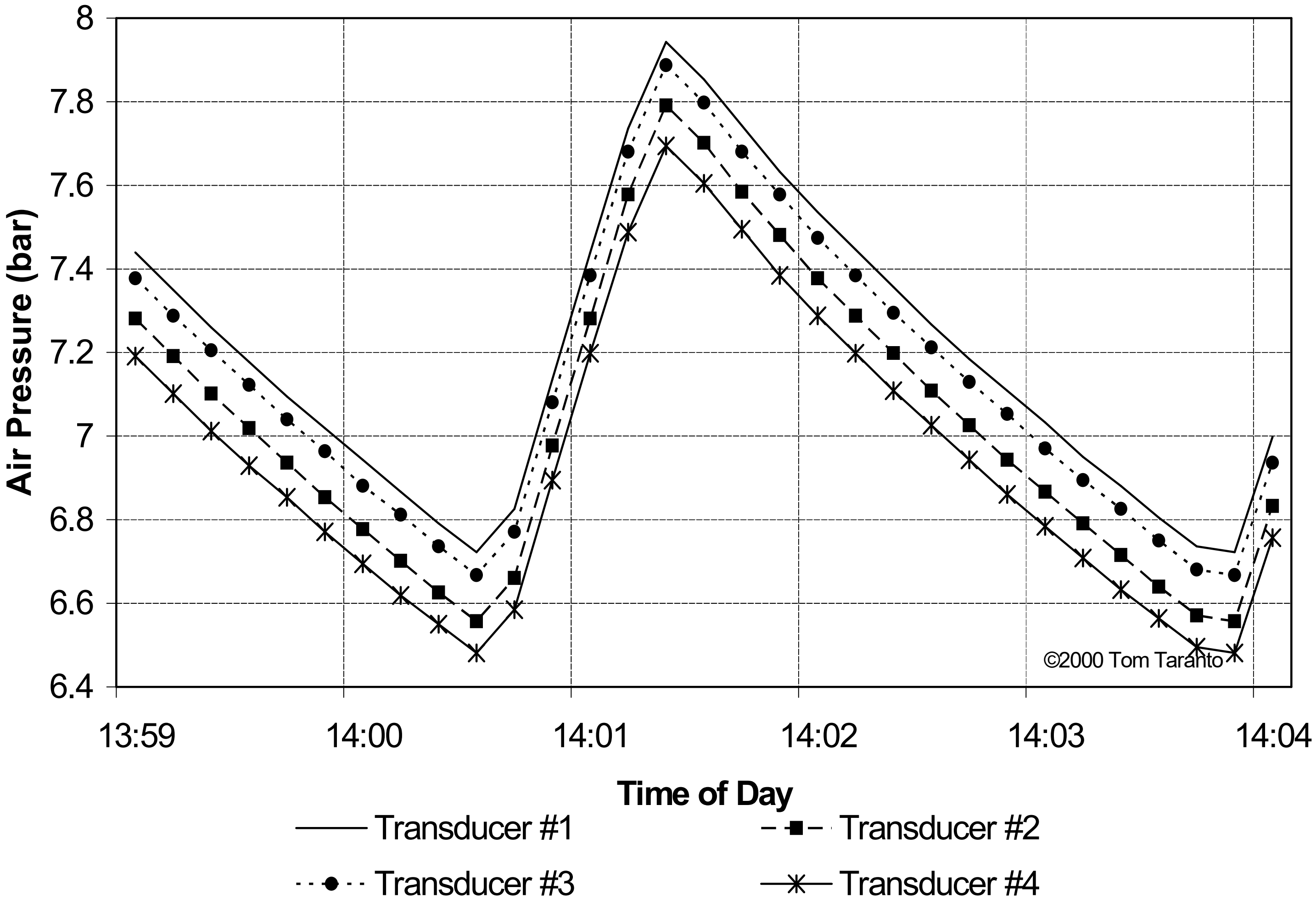
Floating Source Interference

Between Data Logger Power Supply and Flow Probe Power Supply



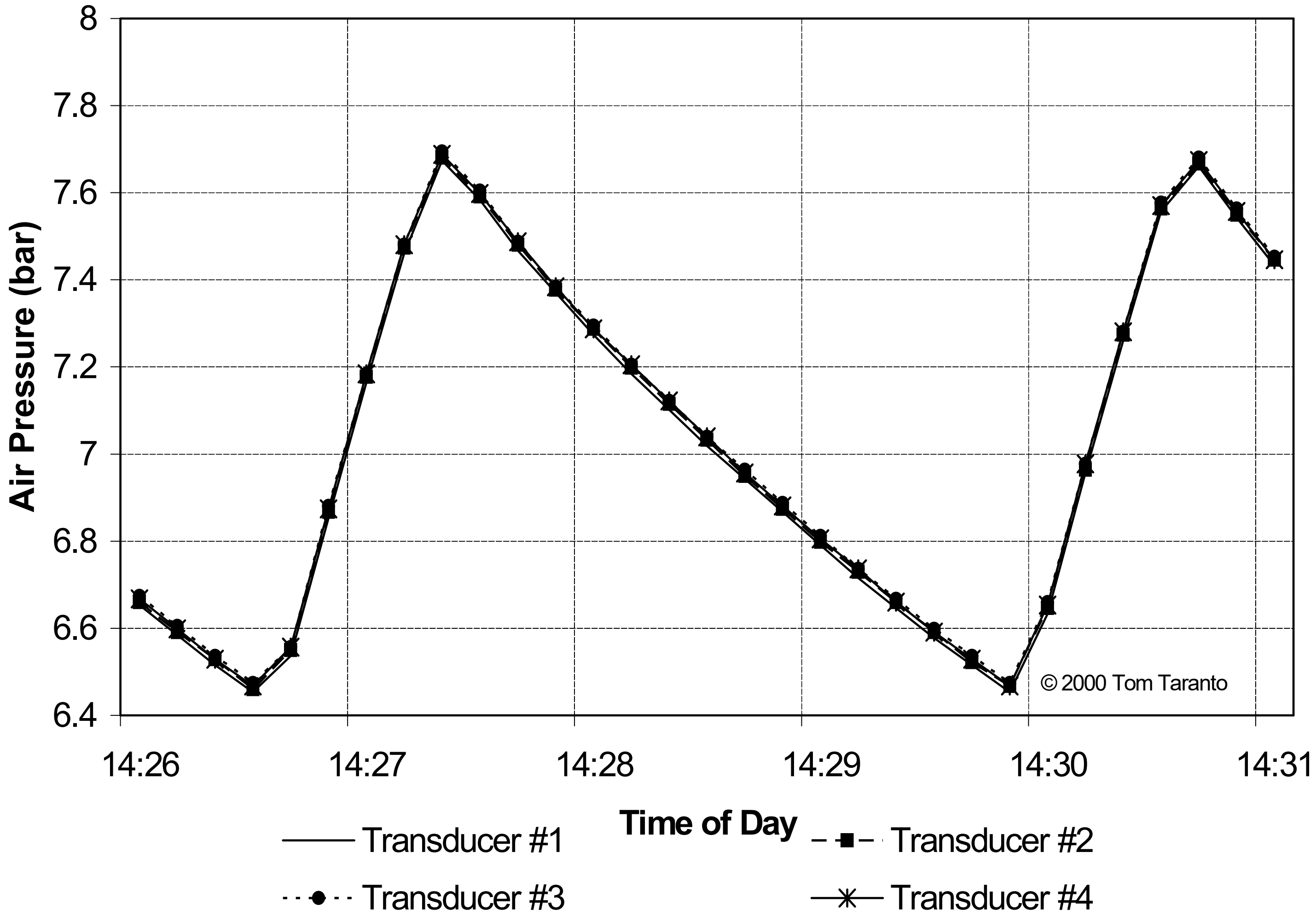
Pressure Transducer Comparison

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



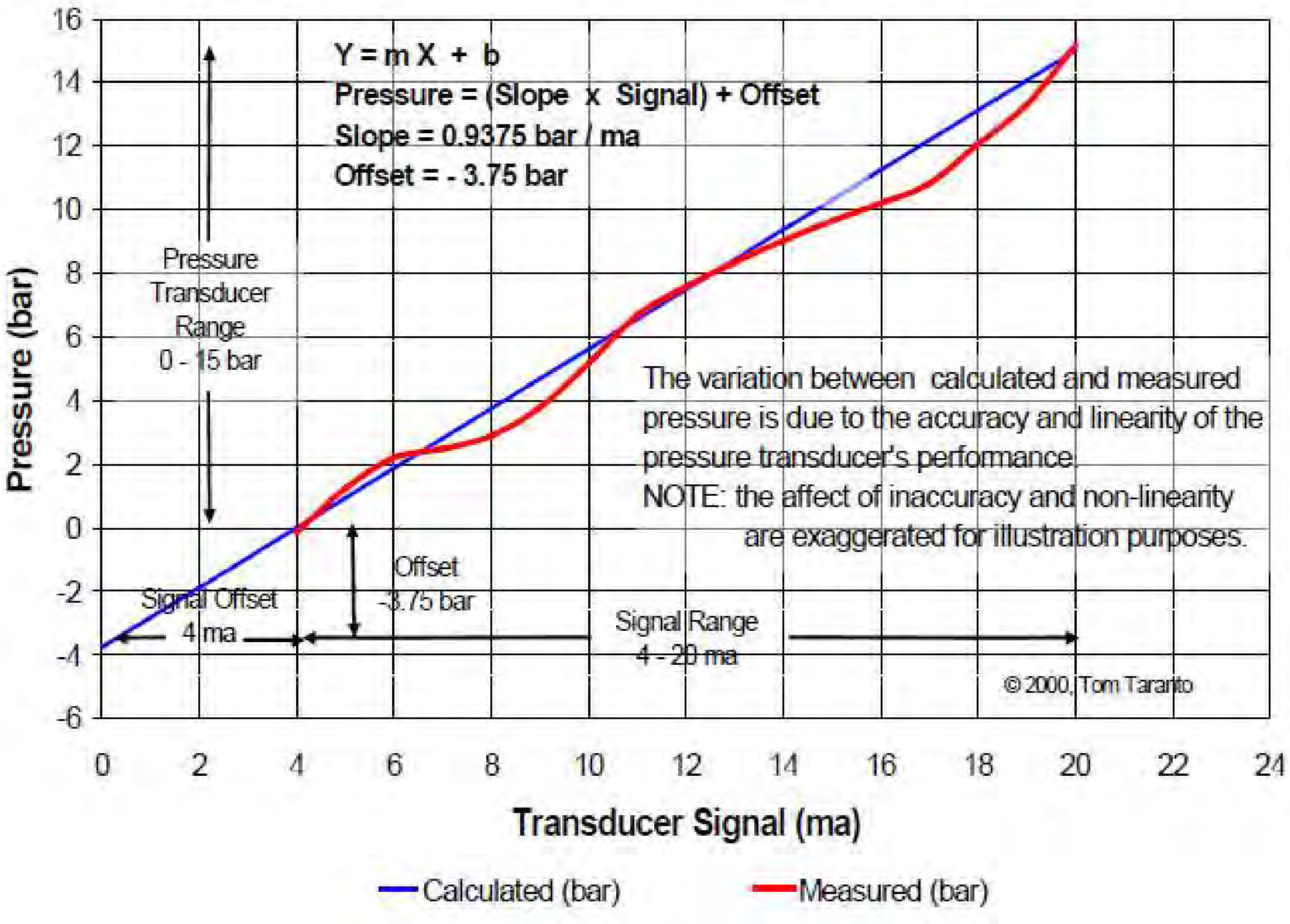
Pressure Transducer Comparison

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



Pressure Transducer Slope and Offset

Pressure Transducer Range 0 to 15 bar - Signal Range 4 - 20 ma



Key Learning Points

1. 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.
2. Sample rate, data averaging, and data intervals depend on system characteristics.
3. Use appropriate sensors, transducers, and measurement system accuracy.
4. Transducers output various signals in proportion to the physical parameter being measured.
5. Signals must be properly scaled to correctly record the measurement.

12. Maintenance

- Inadequate maintenance can have an impact on;
  - energy consumption via lower compression efficiency,
  - air leakage,
  - pressure variability,
  - high operating temperatures,
  - poor moisture control, and
  - excessive contamination
- All equipment in the compressed air system should be maintained in accordance with manufacturers' specifications
- Do periodic benchmarking by tracking power, pressure, flow, and temperature

Stopping for Maintenance

1. Disconnect and lock out the main power source.
2. Isolate the compressor from the compressed air supply
3. Open and lock a pressure relief valve to de-pressurize the system
4. Shut off the water-cooling supply
5. Open all manual drain valves within the area
6. Wait for the unit to cool before starting to service
7. Give preference to the manufacturer's manuals over these typical maintenance procedures.

General Maintenance

- Compressor Package
- Compressor Drives
- Air Treatment Equipment
- Leaks

Routine Maintenance for Air-Cooled Reciprocating Compressors

- Every 8 Hours (or Daily)
  - Maintain lubricant level
  - Drain condensate
  - Compressor overall visual inspection
  - Check for any unusual noise or vibration
  - Check lubricant pressure
  - Check for lubricant leaks

Routine Maintenance for Air-Cooled Reciprocating Compressors

- Every 160 Hours (or Monthly)
  - Check belt tension.
- Every 500 Hours (or Every 3 Months)
  - Change lubricant
  - Check lubricant filter
  - Torque pulley clamp screws or jam-nut.

Routine Maintenance for Air-Cooled Reciprocating Compressors

- Every 1000 Hours (or Every 6 Months)
  – Lubricant change for synthetic lubricant
  – Inspect compressor valves for leakage and/or carbon build-up
- Every 2000 Hours (or Every 12 Months)
  – Inspect the pressure switch diaphragm and contacts.
  – Inspect the contact points in the motor starter.

Routine Maintenance for Water-Cooled, Double-Acting Reciprocating Compressors

- Daily or every 8 hours
  - Check compressor lubricant pressure, feed rate and level in crankcase and cylinder lubricator
  - Check cylinder jacket cooling water temperatures
  - Check capacity control operation
  - Drain control line strainer
  - Check operation of automatic condensate drain trap
  - Drain condensate
  - Check intercooler pressure

Routine Maintenance for Water-Cooled, Double-Acting Reciprocating Compressors

- Monthly or every 360 hours
  - Check piston rod packing for leaks
  - Inspect lubricant scraper rings for leakage
  - Inspect air intake filter
  - Drain lubricant strainer/filter sediment
  - Lubricate un-loader mechanism
  - Check motor amps at compressor full capacity and pressure.

Routine Maintenance for Water-Cooled, Double-Acting Reciprocating Compressors

- Semi-annually or every 3000 hours
  - Perform valve inspection
  - Inspect cylinder or cylinder liner
  - Change crankcase lubricant
  - Clean crankcase breather
  - Change lubricant filter element
  - Remove and clean control air filter/strainer element
  - Check all safety devices for proper operation
  - Perform piston ring inspection

Routine Maintenance for Water-Cooled, Double-Acting Reciprocating Compressors

- Annually or every 6000 hours
  - Remove and clean crankcase lubricant strainer.
  - Check foundation bolts for tightness
  - Perform piston ring inspection
  - Experience from a maintenance log may allow the recommended times to be adjusted.

Routine Maintenance for Lubricant Injected Type Rotary Compressor

- Periodically/Daily-8 hours maximum
  - Monitor all gauges and indicators.
  - Check lubricant level.
  - Check for lubricant leaks.
  - Check for unusual noise or vibration.
  - Drain water from air/lubricant reservoir.
  - Drain control line filter.

Routine Maintenance for Lubricant Injected Type Rotary Compressor

- Weekly
  - Check safety valve operation.
- Monthly
  - Service air filter as needed.
  - Wipe entire unit down, to maintain appearance.
  - Check drive motor amps
  - Check operation of all controls
  - Check operation of lubricant scavenger

Routine Maintenance for Lubricant Injected Type Rotary Compressor

- 6 Months or every 1000 hours
  - Take lubricant sample.
  - Change lubricant filter.
- Periodically/yearly
  - Go over unit and check all bolts for tightness.
  - Change air/lubricant separator
  - Change air filter
  - Lubricate motors
  - Check safety shutdown system.

Routine Maintenance for Lubricant Free Rotary Screw Compressor

- Daily
  - Observe the various control panel displays and local gauges
- After Initial 50 Hours of Operation
  - Rid the system of any foreign materials.
  - Change the lubricant filter element.
  - Clean the control line filter element.
  - Check/replace the sump breather filter element.

Routine Maintenance for Lubricant Free Rotary Screw Compressor

- Every 3000 Hours of Operation
  – Check/change oil charge and filter element.
  – Check/change air filter element.
  – Check/change sump breather filter element.
  – Check/clean control line filter element.
  – Check/clean condensate drain valve.
  – Check condition of shaft coupling element
  – Measure and record vibration signatures

Routine Maintenance for Lubricant Free Rotary Screw Compressor

- Every 15,000 Hours of Operation
  - Operate/test all safety devices.
  - Check/clean heat exchangers, blowdown valve.
  - Check operation of balancing switch/valve assembly.
  - Check/clean water regulating and check valve.
  - Check/clean galvanized interstage pipe work.
  - Check condition of isolation mounts
  - Check/clean strainer and check valve included in oil pump suction line, inside oil sump.
  - Check compressor unit internal clearances.

Routine Maintenance for Centrifugal Air Compressors

- Daily
  - Record air inlet, interstage, discharge pressures and temperatures.
  - Record cooling water inlet and outlet pressures and temperatures.
  - Record lubricant pressure and temperatures.
  - Record all vibration levels.
  - Check air inlet filter differential pressure.
  - Check proper operation of drain traps.
  - Drain control air filter.
  - Check for leaks, air, water and lubricant.
  - Check lubricant sump level
  - Check drive motor for smooth operation and record amperes.

Routine Maintenance for Centrifugal Air Compressors

- Every 3 months
  - Check lubricant filter differential pressure.
  - Check lubricant sump venting system.
  - Check operation of capacity control system.
  - Check operation of surge control system.
  - Check main drive motor amperes
  - Check automatic drain traps and strainers.

Routine Maintenance for Centrifugal Air Compressors

- Every 3 months
  - Check lubricant filter differential pressure.
  - Check lubricant sump venting system.
  - Check operation of capacity control system.
  - Check operation of surge control system.
  - Check main drive motor amperes
  - Check automatic drain traps and strainers.
- Every 6 months
  - Check air inlet filter.
  - Take oil sample for analysis.

Routine Maintenance for Centrifugal Air Compressors

- Annually
  - Inspect intercooler, aftercooler, and lubricant cooler.
  - Inspect main drive motor for loose mounting bolts, frayed or worn electrical cables, accumulated dirt.
  - Inspect main drive coupling for alignment and lubrication.
  - Inspect gearbox
  - Check impeller inlets and diffusers
  - Check control panel for complete and proper operation.
  - Check all control valves for proper operation.
  - Check all safety devices for proper settings and operation.
  - Inspect check valve; replace worn parts.
  - Keep all components/accessories clean.

13. Heat Recovery

- As much as 80-93% of the electrical energy used by an industrial air compressor is converted into heat.
- A properly designed heat recovery unit can recover anywhere from 50-90% of this available thermal energy
- Typical uses: space heating, industrial process heating, water heating, makeup air heating, and boiler makeup water preheating.

Heat Recovery with Air-Cooled Rotary Screw Compressors

- **Heating Air**
  - Ambient atmospheric air is heated by passing it across the system's aftercooler and lubricant cooler
  - Only system modifications needed are the addition of ducting and another fan
  - As a rule of thumb, ± 5.3 kW of energy is available for each m^3/min of capacity (at full-load).
  - Air temperatures of 17-22°C above the cooling air inlet temperature can be obtained.
  - Recovery efficiencies of 80-90% are common.

Heat Recovery with Air-Cooled Rotary Screw Compressors

- **Heating Water**
  - Extract waste heat from the lubricant coolers
  - Can produce non-potable (gray) or potable water
  - Heat exchangers also offer an opportunity to produce a varying ratio of hot air and hot water

Heat Recovery with Water-Cooled Compressors

- Heat recovery for space heating is not as common because an extra stage of heat exchange is required and the temperature of the available heat is lower.
- Since many water-cooled compressors are quite large, heat recovery for space heating can be an attractive opportunity.
- Recovery efficiencies of 50-60% are typical.

Calculating Energy Savings

Energy Savings Calculations
Energy Savings (kWh/year) = 0.8 x Compressor kW x hours of operation **Example:** A 75kW compressors running two shifts, 5 days per week = (0.80) x 75kW x 4160 hours per year ***= 249,600 kWh per year*** *Where 0.80 is the recoverable heat as a percentage of the unit's output* $$\text{Cost savings}(\$/\text{y}) = \frac{\text{Energy savings in kWh/y} \times \text{kWh/unit of fuel} \times \$/\text{unit of fuel}}{\text{Primary heater efficiency}}$$ **Example:** Waste heat will be displacing heat produced by a natural gas forced air system with an efficiency of 85%. Assume the cost for natural gas is $0.14/m³, and the energy content of natural gas is 37MJ per m³. $$\text{Cost savings} = \frac{249{,}600\ \text{kWh/y} \times \frac{\text{m}^3}{37\text{MJ}} \times \frac{3.6\text{MJ}}{1\text{kWh}} \times \frac{\$0.14}{\text{m}^3}}{85\%}$$ $$\text{Cost savings} = \$4000\ \text{per year}$$ ** Cost of operating an additional fan for duct loading has not been included*