Construction Planning, Equipment, and Methods

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CHAPTER

11

COMPRESSED AIR

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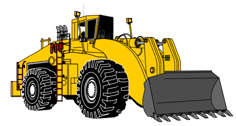

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COMPRESSED AIR

INTRODUCTION

- Compressed air is used for:
  - ✓Drilling rock
  - ✓Driving piles
  - ✓Operating hand tools
  - ✓Pumping
  - ✓Cleaning

PUMP

PAVING BREAKER

INTRODUCTION

- In many instances the energy supplied by compressed air is the most convenient method of operating equipment and tools.
- When air is compressed, it receives energy from the compressor. This energy is transmitted through a pipe or hose to the operating equipment, where a portion of the energy is converted into mechanical work.

INTRODUCTION

- The operations of compressing, transmitting, and using air will always result in a loss of energy, which will give an overall efficiency less than 100%, sometimes considerably less.

INTRODUCTION

- Things to consider:
  - ✓Effect of altitude on capacity.
  - ✓Loss of air pressure in pipe and hose systems.
  - ✓Capacity factors.

OVERVIEW

Selecting the right air compressor depends on many factors.

- **Compressor capacity and operating pressure depend on the tools used.**
- **Engine and compressor lose power and capacity as altitude increases and temperature rises.**

OVERVIEW

- Compressors are rated based on the cubic feet of atmospheric air they take in each minute with a specific discharge pressure, usually 100 psi.

GLOSSARY OF GAS-LAW TERMS

Absolute Pressure: This is the total pressure measured from absolute zero. It is equal to the sum of the gauge and the atmospheric pressure, corresponding to the barometric reading. The absolute pressure is used in dealing with the gas laws.

Absolute Temperature: This is the temperature of a gas measured above absolute zero. It equals degrees Fahrenheit plus 459.6 or, as more commonly used, 460.

GLOSSARY OF GAS-LAW TERMS

Atmospheric Pressure: The pressure exerted by the earth's atmosphere at any given position. Also referred to as barometric pressure.

Celsius Temperature: This is the temperature indicated by a thermometer calibrated according to the Celsius scale. For this thermometer pure water freezes at OºC and boils at 100ºC, at a pressure of 14.7 psi.

GLOSSARY OF GAS-LAW TERMS

Fahrenheit Temperature: This is the temperature indicated by a thermometer calibrated according to the Fahrenheit scale. For this thermometer pure water freezes at 32ºF and boils at 212ºF, at a pressure of 14.7 psi. Thus, the number of degrees between the freezing and boiling point of water is 180.

GLOSSARY OF GAS-LAW TERMS

Relation between Fahrenheit and Celsius temperatures: A difference of 180' on the Fahrenheit scale equals 100º on the Celsius scale; 1ºC equals 1.8ºF. A Fahrenheit thermometer will read 32º when a Celsius thermometer reads 0º. Let T_F = Fahrenheit temperature and T_C = Celsius temperature. For any given temperature the thermometer readings are expressed by the following equation:

$$T_F = 32 + 1.8T_C \quad (1)$$

GLOSSARY OF GAS-LAW TERMS

Gauge Pressure: This is the pressure exerted by the air in excess of atmospheric pressure. It is usually expressed in psi or inches of mercury and is measured by a pressure gauge or a mercury manometer.

Temperature: Temperature is a measure of the amount of heat contained by a unit quantity of gas (or other material). It is measured with a thermometer or some other suitable temperature-indicating device.

GLOSSARY OF GAS-LAW TERMS

Vacuum: This is a measure of the extent to which pressure is less than atmospheric pressure. For example, a vacuum of 5 psi is equivalent to an absolute pressure of 14.7- 5 = 9.7 psi.

Standard Conditions: Because of the variations in the volume of air with pressure and temperature, it is necessary to express the volume at standard conditions if it is to have a definite meaning. Standard conditions are an absolute pressure of 14.696 psi (14.7 psi is commonly used in practice) and a temperature of 60ºF.

GLOSSARY

Gas-law equations are based on absolute temperature.

- ***Absolute temperature*** **is Fahrenheit plus 460°.**
- ***Capacity*** **is the volume of air delivered by a compressor.**

GLOSSARY

- ***Diversity factor*** **is the ratio of the actual quantity of air required for all uses to the sum of the individual quantities for each use.**

TAMPER

TYPES OF COMPRESSION

- Isothermal Compression:

  When a gas undergoes a change in volume without any change in temperature, this is referred to as *isothermal expansion or compression*.

TYPES OF COMPRESSION

- Adiabatic Compression:

  When a gas undergoes a change in volume without gaining or losing heat, this is referred to as *adiabatic expansion or compression*.

BOYLE'S LAW

- Boyle's Law states that when a gas is subjected to a change in volume due to a change in pressure, at a *constant* temperature, the product of the pressure times the volume will remain constant

$$P_1V_1 = P_2V_2 = K \qquad \textbf{(2)}$$

P_1 = initial absolute pressure
V_1 = initial volume
P_2 = final absolute pressure
V_2 = final volume
K = a constant

Example 1

Determine the final volume of 1,000 ft^3 of air when the gauge pressure is increased from 20 to 120 psi, with no change in temperature. The barometer indicates an atmospheric pressure of 14.7 psi.

P_1 = 20 + 14.7 = 34.7 psi
P_2 = 120 + 14.7 = 134.7 psi
V_1 = 1,000 ft^3

$$P_1V_1 = P_2V_2 = K$$

$$V_2 = \frac{P_1V_1}{P_2} = \frac{34.7(1000)}{134.7} = 257.6\ \text{ft}^3$$

BOYLE'S AND CHARLES' LAWS

- When a gas undergoes a change in volume or pressure with a change in temperature, Boyle's law will not apply
- Charles law states that the volume of a given weight of gas at <u>*constant pressure*</u> varies in direct proportion to its absolute temperature, that is

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = C \qquad (3)$$

V_1 = initial volume
T_1 = initial absolute temperature
V_2 = final volume
T_2 = final absolute temperature
C = a constant

BOYLE'S AND CHARLES' LAWS

- The laws of Boyle and Charles may be combined to give the following expression:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \text{a constant} \qquad (4)$$

V_1 = initial volume
T_1 = initial absolute temperature
P_1 = initial absolute pressure
V_2 = final volume
T_2 = final absolute temperature
P_2 = final absolute pressure
C = a constant

Example 2

One thousand cubic feet of air, at initial gage pressure of 40 psi and temperature of 50⁰F, is compressed to a volume of 200 ft³ at a final temperature of 110⁰F. Determine the final gauge pressure.

$P_1 = 40 + 14.7 = 54.7$ psi
$V_1 = 1{,}000$ ft³
$T_1 = 460 + 50 = 510^0$F
$V_2 = 200$ ft³
$T_2 = 460 + 110 = 570^0$F

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \text{a constant}$$

$$P_2 = \frac{P_1V_1}{T_1} \times \frac{T_2}{V_2} = \frac{54.7(1000)}{510} \times \frac{570}{200} = 304.7 \text{ psi}$$

$$\text{Final Gauge} = 304.7 - 14.7 = \underline{291 \text{ psi}}$$

ENERGY REQUIRED TO COMPRESS AIR

- Recall that for constant temperature Boyle's law gives

$$P_1V_1 = P_2V_2 = K \qquad (5)$$

- For variable temperature,

$$P_1V_1^n = P_2V_2^n = K \qquad (6)$$

ENERGY REQUIRED TO COMPRESS AIR

- *n* = 1.0 for isothermal compression (constant temperature).
- *n* = 1.4 for adiabatic compression (no gaining or loosing of heat).
- Energy is supplied to compress air by means of compressor

ENERGY REQUIRED TO COMPRESS AIR

- The work done may be obtained by integrating the following equation:

$$dW = VdP \qquad (7)$$

- But

$$V = \left(\frac{K}{P}\right)^{\frac{1}{n}} \qquad (8)$$

- Hence

$$dW = \left(\frac{K}{P}\right)^{\frac{1}{n}} dP \qquad (9)$$

ENERGY REQUIRED TO COMPRESS AIR

- Integrating yields

$$W = K^{\frac{1}{n}} \int_1^2 \frac{dP}{P^{\frac{1}{n}}} \qquad \textbf{(10)}$$

- For isothermal compression, $n = 1$, therefore

$$W = K \int_1^2 \frac{dP}{P} = -K \ln\left(\frac{P_2}{P_1}\right) + C \qquad \textbf{(11)}$$

- It can be shown that the constant of integration C is equal to zero. When $P_1 = P_2$, no work is done and $C = 0$

ENERGY REQUIRED TO COMPRESS AIR

- For isothermal compression of air the equation may be written as

$$\boxed{W = K \ln\left(\frac{P_2}{P_1}\right) = (2.3026) K \log\left(\frac{P_2}{P_1}\right)} \qquad \textbf{(12)}$$

Note that $K = P_1 V_1$,

and P_1 = 14.7 psi = 2,116.8 psf at standard condition

ENERGY REQUIRED TO COMPRESS AIR

$$W = (2.3026)K\log\left(\frac{P_2}{P_1}\right) = (2.3026)(2116.8)V_1\log\left(\frac{P_2}{P_1}\right)$$

or

$$W = (4.873)V_1\log\left(\frac{P_2}{P_1}\right) \quad \textbf{(13)}$$

ENERGY REQUIRED TO COMPRESS AIR

- The value of W will be foot-pounds per cycle when V1 is expressed as cubic feet.
- One horsepower is equivalent to 33,000 ft-lb per minute.

ENERGY REQUIRED TO COMPRESS AIR

- If V_1 is replaced by V, the volume of free air per minute, the horsepower required to compress V cu ft of air from an absolute pressure of P_1 to P_2 will be

$$\text{hp} = \frac{(4.873)V_1 \log\left(\frac{P_2}{P_1}\right)}{33{,}000} = (0.1477)V \log\frac{P_2}{P_1} \qquad \textbf{(14)}$$

Example 3

- Determine the theoretical horsepower required to compress 100 ft^3 of free air per minute, measured at standard conditions, from atmospheric pressure to 100 psi gauge pressure.

$$\text{hp} = (0.1477)V \log\frac{P_2}{P_1} = 0.1477(100)\log\frac{114.7}{14.7}$$

$$\text{hp} = 14.77 \log 7.8$$

$$\text{hp} = 14.77(0.892) = \underline{13.2}$$

ENERGY REQUIRED TO COMPRESS AIR

- If air is compressed under other than *isothermal* conditions, the equation for the required horsepower may be derived in a similar manner
- The following equation gives the horsepower for for non-isothermal conditions:

$$\text{hp} = (0.0642)\frac{nV}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \quad \textbf{(15)}$$

Example 4

Determine the theoretical horsepower required to compress 100 ft^3 of free air per minute, measured at standard conditions, from atmospheric pressure to100 psi gauge pressure, under adiabatic conditions. The value for n = 1.4 for air under adiabatic compression.

$$\text{hp} = (0.0642)\frac{nV}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$\text{hp} = (0.0642)\frac{1.4(100)}{1.4-1}\left[\left(\frac{114.7}{14.7}\right)^{\frac{1.4-1}{1.4}} - 1\right] = \underline{17.9 \text{ hp}}$$

EFFECT OF ALTITUDE

- When a given volume of air, measured as free air prior to its entering a compressor, is compressed, the original pressure will average 14.7 psi absolute pressure at sea level.
- If the same volume of free air is compressed to the same gauge pressure at a higher altitude, the volume of the air after being compressed will be less than the volume compressed at sea level.

EFFECT OF ALTITUDE

- The reason for this difference is that the density of a cubic foot of free air at 5,000 ft is less than at sea level.
- Thus, while a compressor may compress air to the same discharge pressure at a higher altitude, the volume supplied in a given time interval will be less at the higher altitude.

EFFECT OF ALTITUDE

- Because a compressor of a specified capacity actually supplies a smaller volume of air at a given discharge pressure at a higher altitude, it requires less power to operate a compressor at a higher altitude.

EFFECT OF ALTITUDE

- The following table (Table 1) provides the theoretical horsepower required to compress 100 cu ft of free air per minute at different altitudes.

EFFECT OF ALTITUDE

Table 1. Theoretical Horsepower Required to Compress 100 ft^3 of Free Air per Minute at Different Altitudes

	Isothermal compression— single- and two-stage gauge pressure (psi)				Adiabatic compression Single-stage gauge pressure (psi)			Adiabatic compression Two-stage gauge pressure (psi)			
Altitude (ft)	60	80	100	125	60	80	100	60	80	100	125
0	10.4	11.9	13.2	14.4	13.4	15.9	18.1	11.8	13.7	15.4	17.1
1,000	10.2	11.7	12.9	14.1	13.2	15.6	17.8	11.6	13.5	15.1	16.8
2,000	10.0	11.4	12.6	13.8	13.0	15.4	17.5	11.4	13.2	14.8	16.4
3,000	9.8	11.2	12.3	13.5	12.8	15.2	17.2	11.2	13.0	14.5	16.1
4,000	9.6	11.0	12.1	13.2	12.6	14.9	16.9	11.0	12.7	14.2	15.7
5,000	9.4	10.7	11.8	12.8	12.4	14.7	16.5	10.8	12.5	13.9	15.4
6,000	9.2	10.5	11.5	12.5	12.2	14.4	16.2	10.6	12.2	13.6	15.1
7,000	9.0	10.3	11.2	12.2	12.0	14.2	16.0	10.4	12.0	13.4	14.8
8,000	8.9	10.0	11.0	11.9	11.8	14.0	15.7	10.2	11.8	13.1	14.5
9,000	8.7	9.8	10.7	11.6	11.6	13.7	15.4	10.0	11.6	12.8	14.1
10,000	8.5	9.6	10.4	11.4	11.5	13.5	15.1	9.8	11.3	12.6	13.8

Source: Compressed Air and Gas Institute.

EFFECT OF ALTITUDE

The capacity of an air compressor is rated at a barometric pressure of

14.7 psi, (sea level).

At higher altitudes the capacity of the compressor is reduced.

This is a result of Boyle's law.

BOYLE'S LAW

$$P_1V_1 = P_2V_2$$

P_1 is the pressure of the free air when we are considering the use of a compressor.

BOYLE'S LAW

P_1 (psi) changes with altitude:

Alt.	0	1000	2000	3000	4000	5000
P_1	14.7	14.2	13.7	13.2	12.7	12.2

EFFECT OF ALTITUDE

Consider 100 cu ft of free air compressed to 100 psi gauge. Applying Boyle's law.

$$V_2 = \frac{P_1 V_1}{P_2}$$

V_1 = 100 cfm

P_1 = atmospheric pressure

P_2 = atmospheric pressure + 100

EFFECT OF ALTITUDE

Change in V_2 (cu ft) with altitude, for V_1 = 100 cf.

Alt.	0	1000	2000	3000	4000	5000
P_1	14.7	14.2	13.7	13.2	12.7	12.2
V_2	12.8	12.4	12.0	11.6	11.3	10.9

STATIONARY COMPRESSORS

- Stationary compressors are generally used for installations where there will be a requirement for compressed air over a long duration of time at fixed locations.
- The compressors may be reciprocating or rotary types, single-stage or multistage.

STATIONARY COMPRESSORS

- One or more compressors may supply the total quantity of air.
- Stationary compressors may be driven by steam, electric motors, or internal combustion engines.

STATIONARY COMPRESSORS

- The installed cost of a single compressor will usually be less than that for several compressors having the same capacity. However, several compressors provide better flexibility for varying load demands, and in the event of a shutdown for repairs the entire plant does not need to be stopped.

TANK MOUNTED COMPRESSORS

Model	Motor (HP)	ASME Receiver size (GAL)	Capacity (ACFM)	Max Pressure (PSIG)	Package Dimensions LxWxH	Net Net Weight (lb)
2340D2	2	80 (Hor.)	7	175	67x22x42	440
2340N2	2	80 (Vert.)	7	175	36x19x69	550
2340D3	3	80 (Hor.)	9.1	175	67x22x42	440
2340N3	3	80 (Vert.)	9.1	175	36x19x69	550
2340L5	5	60 (Vert.)	15.2	175	35x19x70	450
2475N5	5	80 (Vert.)	17	175	37x28x70	500
2475D5	5	80 (Hor.)	17	175	69x23x45	535
2475N7.5	7.5	80 (Vert.)	24.2	175	37x28x70	510
2545D10	10	80 (Hor.)	35.2	175	68x29x47	730
2545E10	10	120 (Hor.)	35.2	175	72x29x52	835
2545N10	10	80 (Vert.)	35.2	175	42x29x74	730
2545K10	10	120 (Vert.)	35.2	175	42x30x77	835
7100E10	10	120 (Hor.)	37.2	175	72x28x57	1035
7100E15	15	120 (Hor.)	50.5	175	72x28x57	1100
3000E20	20	120 (Hor.)	73.5	175	72x34x61	1360
3000E25	25	120 (Hor.)	85.2	175	72x34x61	1410
3000E30	30	120 (Hor.)	100.7	175	72x34x61	1460
Gas Engine Driven						
2475F11G (Kohler)	11	30 (Hor.)	19	175	44x22x46	440
2475X11G (Kohler)	11	4 (Hor.)	19	175	42x27x28	360
2475F11GH (Honda)	11	30 (Hor.)	19	175	44x22x40	425

RECIPROCATING COMPRESSORS

- A reciprocating compressor depends on a piston, which moves back and forth in a cylinder, for the compressing action.
- The piston may compress air while moving in one or both directions.

RECIPROCATING COMPRESSORS

- For the former it is defined as single-acting, whereas for the latter it is defined as double-acting.
- A compressor may have one or more cylinders.

RECIPROCATING COMPRESSORS

ESV OPERATIONAL DATA						
					Nominal	
Model	psig	bar (g)	ACFM*	m^3/hr	HP	kw
7x5	125	8.6	94	160	25	18.7
10x7	125	8.6	128	212	30	22.4
10x7	125	8.6	167	284	40	29.9
10x7	125	8.6	213	362	50	37.3
11x7	100	6.9	275	467	60	44.8

PHE OPERATIONAL DATA						
					Nominal	
Model	psig	bar (g)	ACFM*	m3/hr	HP	kw
10&5x7	500	34.5	320	544	125	93.3
12&5x7	500	34.5	383	651	150	111.9
12&7x7	250	17.2	511	868	150	111.9
12&5&4x7	750	51.7	350	595	150	111.9
12&7&5x7	400	27.6	528	897	200	149.3
14&6x9	500	34.5	560	952	200	149.3
17&9x9	350	24.1	830	1411	250	186.4
17&9&4.5x9	650	44.8	920	1563	350	261

ROTARY COMPRESSORS

These machines offer several advantages compared with reciprocating compressors, such as compactness, light weight, uniform flow, variable output, maintenance-free operation, and long life.

	Free Air Delivery - CFM							
Nominal Horsepower	XF 100 psig	EP 125 psig	HP 140 psig	Receiver gallons	Length inches	Width inches	Height inches	Weight pounds
3		8		80	51	30	51	600
5		14		80	51	30	51	600
7.5		27		120	71	30	51	800
10		35		120	71	30	51	800
20		72		120	78	40	64	1,405
25		81		120	78	40	64	1,470
30		109		120	78	40	64	1,504
60	270	250	235	n/a	77	45	67	2,520
75	324	300	285	n/a	77	45	67	2,775
100	416	400	378	n/a	77	45	67	2950

ROTARY SCREW COMPRESSORS

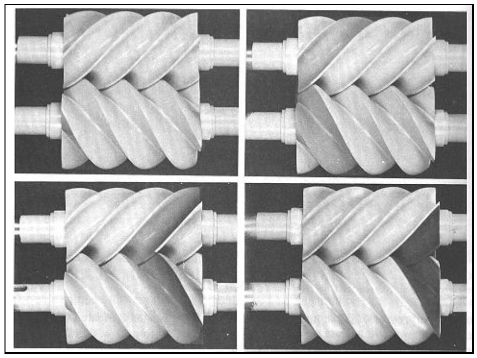
- The working parts of a screw compressor are two helical rotors.
- The male rotor has four lobes and rotates 50% faster than the female rotor, which has six flutes, with which the male motor meshes.

ROTARY SCREW COMPRESSORS

- As air enters and flows through the compressor, it is compressed in the space between the lobes and the flutes.
- The inlet and outlet ports are automatically covered and uncovered by the shaped ends of the rotors as they turn.

ROTARY SCREW COMPRESSORS

Figure 1. The Operation of Helical Rotors of Screw Compressor



ADVANTAGES OF ROTARY SCREW COMPRESSORS

- Quiet operation, with little or no loss in output.
- Few moving parts, with minimum mechanical wear and few maintenance requirements.
- Little or no pulsation in the flow of air, and hence reduced vibrations

ADVANTAGES OF ROTARY SCREW COMPRESSORS

- Automatic controls actuated by the output pressure, which regulate the speed of the driving unit and the compressor to limit the output to only the demand required.

PORTABLE COMPRESSORS

- Portable compressors are more commonly used on construction sites where it is necessary to meet frequently changing job demands.
- The compressors may be mounted on rubber tires steel wheels, or skids. They are usually powered by gasoline or diesel engines and are available in single- or two-stage, reciprocating or rotary types.

COMPRESSOR CAPACITY

- Air compressors are rated by the piston displacement in cubic feet per minute (cfm).
- However, the capacity of a compressor will be less than than the piston displacement because of valve and piston leakage and the air left in the end-clearance spaces of the cylinders.

COMPRESSOR CAPACITY

- The capacity of a compressor is the actual volume of free air drawn into a compressor in a minute.
- For a reciprocating compressor in good mechanical condition, the actual capacity ranges from 80% to 90% of the piston displacement.

COMPRESSOR CAPACITY

- The manufacturers usually give the following information:
  - No. of low-pressure cylinders, 4
  - No. of high-pressure cylinders, 2
  - Diameter of low-pressure cylinders, 7 in.
  - Diameter of high-pressure cylinders, 5 3/4 in.
  - Length of stroke, 5 in.
  - rpm, 870

Example 5

Consider a 315 cfm two stage portable compressor with the following specifications as given by the manufacturer:

No. of low-pressure cylinders = 4
Diameter of low-pressure cylinders = 7 in
Length of stroke = 5 in
Revolution per minute (rpm) = 870

What is the efficiency of this compressor?

$$\text{Area of cylinder} = \frac{\pi\left(\frac{7}{2}\right)^2}{(144)} = 0.267\ \text{ft}^2$$

$$\text{Displacement per cylinder per stroke} = 0.267\left(\frac{5}{12}\right) = \underline{0.111\ \text{ft}^3}$$

Example 5 (continued)

$$\text{Displacement per minute} = 4 \times 0.111 \times 870 = 386.3\,\frac{\text{ft}^3}{\text{min}}$$

$$\text{Efficiency} = \frac{315}{386.3} \times 100 = \underline{81.5\%}$$

EFFECT OF ALTITUDE ON CAPACITY OF COMPRESSORS

- The capacity of an air compressor is normally rated on the basis of its performance at sea level, where the normal absolute barometric pressure is about 14.7 psi.

EFFECT OF ALTITUDE ON CAPACITY OF COMPRESSORS

- If a compressor is operated at a higher altitude, such as 5,000 ft above sea level, the absolute barometric pressure will be about 12.2 psi.
- At the higher altitude, the density is less and the weight of air in ft3 of free volume is less than at sea level.

EFFECT OF ALTITUDE ON CAPACITY OF COMPRESSORS

Table 2. The Effect of Altitude on the Capacity of Single-stage Air Compressors

Altitude above sea level		Operating pressure: psi gauge [psi absolute], (Pa)							
		80 [94.7] (6.53×10^5)		90 [104.7] (7.23×10^5)		100 [114.7] (7.91×10^5)		125 [139.7] (9.65×10^5)	
ft	m	Compressor ratio[†]	Factor[‡]	Compressor ratio	Factor	Compressor ratio	Factor	Compressor ratio	Factor
0	0	6.44	1.000	7.12	1.000	7.81	1.000	9.51	1.000
1,000	305	6.64	0.992	7.34	0.988	8.05	0.987	9.81	0.982
2,000	610	6.88	0.977	7.62	0.972	8.35	0.972	10.20	0.962
3,000	915	7.12	0.967	7.87	0.959	8.63	0.957	10.55	0.942
4,000	1,220	7.36	0.953	8.15	0.944	8.94	0.942	10.92	0.923
5,000	1,525	7.62	0.940	8.44	0.931	9.27	0.925	11.32	0.903
6,000	1,830	7.84	0.928	8.69	0.917	9.55	0.908	11.69	0.883
7,000	2,135	8.14	0.915	9.03	0.902	9.93	0.890	12.17	0.863
8,000	2,440	8.42	0.900	9.33	0.886	10.26	0.873	12.58	0.844
9,000	2,745	8.70	0.887	9.65	0.868	10.62	0.857	13.02	0.824
10,000	3,050	9.00	0.872	10.00	0.853	11.00	0.840	13.50	0.804
11,000	3,355	9.34	0.858	10.38	0.837	11.42	0.823	14.03	
12,000	3,660	9.70	0.839	10.79	0.818	11.88	0.807	14.60	
14,000	4,270	10.42	0.805	11.60		12.78		15.71	
15,000	4,575	10.88	0.784	12.12		13.36		16.43	

[†] The compressor ratio is the ratio of the volume of free air divided by the volume of the same air at the indicated pressure.

[‡] When this factor is multiplied by the specified capacity of the compressor, at sea level, it will give the capacity at the indicated altitude and operating pressure.

Source: Compressed Air and Gas Institute.

Example 6

A 100-cu-ft of free air at sea level is compressed to 100-psi gauge with no change in temperature. What is the volume at an altitude of 5,000 above sea level?

P_1 = 12.2 psi
P_2 = 100 + 12.2 = 112.2 psi
V_1 = 100 ft^3

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{12.2(100)}{112.2} = \underline{10.87\ \text{ft}^3}$$

Example 7

A single-stage compressor having a sea-level capacity of 600 cfm will be operating at a pressure of 90 psi gauge. What will be the actual capacity at altitudes of 7,000 ft and 12,000 ft above sea level?

From Table 2 (Table 12-3 Textbook)
For 7,000 ft, the actual capacity will be:
Capacity = 600 X 0.902 = 541.2 cfm

For 12,000 ft, the actual capacity will be:
Capacity = 600 X 0.818 = 490.8 cfm

INTERCOOLERS

- Intercoolers are installed between the stages of a compressor to *reduce* the temperature of the air and to *remove* moisture from air.
- The reduction in temperature prior to additional compression can reduce the power required by as much as 10 to 15%.

INTERCOOLERS

- An intercooler requires a continuous supply of circulating water to remove the heat from the air. It will require 1.0 to 1.5 gal of water per minute for each 100 cfm of air compressed.

AFTERCOOLERS

- Aftercoolers are installed at the discharged side of a compressor to ***cool*** the air to the desired temperature and to ***remove*** moisture from the air.
- Excess moisture in the air tends to freeze during expansion in air tools, and washes the lubricating oil out of tools, thereby reducing the lubricating efficiency.

RECEIVERS

- An air receiver should be installed on the discharge side of a compressor to equalize the compressor pulsations and to serve as a condensing chamber for the removal of water and oil vapors.

RECEIVERS

- A receiver should have a drain cock at its bottom to permit the removal of the condensate.
- Its volume should be 1/10 to 1/6 the capacity of the compressor.

LOSS OF AIR PRESSURE IN PIPE DUE TO FRICTION

- As air flows in a pipe or a hose, its pressure reduces due to friction.
- The loss of pressure due to friction is a factor that must be considered in selecting the size of a pipe or a hose.

LOSS OF AIR PRESSURE

The loss of pressure due to friction as air flows through a pipe or hose must be considered in selecting the size of pipe or hose to use on a job.

PRACTICAL EXERCISE

What will be the pressure at the end of a compressed air pipeline used to transmit 3,000 cfm of free air?

LOSS OF AIR PRESSURE IN PIPE DUE TO FRICTION

- Failure to use a sufficiently large line may cause the air pressure to drop so low that it will not satisfactorily operate the tool to which it is providing power.
- When the cost of lost efficiency exceeds the cost of providing a larger line, it is cost-effective to use larger line.

LOSS OF AIR PRESSURE IN PIPE DUE TO FRICTION

- The following formula is used to determine the loss of pressure in a pipe due to friction:

$$f = \frac{CL}{r} \times \frac{Q^2}{d^5} \qquad (16)$$

LOSS OF AIR PRESSURE IN PIPE DUE TO FRICTION

- Friction Formula:

$$f = \frac{CL}{r} \times \frac{Q^2}{d^5}$$

Where

f = pressure drop, psi
L = length of pipe, ft
Q = volume of free air, ft^3, per second
r = ratio of compression, based on absolute press.
d = actual ID of pipe, in
C = experimental coefficient

LOSS OF AIR PRESSURE IN PIPE DUE TO FRICTION

- For ordinary steel pipe, the value of C is found to be $0.1025/d^{0.31}$, hence

$$f = \frac{0.1025L}{r} \times \frac{Q^2}{d^{5.31}} \qquad \textbf{(17)}$$

- A chart for determining the loss in pressure in a pipe is given in Figure 2 (Fig 11-5, Text).

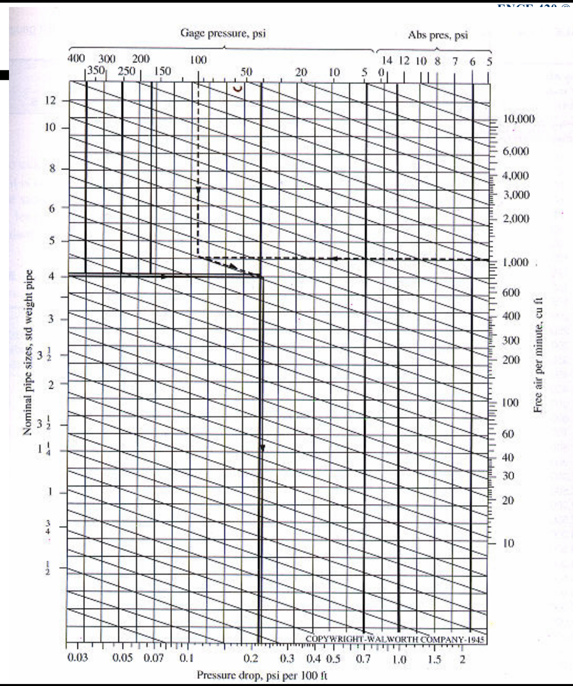


Figure 2
Compressed-Air Flow Chart

Example 8

Determine the pressure loss per 100 ft of pipe resulting from transmitting 1,000 cfm of free air, at 100 psi gauge pressure, through a 4-in. standard-weight steel pipe?

Using the equation:

$$r = \frac{100 + 14.7}{14.7} = 7.803$$

$$f = \frac{0.1025L}{r} \times \frac{Q^2}{d^{5.31}} = \frac{0.1025(100)}{7.803} \times \frac{\left(\frac{1000}{60}\right)^2}{(4)^{5.31}} = 0.232 \text{ psi}$$

Example 8 (continued)

- Using the chart (Figure 2, Fig 12-5, Text):
- Enter the chart at the top at 100 psi
- Then proceed vertically downward to a point opposite 1,000 cfm
- Then proceed parallel to the sloping guide lines to a point opposite the 4-in pipe
- and then proceed vertically downward to the bottom of the chart
- The pressure drop is approximately 0.23 psi

LOSS OF AIR PRESSURE THROUGH FITTINGS AND HOSE

- To provide for the loss of pressure resulting from the flow of air through screw-pipe fitting, it is common practice to convert a fitting to its equivalent length of pipe having the same nominal diameter.

LOSS OF AIR PRESSURE THROUGH FITTINGS AND HOSE

- This equivalent length ***should be added*** to the actual length of the pipe in determining pressure loss.
- Table 3 (Table 11-5 Text)gives the equivalent length of standard-weight pipe.

LOSS OF AIR PRESSURE THROUGH FITTINGS AND HOSE

Table 3. Equivalent Length (ft) of Standard-weight Pipe Having the Same Pressure Losses as Screwed Fittings

Nominal pipe size (in.)	Gate valve	Globe valve	Angle valve	Long-radius ell or on run of standard tee	Standard ell or on run of tee	Tee through side outlet
$\frac{1}{2}$	0.4	17.3	8.6	0.6	1.6	3.1
$\frac{3}{4}$	0.5	22.9	11.4	0.8	2.1	4.1
1	0.6	29.1	14.6	1.1	2.6	5.2
$1\frac{1}{4}$	0.8	38.3	19.1	1.4	3.5	6.9
$1\frac{1}{2}$	0.9	44.7	22.4	1.6	4.0	8.0
2	1.2	57.4	28.7	2.1	5.2	10.3
$2\frac{1}{2}$	1.4	68.5	34.3	2.5	6.2	12.3
3	1.8	85.2	42.6	3.1	6.2	15.3
4	2.4	112.0	56.0	4.0	7.7	20.2
5	2.9	140.0	70.0	5.0	10.1	25.2
6	3.5	168.0	84.1	6.1	15.2	30.4
8	4.7	222.0	111.0	8.0	20.0	40.0
10	5.9	278.0	139.0	10.0	25.0	50.0
12	7.0	332.0	166.0	11.0	29.8	59.6

Example 9

A 4 in ordinary steel pipe with screwed fittings is used to transmit 1200 cfm of free air at an initial pressure of 90 psi gauge pressure. Determine the total loss of pressure in the pipline if the pipline includes the following items:

1450 ft of pipe,	6 standard on-run tees
4 gate valves,	3 angle Valves

Size of pipe = 4 in.

Length of pipe = 1450 ft

Q = 1200 cfm

P_1 = 90 psi gauge

Example 9 (continued)

The equivalent length of the pipe will be:

Pipe	= 1450 ft
Gate valves: 4 X 2.4 (Table 3)	= 9.6 ft
on-run tees: 6 X 7.7 (Table 3)	= 46.2 ft
angle valves: 3 X 56.0 (Table 3)	= 168 ft
Total	1673.8 ft

$$r = \frac{90 + 14.7}{14.7} = 7.122$$

$$f = \frac{0.1025L}{r} \times \frac{Q^2}{d^{5.31}} = \frac{0.1025(1673.8)}{7.122} \times \frac{\left(\frac{1200}{60}\right)^2}{(4)^{5.31}} = \underline{7.86 \text{ psi}}$$

Example 10

If the air from the end of the pipeline of the previous example is delivered through 50 ft of 3/4 in hose to a rock drill that requires 130 cmf of air, determine the pressure at the drill.

From Example 9, the pressure at the end of the pipe:

90 - 7.86 = 82.14 psi

Thus for the drill:

P_1 = 82.14 psi

Q = 130 cfm

Length of hose = 50 ft

Size of hose = 3/4 in

Table 4
(Table 11-7, Text). Loss of Pressure (psi) in 50 Feet of Hose

Size of hose (in.)	Gauge pressure at line (psi)	Volume of free air through hose (cfm)													
		20	30	40	50	60	70	80	90	100	110	120	130	140	150
1/2	50	1.8	5.0	10.1	18.1										
	60	1.3	4.0	8.4	14.8	23.5									
	70	1.0	3.4	7.0	12.4	20.0	28.4								
	80	0.9	2.8	6.0	10.8	17.4	25.2	34.6							
	90	0.8	2.4	5.4	9.5	14.8	22.0	30.5	41.0						
	100	0.7	2.3	4.8	8.4	13.3	19.3	27.2	36.6						
	110	0.6	2.0	4.3	7.6	12.0	17.6	24.6	33.3	44.5					
3/4	50	0.4	0.8	1.5	2.4	3.5	4.4	6.5	8.5	11.4	14.2				
	60	0.3	0.6	1.2	1.9	2.8	3.8	5.2	6.8	8.6	11.2				
	70	0.2	0.5	0.9	1.5	2.3	3.2	4.2	5.5	7.0	8.8	11.0			
	80	0.2	0.5	0.8	1.3	1.9	2.8	3.6	4.7	5.8	7.2	8.8	10.6		
	90	0.2	0.4	0.7	1.1	1.6	2.3	3.1	4.0	5.0	6.2	7.5	9.0		
	100	0.2	0.4	0.6	1.0	1.4	2.0	2.7	3.5	4.4	5.4	6.6	7.9	9.4	11.1
	110	0.1	0.3	0.5	0.9	1.3	1.8	2.4	3.1	3.9	4.9	5.9	7.1	8.4	9.9
1	50	0.1	0.2	0.3	0.5	0.8	1.1	1.5	2.0	2.6	3.5	4.8	7.0		
	60	0.1	0.2	0.3	0.4	0.6	0.8	1.2	1.5	2.0	2.6	3.3	4.2	5.5	7.2
	70	—	0.1	0.2	0.4	0.5	0.7	1.0	1.3	1.6	2.0	2.5	3.1	3.8	4.7
	80	—	0.1	0.2	0.3	0.5	0.7	0.8	1.1	1.4	1.7	2.0	2.4	2.7	3.5
	90	—	0.1	0.2	0.3	0.4	0.6	0.7	0.9	1.2	1.4	1.7	2.0	2.4	2.8
	100	—	0.1	0.2	0.2	0.4	0.5	0.6	0.8	1.0	1.2	1.5	1.8	2.1	2.4
	110	—	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1.1	1.3	1.5	1.8	2.1
1 1/4	50	—	—	0.2	0.2	0.2	0.3	0.4	0.5	0.7	1.1				
	60	—	—	—	0.1	0.2	0.3	0.3	0.5	0.6	0.8	1.0	1.2	1.5	
	70	—	—	—	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.7	0.8	1.0	1.3
	80	—	—	—	—	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0
	90	—	—	—	—	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8
	100	—	—	—	—	—	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.7
	110	—	—	—	—	—	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6
1 1/2	50	—	—	—	—	—	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.6
	60	—	—	—	—	—	—	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5
	70	—	—	—	—	—	—	—	0.1	0.2	0.2	0.2	0.3	0.3	0.4
	80	—	—	—	—	—	—	—	—	0.1	0.2	0.2	0.2	0.3	0.4
	90	—	—	—	—	—	—	—	—	—	0.1	0.2	0.2	0.2	0.2
	100	—	—	—	—	—	—	—	—	—	—	0.1	0.2	0.2	0.2
	110	—	—	—	—	—	—	—	—	—	—	0.1	0.2	0.2	0.2

Example 10 (continued)

From Table 4 (Table 11-7)and for 3/4-in hose:

Gauge Pressure (psi)	Loss of Pressure at 130 cfm (psi)
80	10.6
82.14	P_{drop}
90	9.0

$$\frac{82.14-80}{90-80}=\frac{P_{drop}-10.6}{9.0-10.6} \quad \Rightarrow P_{drop}=\frac{(9.0-10.6)(82.14-80)}{90-80}+10.6$$

$$\therefore P_{drop}=10.26 \text{ psi}$$

The pressure at the drill = 82.14 - 10.26 = <u>71.88 psi</u>

DIVERSITY OR CAPACITY FACTOR

- While it is necessary to provide as much compressed air as will be required to supply the needs for all operating equipment, providing more air capacity than is actually needed is extravagant.

CAPACITY FACTORS

All tools will not be operating at the same time.

Therefore Capacity (Diversity) factors are used in planning systems.

DIVERSITY OR CAPACITY FACTOR

- In most cases, all the equipment nominally used on a project will not be operating at any given time.
- An analysis of the job should be made to determine the probable maximum actual prior to designing the compressed-air system.

DIVERSITY OR CAPACITY FACTOR

- For example, if 10 jackhammers are nominally drilling, normally no more 5 or 6 will be consuming air at any given time.
- The others will be out of use temporarily for changes in bits or drill steel or moving to new locations.

DIVERSITY OR CAPACITY FACTOR

- The actual amount of air demand should be based on 5 or 6 drills instead of 10.
- The same condition applies to other pneumatic tools.
- The diversity or capacity factor is the ratio of the actual load to the maximum mathematical load that will exist if all tools are operating at the same time.

DIVERSITY OR CAPACITY FACTOR

- For example, if a jackhammer required 90 cfm of air, 10 hammers would require a total of 90 X 10 = 900 cfm of air if they all operated at the same time.
- However, with only 5 hammers operating at the same time, the demand for air would be 450 cfm.
- The diversity factor would be 450/900 = 0.5.

AIR REQUIRED BY PNEUMATIC EQUIPMENT AND TOOLS

- The approximate quantities of compressed air required by pneumatic equipment and tools are given in Table 5 (Table 11-8, Text).
- The quantities are based on continuous operation at a pressure of 90 psi gauge.

AIR REQUIRED BY PNEUMATIC EQUIPMENT AND TOOLS

Table 5a. Quantities of Compressed air Required by Pneumatic Equipment

Quantities of compressed air required by pneumatic equipment and tools†

Equipment or tools	Capacity or size: Weight (lb)	Capacity or size: Depth of hole (ft)	Air consumption (cfm)
Jackhammers	10	0–2	15–25
	15	0–2	20–35
	25	2–8	30–50
	35	8–12	55–75
	45	12–16	80–100
	55	16–24	90–110
	75	8–24	150–175
Paving breakers	35	—	30–35
	60	—	40–45
	80	—	50–50

†Air pressure at 90 psi guage.

Table 5b. (Table 11.8 Text) Quantities of Compressed air Required by Pneumatic Equipment

Equipment or tools	Capacity or size	Air consumption (cfm)
Chipping hammers	Light	15–25
	Heavy	25–30
Clay diggers	Light, 20 lb	20–25
	Medium, 25 lb	25–30
	Heavy, 35 lb	30–35
Concrete vibrators	$2\frac{1}{2}$-in.-tube diameter	20–30
	3-in.-tube diameter	40–50
	4-in.-tube diameter	45–55
	5-in.-tube diameter	75–85
Drills or borers	1-in. diameter	35–40
	2-in. diameter	50–75
	4-in. diameter	50–75
Hoist	Single-drum, 2,000-lb pull	200–220
	Double-drum, 2,400-lb pull	250–260
Impact wrenches	$\frac{5}{8}$-in. bolt	15–20
	$\frac{3}{4}$-in. bolt	30–40
	$1\frac{1}{4}$-in. bolt	60–70
	$1\frac{1}{2}$-in. bolt	70–80
	$1\frac{3}{4}$-in. bolt	80–90
Saws:		
Circular	12-in. blade	40–60
Chain	18–30-in. blade	85–95
	36-in. blade	135–150
	48-in. blade	150–160
Reciprocating	20-in.	45–50
Spray guns	Light duty	2–3
	Medium duty	8–15
	Heavy duty	14–30
Sump pump	Single-stage, 10–40-ft head	80-90
	Single-stage, 100–150-ft head	150–170
	Two-stage, 100–150-ft head	160–180
Trampers, earth	35 lb	30–35
	60 lb	40–45
	80 lb	50–60
Wagon drills—drifters	3-in. piston	150–175
	$3\frac{1}{2}$-in. piston	180–210
	4-in. piston	225–275

†Air pressure at 90 psi gauge.

EFFECTS OF ALTITUDE ON THE CONSUMPTION OF AIR BY ROCK DRILLS

- The capacity of air compressor is the volume of free air that enters the compressor during a stated time, usually expressed in cfm.
- Because of the lower atmospheric pressure at higher altitude due to decrease of air density, the quantity of air supplied by a compressor at a given gauge pressure will be less than at sea level.

EFFECTS OF ALTITUDE ON THE CONSUMPTION OF AIR BY ROCK DRILLS

- Therefore, it necessary to provide more compressor capacity at higher altitudes to assure adequate supply of air at the specified pressure to rock drills.
- The following table (Table 6 or Table 11-9 Text) provides representative factors to be applied to specific compressor capacities to determine the required capacities at different altitude.

EFFECTS OF ALTITUDE ON THE CONSUMPTION OF AIR BY ROCK DRILLS

Table 6. Factors to be Used in Determining the Capacities of Compressed air Required by Rock Drills at Different Altitudes

Altitude (ft)	Number of drills: 1	2	3	4	5	6	7	8	9	10
	Factor									
0	1.0	1.8	2.7	3.4	4.1	4.8	5.4	6.0	6.5	7.1
1,000	1.0	1.9	2.8	3.5	4.2	4.9	5.6	6.2	6.7	7.3
2,000	1.1	1.9	2.9	3.6	4.4	5.1	5.8	6.4	7.0	7.6
3,000	1.1	2.0	3.0	3.7	4.5	5.3	5.9	6.6	7.2	7.8
4,000	1.1	2.1	3.1	3.9	4.7	5.5	6.1	6.8	7.4	8.1
5,000	1.2	2.1	3.2	4.0	4.8	5.6	6.3	7.0	7.6	8.3
6,000	1.2	2.2	3.2	4.1	4.9	5.8	6.5	7.2	7.8	8.5
7,000	1.2	2.2	3.3	4.2	5.0	5.9	6.6	7.4	8.0	8.7
8,000	1.3	2.3	3.4	4.3	5.2	6.1	6.8	7.6	8.2	9.0
9,000	1.3	2.3	3.5	4.4	5.3	6.2	7.0	7.7	8.4	9.2
10,000	1.3	2.4	3.6	4.5	5.4	6.3	7.1	7.9	8.6	9.4
12,000	1.4	2.5	3.7	4.6	5.6	6.6	7.4	8.2	8.9	9.7
15,000	1.4	2.6	3.9	4.7	5.9	6.9	7.7	8.6	9.3	10.2

Source: Compressed Air and Gas Institute.

Example 11

A single drill requires a capacity of 600 cfm of air at sea level. What would be the required capacities at altitudes of 5,000 ft and 15,000 ft?

Using Table 6 (Table 11-9, Text):

For an altitude of 5,000 ft:

Required Capacity = 600 X 1.2 = 720 cfm

For an altitude of 15,000 ft:

Required Capacity = 600 X 1.4 = 840 cfm

THE COST OF COMPRESSED AIR

- The Department of Energy (DOE) has determined that air compressors are one of the largest users of electricity in industry. Although at one time the DOE considered electric motors as the largest user of electricity, savings through improved electric motor efficiency are dwarfed by those available through improving the compressed air system design and operation

THE COST OF COMPRESSED AIR

- Energy savings through improved design and operation of the air system can range from 20-50%. Most facilities consider compressed air a utility on par with electricity, gas, and water. Unlike other utilities, few people know their cost per CFM.

THE COST OF COMPRESSED AIR

- The cost of compressed air may be determined at the compressor or at the point of use
- The former will include the cost of compressing plus transmitting, including line losses.

THE COST OF COMPRESSED AIR

- The cost of compressing should include the total cost of the compressor (both ownership and operation costs).
- The cost is usually based on 1,000 cu ft of free air

THE COST OF COMPRESSED AIR

- What are your costs per CFM?

Assumptions:

Motor Service Factor = 110%

Power Factor = 0.9

A typical compressor produces 4 CFM per 1 HP

1 HP = 110% x 0.746 KW/0.9= 0.912 KW

Therefore,1 CFM = 0.228 kW

At 0.06 $/kW/hr : 1 CFM = $0.0137/hr

Therefore, 10 CFM over 8000 hr will cost: 10 x 8000 x .0137 = $1096.

Example 12

Determine the cost of compressing 1,000 ft^3 of free air to a gauge pressure of 100 psi by using a 600-cfm, two-stage portable compressor driven by a 180-hp diesel engine. Assume that the following information will apply:

Annual ownership cost = $19,686

Based on a 5-year life at 1,400 hr per year

Fuel consumption per hr, 0.04 X 180 = 7.2 gal

Lubricating oil consumed per hr, 0.125 gal

Example 12 (continued)

Hourly Costs:

Fixed cost: 19,686 ÷ 1,400	=	\$14.06
Fuel: 7.2 X 1.00	=	7.2
Lubricating oil: 0.125 X 3.20	=	0.4
Operator:	=	8.0
Total cost per hour	=	\$29.66

Volume of compressed per 50 min hr:

= 50X600 = 30,000 ft³

$$\text{Cost per } 1{,}000 \text{ ft}^3 = \$29.66 \div \frac{30{,}000}{1{,}000} = \$0.99$$

THE COST OF AIR LEAKS

- The loss of air through leakage in a transmission line can be large and costly
- Leakage results from:
  - ✓poor pipe connections
  - ✓loose valve stems
  - ✓deteriorating hose
  - ✓loose hose connections

THE COST OF AIR LEAKS

- If the cost of such leaks were more fully known, most of them would be eliminated.
- The rate of leakage through an opening of known size can be determined by the formula for the flow of air through an orifice.

THE COST OF AIR LEAKS

- In a typical plant, air leaks account for 20% of the total air usage!

8000 hr per year operation

Electrical costs = 0.06 $/kwhr

Line pressure = 100 psi

Plant Demand (cfm) » 400 cfm

Air leaks (cfm) » 20% » 80 cfm

Total Compressor Demand » 480 cfm

THE COST OF AIR LEAKS

400 cfm x 8000 hrs X .0137/hr	=	**$43,840**
80 cfm x 8000 hrs X .0137/hr	=	**$ 8,768**
TOTAL	=	**$52,608**

COMPRESSOR SELECTION

1. Tools or equipment to be used.
2. Air (cfm) requirement of each.
3. Pressure (gpsi) requirement of each
4. Piping and hose lengths

COMPRESSOR SELECTION

5. Capacity factor.
6. Theoretical compressor size.
7. Economical compressor available, that exceeds theoretical requirement and provides flexibility.