CHAPTER C16
COMPRESSED GASES AND VACUUM SYSTEMS FOR LABORATORIES

Michael Frankel, CIPE
Utility Systems Consultants, Somerset, New Jersey

GENERAL

This chapter will describe piping for vacuum, compressed air, and specialty compressed gas systems typically found in general, teaching, chemical, pharmaceutical, biological, and physics laboratories.

Compressed gases used in laboratories are characterized by low delivery pressure, low to intermittently high volume, and high purity requirements of the gas and of the piping distribution system. The usual working pressure is in the range of 50 to 55 psig (345 to 380 kPa). The primary source of pure gases is from cylinders, since it is extremely rare that the quantity of pure gases used for laboratory and research purposes would justify large bulk storage.

Principal uses of vacuum are drying, filtering, fluid transfer, and evacuating air from apparatus. The usual working pressure of vacuum systems is in the range of 15 to 20 in Hg vacuum (50 to 35 kPa abs). In some cases, there is a local need for ''high'' vacuum in the range of 24.0 to 29.6 in Hg vacuum (20 to 0.1 kPa abs), which is usually produced with a separate vacuum pump.

CODES AND STANDARDS

There are no building codes directly regulating the installation of these systems. The building codes impacting the installation of various laboratory vacuum and gas systems are concerned with safety and health of operating personnel and building occupants, and requirements concerning fire and structural consequences of accidents. Standards—which are generally consensus standards published by interested organizations—are concerned with the purity of a gas for specific uses and standard dimensions of pipe, fittings, and connectors. There are no mandated code sizing requirements.

Compressed Gas Association (CGA)

Minimum purity requirements for various gases are addressed in CGA publications called *Commodity Standards,* which also contain material, pressure, and dimensional standards for pipe connections to terminals.

National Fire Protection Association (NFPA)

The NFPA has various standards for the storage of flammable gases in tanks and cylinders both inside buildings and on the site.

Compressed gas systems for laboratories within a facility are often required to conform to NFPA99, Standard for Health Care Facilities, even though this standard does not apply to laboratories outside of health care facilities.

Environmental Protection Agency (EPA)

There are EPA health hazard classifications, fire hazard classifications, and a sudden release-of-pressure hazard classification. All of these ratings are available from a *material safety and data sheet* (MSDS). There are gases that fall under a classification of *Reactive Hazard,* which requires separation of gases that react with one another. There are also EPA *Threshold Limit* values for the concentration of any particular gas in air for breathing purposes.

For gases not covered by NFPA and CGA standards, accepted engineering practice is used to adequately locate the tanks, piping, and other system components.

COMPRESSED GAS FUNDAMENTALS

Fundamentals for compressed gases are given in Chap. C15 of this handbook.

VACUUM FUNDAMENTALS

The performance of any vacuum system is based on three factors: (1) flow rate, (2) initial vacuum pressure at the source, and (3) the minimum acceptable vacuum level required at the farthest point of the system. The minimum level of vacuum requires that all pressure lost in the system be taken into consideration, including pressure lost in vacuum source devices, the pressure lost from the friction of fluid flow through piping, and the pressure lost through the resistance of valves and fittings to the flow of fluids.

For vacuum systems to function, air is the transporting medium, and the negative vacuum pressure provides the energy for transportation. These two essential factors operate in inverse proportion—as the airflow increases, the vacuum pressure decreases. The system must be designed to produce specific vacuum pressure and airflow levels that have been determined, often by experience and experimentation, to be most effective in performing the task required in the laboratory.

Vacuum Definition

Vacuum is defined as an air pressure less than atmospheric. The vacuum level (or pressure) is the difference in pressure between that in the evacuated system and the atmospheric pressure.

While the definition of vacuum is straightforward, measuring a vacuum level is not. The method and units of measurement depends on different reference points.

Units of Measurement and Reference Points

Units of Measurement. Flow rates in Inch Pound (IP) units are most commonly measured in cubic feet per minute (cfm). When referring to standard conditions the prefix "s" is used, meaning standard cubic feet per minute (scfm). For System International (SI), or metric units, liters per second (l/s) is the most commonly used value. When referring to standard conditions the prefix "n" is used, meaning normal liters per second (nl/s).

Vacuum is used by having air at atmospheric pressure enter a piping system that has a lower pressure than atmospheric. Gas at standard atmospheric pressure will then expand to fill the piping system. The expanded air in the vacuum piping system is called *actual cubic feet per minute* or *actual liters per second* (acfm or al/s). Acfm or al/s is greater than scfm or ml/s.

In order to compute vacuum pressure and changes in volume, conversion to negative gauge pressure in pounds per square inch (psig), absolute pressure pounds per square inch (psia) or kilopascals (kPa) will be required. Other units commonly used are inches of mercury (in Hg), millibar (mbar), microns (μ) and torr.

Standard Reference Points. The two basic reference points for measuring vacuum are *standard atmospheric pressure* and a *perfect vacuum*. When the point of reference is from standard atmospheric pressure to a specified vacuum pressure it is called *gauge pressure* and is recorded as a minus pressure reading. It is general practice that gauge pressure is the intended unit of measurement when no specific reference is used. If the reference pressure level is measured from a perfect vacuum, the term used is *absolute pressure*.

On the dials of most pressure gauges, atmospheric pressure is assigned the value of zero. Vacuum measurements will then have a value of less than zero. *Negative gauge pressure* is the difference between the system vacuum pressure and atmospheric pressure. *Absolute pressure* is the positive pressure above a perfect vacuum.

These units originate from the use of a barometer. The basic barometer is an evacuated vertical tube with its top end closed and the open bottom placed in an container of mercury open to the atmosphere. The pressure or "weight" exerted by the atmosphere on the open container forces the mercury up into the tube. For standard conditions at sea level, this pressure will support a column of mercury 29.92 in (759.92 mm) high. In pressure units, this becomes 14.69 psi and 101.4 kPa. For practical purposes and ease of calculations in the United States, 29.92 is commonly increased to read 30.00 in (760 mm).

Local barometric pressure, which is variable, is the prevailing pressure at any specific location. This should not be confused with *standard atmospheric pressure,* always a constant, which is mean barometric pressure at sea level.

TABLE C16.1 Basic Vacuum Pressure Measurements

Units			KiloPascals absolute
Negative gauge pressure, psig	Absolute pressure, psia	Inches of mercury,	
0	14.7	0	101.4
Atmospheric pressure at sea level			
− 1.0	13.7	2.04	94.8
− 2.0	12.7	4.07	87.5
− 4.0	10.7	8.14	74.9
− 6.0	8.7	12.20	59.5
− 8.0	6.7	16.30	46.2
−10.0	4.7	20.40	32.5
−12.0	2.7	24.40	17.5
−14.0	0.7	28.50	10.0
−14.6	0.1	29.70	1.0
−14.7	0	29.92	0
Perfect vacuum (zero reference pressure)			

Vacuum pressures in IP units generally used in the United States fall into three general categories:

1. Rough (or course) vacuum, up to 28 in Hg
2. Medium (or fine) vacuum, up to 1 micron
3. Ultrahigh vacuum, greater than one micron

In other parts of the world, the categories are often classified as follows in SI units:

1. Rough vacuum, 760 to 1 torr
2. Medium vacuum, greater than 1 to 10^{-3} torr
3. High vacuum, 10^{-4} to 10^{-7} torr
4. Ultrahigh vacuum, greater than 10^{-7}

Conversions. Tables C16.1 and Table C16.2 presents different basic IP and SI vacuum pressure conversion units commonly used for calculations and by equipment manufacturers. Table C16.3 gives numerical conversion multipliers for converting torr into various other vacuum pressure units.

Conversion of SCFM to ACFM (NL/S TO AL/S)

For the most accurate method of converting scfm to acfm in IP units with a given pressure of in Hg (kPa) and temperature in F° (°C), use the following formula:

$$\text{acfm} = \text{scfm} \quad \frac{30.00}{P} \times \frac{T + 460}{520} \qquad \text{(C16.1)}$$

where P = Actual pressure, in Hg, for the scfm being converted.
T = Actual temperature in °F for the scfm being converted.

TABLE C16.2 Basic Vacuum Pressure Conversion

KPa ABS	In Hg	In Hg abs.	psia	In Hg	KPa ABS	In Hg abs.	psia
101.4	0	29.92	14.70	17	43.71	12.92	6.3477
97.9	1	28.92	14.2086	18	40.33	11.92	5.8564
94.5	2	27.92	13.7173	19	36.95	10.92	5.3651
91.5	3	26.92	13.2260	20	33.57	9.92	4.8738
87.77	4	25.92	12.7347	21	30.20	8.92	4.3824
84.39	5	24.92	12.2434	22	26.82	7.92	3.8911
81.01	6	23.92	11.7521	23	23.27	6.92	3.3998
77.63	7	22.92	11.2608	24	19.99	5.92	2.9085
74.19	8	21.92	10.7695	25	16.61	4.92	2.4172
70.81	9	20.92	10.2782	26	13.23	3.92	1.9259
67.43	10	19.92	9.7869	27	9.85	2.92	1.4346
64.05	11	18.92	9.2955	28	6.48	1.92	0.9433
60.67	12	17.92	8.8042	29	3.10	0.92	0.4520
57.29	13	16.92	8.3129	29.22	2.36	0.80	0.3930
53.91	14	15.92	7.8216	29.52	1.35	0.70	0.3439
50.54	15	14.92	7.3303	29.72	0.61	0.60	0.2947
47.09	16	13.92	6.8390	29.92	0	0	0

For practical purposes, a numerical method for solving Eq. C16.1 can be used if the temperature is assumed to be 60°F (18°C). At that temperature, the second part of the equation becomes unity. Table C16.4 gives numerical values for $29.92/P$. To find acfm, multiply the scfm by the value found opposite the calculated result of $29.92/P$. Table C16.5 is a direct ratio for converting scfm to acfm knowing only the pressure.

To convert acfm into nl/s, multiply acfm by 0.472.

General Vacuum Criteria

Adjusting Vacuum Pump Rating for Altitude. The vacuum pressure rating of a pump at altitude is a lower percentage of its rating at sea level. For each 1,000 ft

TABLE C16.3 Conversions From Torr to Various Vacuum Pressure Units

0.0010 torr	=	1 micron (μmHg)
0.0075 torr	=	1 pascal (Pa)
0.7501 torr	=	1 millibar (mbar)
1.000 torr	=	1 mm mercury (mmHg)
1.868 torr	=	1 in. water at 4°C (in. H_2O)
25.40 torr	=	1 in. mercury (in. Hg)
51.71 torr	=	1 lb/in.^{2} (psi)
735.6 torr	=	1 tech. atmosphere (at)
750.1 torr	=	1 bar
760.0 torr	=	1 standard atmosphere (atm)

TABLE C16.4 Expanded Air Ratio (29.92/P) as a Function of Pressure, P, in Hg

P	29.92/P	P	29.92/P	P	29.92/P	P	29.92/P
29.92	1.00	19.92	1.5020	9.92	3.0161	0.80	37.40
28.92	1.0345	18.92	1.5813	8.92	3.3542	0.70	42.0742
27.92	1.0716	17.92	1.6696	7.92	3.7777	0.60	49.8667
26.92	1.1114	16.92	1.7683	6.92	4.3236	0.50	59.84
25.92	1.1543	15.92	1.8793	5.92	5.0540	0.40	74.80
24.92	1.2006	14.92	2.0053	4.92	6.0813	0.30	99.7334
23.92	1.2508	13.92	2.1494	3.92	7.6326	0.20	149.60
22.92	1.3054	12.92	2.3157	2.92	10.2465	0.10	299.20
21.92	1.3649	11.92	2.5100	1.92	15.5833	—	—
20.92	1.4302	10.92	2.7399	0.92	32.5217	—	—

1 in Hg = 3.38 KPa

(304 m) increase in altitude, atmospheric pressure drops by approximately 1 in Hg (3.38 kPa). Refer to Table C16.6 for actual barometric pressure at various altitudes.

As an example, for the city of Denver at 5,000 ft (1520m), the local atmospheric pressure is 24.90 in hg (84.1 kPa). Dividing 24.90 (local barometric pressure into 30 gives a percentage of 83.3 percent. If a pump is rated at 25 in Hg (84.25 kPa) at sea level, 83.3 percent of 24.90 (84.1 kPa) equals 20.8 in Hg (70 kPa) at 5,000 feet (304 m). Therefore, a pump rated by the manufacturer at 25 in Hg at sea level would be rated at 20.8 in Hg at Denver.

At altitudes above sea level, there is a reduction in the flow rate delivered because of the difference in local pressure compared to standard pressure. The flow rate must be increased to compensate for this difference. Table C16.7 presents a multiplication factor to accomplish this. To find the adjusted scfm (nl/s), multiply the actual scfm (nl/s) by the factor found opposite the altitude where the project is located.

TABLE C16.5 Direct Ratio for Converting scfm to acfm (nl/s to al/s)

inHg	KPa abs.	Factor	inHg	KPa abs.	Factor
1			16	47.09	2.15
2	94.5	1.1	17	43.71	2.3
3	91.15	1.1	18	40.33	2.5
4	87.77	1.15	19	36.95	2.73
5	84.39	1.2	20	33.57	3
6	81.01	1.25	21	30.20	3.33
7	77.63	1.3	22	26.82	3.75
8	74.19	1.35	23	23.37	4.28
9	70.81	1.4	24	19.99	5
10	67.43	1.5	25	16.61	6
11	67.05	1.55	26	13.23	7.5
12	60.67	1.62	27	9.85	10
13	57.29	1.75	28	6.48	15
14	53.91	1.85	29	3.10	30
15	50.54	2.0	29.92	0	60

TABLE C16.6 Barometric Pressure in Inches of Mercury (kPa) Corresponding to Altitude

Altitude (sea level equals zero)			Barometric Pressure	
M	FT.		Inches of mercury	KPa
−3040	−10000		31.00	104.5
−152	−500		30.50	102.8
0	0	sea level	29.92	100.8
152	+500		29.39	99.0
304	1000		28.87	97.3
456	1500		28.33	95.5
608	2000		27.82	93.7
760	2500		27.31	92.0
912	3000		26.81	90.3
1064	3500		26.32	88.7
1216	4000		25.85	87.1
1368	4500		25.36	85.5
1520	5000		24.90	83.9
1672	5500		24.43	81.9
1824	6000		23.98	80.8
1976	6500		23.53	79.3
2128	7000		23.10	77.8
2280	7500		22.65	76.3
2432	8000		22.22	74.9
2584	8500		21.80	73.4
2736	9000		21.39	72.1
2888	9500		20.98	70.7
3040	10000		20.58	69.3

TABLE C16.7 Factor for Flow Rate Reduction Due to Altitude

Meters	Altitude (feet)	Factor used for required scfm
	0	1.0
152	500	1.02
304	1,000	1.04
456	1,500	1.06
608	2,000	1.08
760	2,500	1.10
912	3,000	1.12
1064	3,500	1.14
1216	4,000	1.16
1520	5,000	1.20
1824	6,000	1.25
2128	7,000	1.30
2432	8,000	1.35
2736	9,000	1.40
3040	10,000	1.45
3344	11,000	1.51

1 CFM = 0.472 l/s

Time for Pump to Reach Rated Vacuum. The time a given pump will take to reach its rated vacuum pressure depends on the volume of the system in cubic feet and the capacity of the pump in scfm at the vacuum rated pressure. But simply dividing the system volume by the capacity of the pump will not produce an accurate answer. This is because the vacuum pump does not pump the same quantity of air at different pressures. There is actually a logarithmic relationship that can be approximated by the following formula:

$$T = \frac{V}{Q} \quad N \tag{C16.2}$$

where T = time in minutes
V = Volume of system in cubic feet (cubic meters)
Q = Flow capacity of pump in scfm (l/s)
N = Natural log constant
for vacuum up to 15 in Hg − N = 1
for vacuum up to 22.5 in Hg − N = 2
for vacuum up to 26 in Hg − N = 3
for vacuum up to 28 in Hg − N = 4

In order to obtain the most accurate answer, obtain pump curves from the manufacturer and substitute the scfm capacity for the pump at each 5 in Hg (17 kPa) increment. Add them together to find the total time. The selection of the value for N depends on the highest level of system vacuum pressure and is constant throughout the several calculations.

Adjusting Pressure Drop for Different Vacuum Pressures. The chart for friction loss in a vacuum pipe presented later in this section is based on 15 in Hg. For a given scfm and pipe size, the pressure loss at any vacuum pressure other than the 15 in Hg the medical/surgical vacuum sizing chart was developed for can be found by dividing the pressure drop in the chart by the ratio found from the following formula:

$$\frac{30 - \text{new vacuum pressure}}{15} \tag{C16.3}$$

Simplified Method of Calculating Velocity. Use the following formula to find the velocity of a gas stream under a vacuum in IP units:

$$V = C \times Q \tag{C16.4}$$

where V = Velocity in fpm
C = Constant based on pipe size (refer to Table C16.8)
Q = Flow rate in acfm, based on an absolute vacuum pressure

As an example, calculate the velocity of 100 scfm through a NPS 2 (DN50) pipe with a pressure of 20 in Hg:

1. First, find the equivalent absolute pressure of 20 in Hg. Using Table C16.2, read 9.92 in Hg abs.

2. Convert 100 scfm to acfm at a pressure of 9.92 in Hg abs by using Table C16.5 Opposite 10 in Hg read 1.5.

$$100 \times 1.5 = 150 \text{ acfm}$$

TABLE C16.8 Constant for Finding Mean Air Velocity

Schedule 40			Schedule 40		
NPS	DN	C	NPS	DN	C
⅜	(12)	740.9	2½	(65)	30.12
½	(15)	481.9	3	(80)	19.53
¾	(20)	270.0	3½	(90)	14.7
1	(25)	168.0	4	(100)	11.32
1¼	(32)	96.15	5	(125)	7.27
1½	(40)	71.43	6	(150)	5.0
2	(50)	42.92	8	(200)	2.95

3. Refer to Table C16.8 to obtain *C*. This table has been developed from flow characteristics of air in schedule 40 steel pipe. Opposite NPS 3 (DN80) pipe read 19.53. When using copper pipe, increase velocity by 5 percent.

4. $V = 150 \times 19.53$
V (steel pipe) = 2930 fps.
V (copper pipe) 2,930 × 1.05 = 3076 fps

Vacuum Work Forces. The total force of the vacuum system acting on a load is based on the vacuum pressure and the surface area on which the vacuum is acting. This is expressed in the following formula:

$$F = P \times A \tag{C16.5}$$

Where F = Force, lbs (Newtons)
P = Vacuum pressure, in psia (kPa abs)
A = Area, in square inches (mm)

Since this formula is theoretical, it is common practice to use a safety factor in the range of 3 to 5 times the calculated force to compensate for the quality of the air seal and other factors such as configuration of the load and outside forces such as acceleration.

CLASSIFICATION OF SPECIALTY COMPRESSED GASES

Compressed gases are classified into the following general categories:

1. *Oxidizers*. These gases are nonflammable but support combustion. No oil or grease is permitted to be used with any device that uses these gases. Combustibles shall not be stored near these gases. Oxygen is an example.

2. *Inert gases*. These are gases that do not react with other materials. If released into a confined space, they will reduce the oxygen level to a point that asphyxiation could occur. Storerooms should be provided with oxygen monitors and be well-ventilated.

3. *Flammable gases*. These are gases that, when combined with air or oxidisers, will form a mixture that will burn or possibly explode if ignited. Flammable mixtures have a range of concentration below which they are too lean to be ignited, and above which the mixture is too rich to burn. The most often used figure is the *lower explosive level* (LEL), which is the minimum percent, by volume, that will form a flammable mixture at normal temperatures and pressures. The high level setting for alarms is generally one half of the LEL, with warnings issued at one forth of the LEL. The area where flammable gases are stored must be well ventilated, use approved electrical devices suitable for explosive atmospheres, and restrict all ignition sources. Flammability limits and specific gravity for common gases are given in Table C16.9.

TABLE C16.9 Flammability Limits and Specific Gravity for Common Gases

Gas	Specific gravity	Flammability in air, % volume	
		Low	High
Acetylene	0.906	25	100
Air	1.00	—	—
Ammonia	0.560	15	28
Argon	1.38	—	—
Arsine	2.69	5.1	78
Butane	0.600	1.8	8.4
Carbon dioxide	1.52	—	—
Carbon monoxide	0.967	12.5	74
Chlorine	2.49	—	—
Cyclopropane	0.720	2.4	10.4
Ethane	1.05	3.0	12.4
Ethylene	0.570	2.7	36
Ethyl chloride	2.22	3.8	15.4
Fluorine	1.31	—	—
Helium	0.138	—	—
Hydrogen	0.069	4.0	75
Hydrogen sulfide	1.18	4	44
Isobutane	2.01	1.8	9.6
Isopentane	2.48		
Krypton	2.89	—	—
Methane	0.415	5.0	15
Methyl chloride	1.74	10.7	17.4
Natural gas	0.600		
Neon	0.674	—	—
Nitrogen	0.966	—	—
Nitrous oxide	1.53	—	—
Oxygen	1.10	—	—
Phosgene	1.39	—	—
Propane	1.580	2.1	9.5
Silane	1.11	1.5	98
Sulphur dioxide	2.26	—	—
Xenon	4.53	—	—

TABLE C16.10 Gas Categories

Gas	Compressed gas	Liquefied gas	Oxidant	Inert	Corrosive	Toxic
Acetylene	(1)					
Air	X		X			
Allene		X				
Ammonia		X			X	X
Argon		X		X		
Arsine		X				(3)
Butane		X				
Carbon dioxide		X		X	(2)	
Carbon monoxide	X					X
Chlorine		X	X		(2)	(3)
Cyanogen		X				(3)
Cyclopropane		X				
Deuterium	X					
Ethane		X				
Ethyl chloride		X				
Ethylene	X					
Ethylene oxide		X				(4)
Fluorine	X		X			(3)
Helium	X			X		
Hydrogen	X					
Hydrogen bromide		X			(2)	(3)
Hydrogen chloride		X			(2)	(3)
Hydrogen fluoride		X			X	(3)
Hydrogen sulfide		X				(3)
Isobutane		X				
Neon	X			X		
Nitric oxide	X		X		(2)	(3)
Nitrogen	X			X		
Nitrogen dioxide		X	X		(2)	(3)
Oxygen	X		X			
Phosgene		X				(3)
Phosphine		X				(3)
Propane		X				
Propylene		X				(3)
Silane	X					(3)
Sulfur dioxide		X			(2)	(3)
Vinyl bromide		X				X
Vinyl chloride		X				(5)
Xenon	X			X		

(1) Dissolved in solvent under pressure. Gas may be unstable and explosive above 15 psig.
(2) Corrosive in presence of moisture.
(3) Toxic—it is recommended that the user be thoroughly familiar with the toxicity and other properties of this gas.
(4) Cancer suspect agent.
(5) Recognized human carcinogen.

4. *Corrosive gases*. These are gases that will attack the surface of rubber, metals and other substances and also damage human tissue upon contact.
5. *Toxic and poisonous gases*. These are gases that will harm human tissue by contact or inhalation. Protective clothing and equipment must be used.
6. *Pyrophoric gases*. These are gases which spontaneously ignite upon contact with air under normal conditions.
7. *Cryogenic*. Gases that are stored as a cold liquid under pressure and vaporized in order to be used as a gas.

The categories of various gases are given in Table C16.10.

GRADES OF SPECIALTY GASES

There are many grades of pure and mixed gases available. Since there is no industry-recognized standard grade designation for purity, each supplier has their own individual designations. It is possible for the same gas used for different purposes to have a different designation for the same purity. The end-user must be consulted for the maximum acceptable level of the various impurities based on the proposed type of instrument used and the analytical work to be performed. The supplier must then be informed of these requirements in order to determine the grade of gas they will supply that meets or exceeds the allowable presence of various impurities.

The following list, although not complete, covers some manufacturers' designations for different grades of gases available. There are additional grades for specific instruments, such as ''Hall'' grades of gases.

1. Research grade
2. Carrier grade
3. Zero gas
4. Ultra zero
5. Ultra high purity plus
6. Ultra high purity
7. Purified
8. USP

STORAGE AND GENERATION OF GASES

Cylinder Storage

Where the anticipated gas usage does not require the installation of a cryogenic bulk supply, it is more convenient and less expensive to have gases compressed and stored in cylinders. Cylinders are available in various pressure ratings, with nomenclature different between the several manufacturers. The high-pressure cylinder has gas stored at pressures ranging to 6000 psig (410 bar), with the most common pressures between 2000 and 2500 psig (140 and 175 bar). The low-pressure cylinder has gas pressures up to about 480 psig (34 bar). The most common size high-pressure cylinder contains about 350 cubic feet (10.5 cubic meters) of gas, with the exact amount depending on the actual cylinder volume and specific gas stored.

Cylinders do not have a standard designation from one supplier to another. If the actual cylinder capacity of any compressed gas must be determined in terms of the actual free air stored at a higher pressure, it can be found by using the following formula for IP units:

$$VG = \frac{CP}{14.7} \times CV \tag{C16.6}$$

where VG = volume of gas stored at the higher pressure, in cubic feet
CP = actual cylinder pressure, psig, obtained from the supplier
CV = actual cylinder volume, in cubic feet.

Cylinders are available in many sizes and pressure ratings. Refer to manufacturers' catalogs for exact dimensions. They are available in four general categories. The first is *plain carbon steel.* The second is called the *ultraclean* tank, which is made of a slightly different alloy steel and in addition, has been completely cleaned, prepared, and dried to reduce contaminants in the cylinder. The third classification is *aluminum* tanks. The tank interior has been specially prepared, and the walls treated to maintain stability and reduce particulates. Aluminum is used for cleanliness and for gases that will react with steel. In many cases, the exterior is also treated in order to be more easily kept clean, such as required for clean room installations. The fourth type of cylinder is made of *stainless steel,* which is often used for ultrapure gases.

The following are general recommendations for the installation and storage of cylinders:

1. The room or area in which cylinders are placed shall have adequate ventilation, be free of combustible material, and be separated from sources of ignition. Generally, a one- or two-hour fire rated wall is required around flammable gas storage. Check with local authorities for requirements.

2. Consideration should be given for additional space required for storage of empty cylinders.

3. Enough room should be allowed for the easy changing of cylinders. They are brought in on a hand truck or cart, and room should be allowed for maneuvering.

4. Gas cylinders shall be individually secured against falling by means of floor stands, wall brackets, or bench brackets. These brackets use straps to attach the cylinder to the bracket. Also available are floor racks and stands that can be provided for the installation and support of cylinders that can't be located near walls.

5. When toxic or reactive gasses are used, the cylinders should be placed in a gas cabinet. The basic purpose of the cabinet is to isolate the cylinder(s), contain gases in the event of a leak, and direct those gases away from the immediate vicinity of the cylinder and cylinder storage area to a point outside the building where they are diluted with the outside air. The cabinet could also contain panel-mounted manifolds, purging equipment, and other devices to allow some degree of control of operating parameters. Typical cabinet construction is 11-gauge painted steel or thicker to give a one-half-hour fire rating. They could also be provided with vertical and horizontal adjustable cylinder brackets. The following options are available for a cylinder cabinet:

Automatic shutoff of the gas in the event of a catastrophic failure.

Purging of gas lines after cylinder changes.

Mechanical cabinet exhaust. A typical system is designed for 13 air changes per minute with the access window open.

A sprinkler head for flammable gases. A typical head should be rated at 135°F (55°C), with a minimum water pressure of 25 psig (172.5 kPa).

For toxic and reactive gases, a small operable access window could be provided to operate valves without having to open the main door and compromising the exhaust system. A fixed access window is acceptable for inert gases.

When more than one cylinder is used to supply a system, the multiple arrangement is referred to as a *bank* of cylinders. The bank of cylinders actually supplying the facility is called the *primary* bank. A second bank that will be used when the primary bank is exhausted is called the *secondary* bank. If there is another bank that is used only for emergency purposes, those cylinders are called the *reserve* bank.

Cylinders in a bank are connected together by a *header* and controlled by a *manifold assembly*. The arrangement of the cylinders is chosen by the space available for the installation and the relative ease desired for the changing of cylinders. The space typically required for various cylinder arrangements is shown in Fig. C16.1. Any additional space between banks of cylinders required for specialized devices such as manifold controls, purging devices, filters, and purifiers should be added to the cylinder-bank dimensions. These additional dimensions shall be obtained from the equipment manufacturer.

Specialty Gas Generators

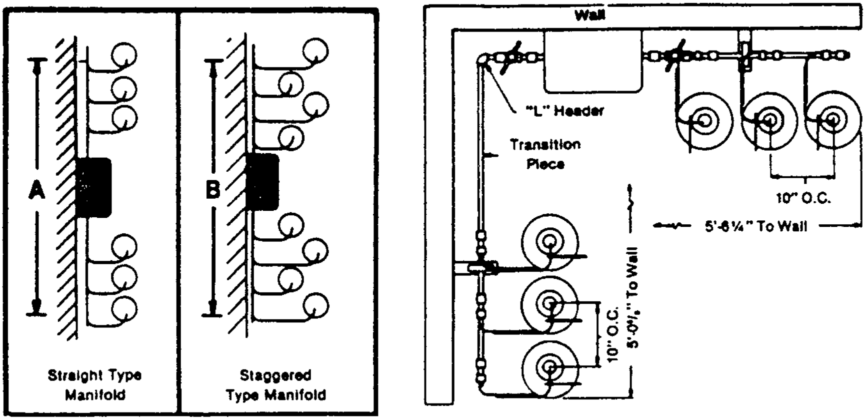
In some cases, it is more desirable for a small facility to generate its own high-purity specialty gases rather than have them supplied in cylinders. There are a limited number of gases for which anticipated volume allows this choice in laboratory or research facilities. Among them are nitrogen, hydrogen, helium, and compressed air. The generating units have their own filters and purifiers that can create gases of ultrahigh purity. In particular, the use of these units for generation of hydrogen eliminates flammable cylinders in the laboratory or separate storage areas, and keeps the actual amount of gas stored below that capable of exploding.

Depending upon the type of generator and the type of gas generated (except compressed air), pressures are available to about 60 psig (414 kPa), and flow rates of up to 300 cubic centimeters per min are common. Compressed air generators are available that will deliver up to 20 scfm (9.5 l/s) and 100 psig (690 kPa).

This type of unit is ideally suited for analytical purposes in widely separated areas of use, where the installation of cylinders is inconvenient and the changing of cylinders may cause disruption of continuing work. The operating cost is low, but the initial cost is high. However, the payback period is short compared to using cylinders.

Depending on the type of gas generated, many of these units take their air supply from the room they are installed in, and others require a connection to a separate compressed air supply.

ARRANGEMENTS



DIMENSIONAL DATA, FT[a]

CYLINDERS PER BANK	DIMENSION "A"	DIMENSION "B"
2 Banks Of 2 Each	5'-0"	4'-6"
2 Banks Of 3 Each	6'-8"	5'-8"
2 Banks Of 4 Each	8'-4"	6'-10"
2 Banks Of 5 Each	10'-0"	8'-0"
2 Banks Of 6 Each	11'-8"	9'-2"
2 Banks Of 7 Each	13'-4"	10'-4"
2 Banks Of 8 Each	15'-0"	11'-6"
2 Banks Of 9 Each	16'-8"	12'-8"
2 Banks Of 10 Each	18'-4"	13'-10"
2 Banks Of 12 Each	21'-8"	16'-2"

[a] 1 FT = 0.304 m

FIGURE C16.1 Typical arrangements dimensions for cylinder installations.

GAS DISTRIBUTION SYSTEM COMPONENTS

Manifolds

A *manifold* is an assembly used to connect multiple cylinders or banks of cylinders together. This assembly usually contains regulators, changeover devices, shut-off valves, gauges, and so forth. Manifold components shall be compatible with any specific gas being used. A *header* (a pipe undiminished in size) manifold with individual shut-off valves and connecting pigtail is used to physically connect several cylinders to a changeover manifold. The most-often-used materials for the header manifold, interconnecting pipe, and fittings are brass and stainless steel, with stain-

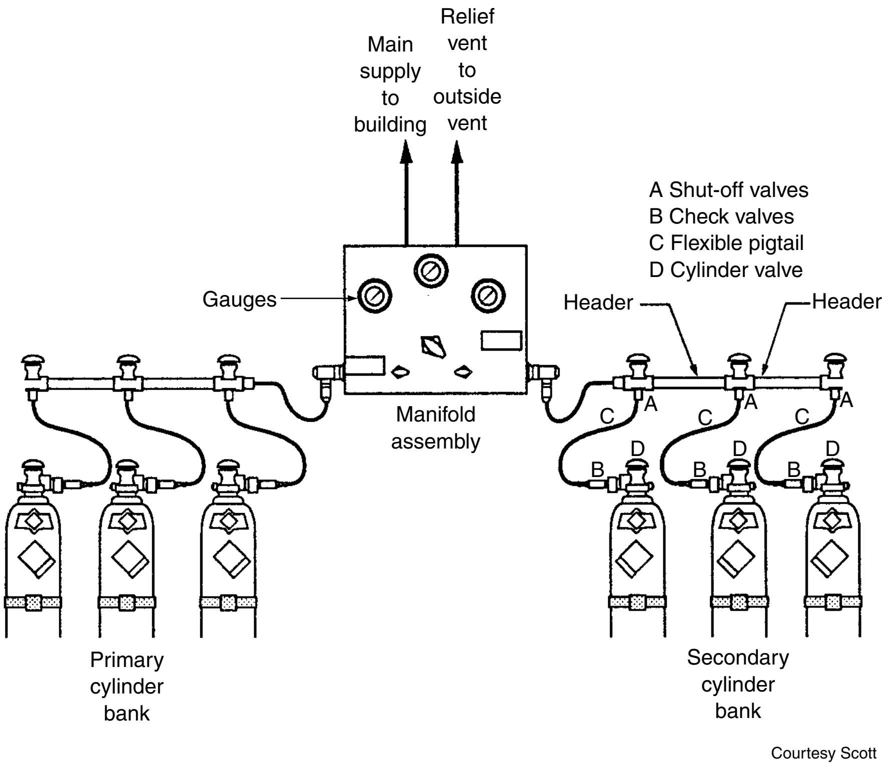


FIGURE C16.2 Typical manifold assembly.

less steel flexible connections connecting the cylinders to the header. Changeover can be accomplished by manual, semiautomatic, or fully automatic methods.

A typical manifold assembly is illustrated in Fig. C16.2. Exact manifold dimensions vary and should be obtained from the manufacturer. A typical single-cylinder installation detail is shown in Fig. C16.3.

Regulators

A regulator is a device used to reduce a variable high inlet pressure to a constant lower outlet pressure. There are two broad categories of regulators: *cylinder regulators* and *line regulators*. Cylinder pressure regulators are used on high-pressure cylinders to reduce high-pressure gases, generally in the range of 2000 to 6000 psig (140 to 410 bar), to a lower pressure. Line regulators are used to reduce an intermediate pressure, generally in the range of 150 to 250 psig (1035 to 1725 kPa) to the working pressure of the distribution system. They are also used on cryogenic tanks to reduce the pressure of the vapor above the cold liquid. Depending on the purity of the gas, an integral inlet filter should be considered to keep particulates from entering the regulator.

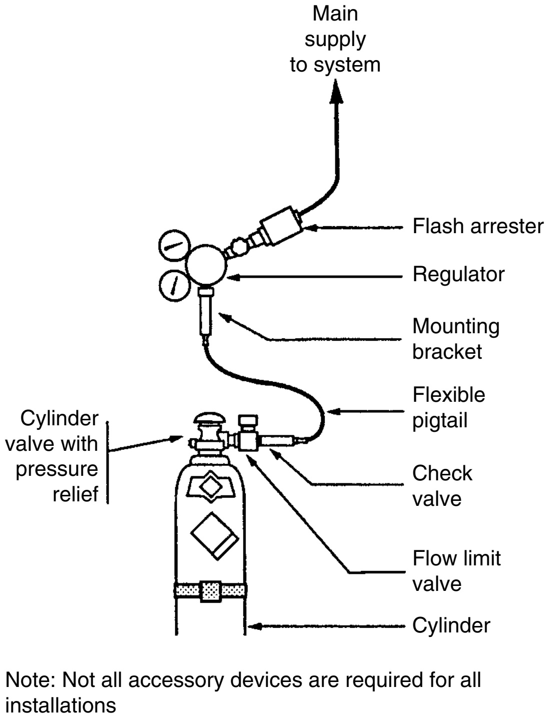


FIGURE C16.3 Typical single-cylinder installation.

The following are considerations used in the selection of a regulator for a specific purpose:

1. The regulator should have a positive gas vent.
2. The regulator must be rated for the highest possible working pressure.
3. The operating temperature must be compatible for the environment where the valve is located.
4. The valve body and internal materials should be selected for the specific purity of the desired gas. High-purity regulators shall have little dead space internally and diaphragm seals consistent with the required purity.
5. The pressure range of the gauges must be compatible with the pressures expected. As an ideal, the working pressure should be one-half the maximum outlet gauge reading.

Filters and Purifiers

Filters and purifiers are necessary to reduce or eliminate specific unwanted contaminants and particulates in the gas stream. The most common purifiers are those used to remove oxygen, water vapor, hydrocarbons, and particulates. They are also used to eliminate other unwanted trace elements. There are a number of materials used for filters:

1. To remove hydrogen, palladium filters are used.
2. Ceramic, fiberglass, sintered metal, and other adsorbent materials are used to remove oil, moisture, and other trace contaminants.
3. A molecular sieve is a synthetically produced crystalline metal powder that has been manufactured specifically for adsorption.
4. The 0.2 micron size filter to remove particulates is the most commonly used filter in laboratory service. This size absolute filter will also remove all living or dead organisms.
5. The housing has to be compatible with the gas being filtered and the pressure involved.
6. Pressure drop through the filter medium is a critical factor in the selection of the material used.
7. It is not possible to improve the purity of a gas with the use of purifiers. If a gas of a certain purity is required, a gas of that grade must be used from the outset.

The exact arrangement of purifier devices shall be obtained from the various manufacturers. Not all of the devices dicussed will be required for all installations.

Gauges

Gauges for pressures up to 10 psig (69 kPa) are usually the diaphragm-sensing-element type. For pressures over 10 psig (69 kPa), use the bourdon type. They should be cleaned for oxygen service and the materials must be compatible with the intended gas. Provide a small gas cock between the pipeline and the gauge to shut off the flow and allow the gauge to be replaced without having to shut down the system.

Relief Valves

Relief valves are used to protect a system from overpressure. A relief valve must be provided between the regulator and the first shutoff valve in the system, with the discharge independently piped outdoors, Multiple discharges from a single gas source, including the manifold and regulators, may be connected together but shall not be connected to the relief discharge from any other system. The discharge pipe should be a minimum size of NPS ¾ (DN 20). The relief valve shall be located at the first point in the system that could be subject to full cylinder pressure if the regulator should fail. There shall be no valve between the relief valve and the regulator. The relief valve set point should be set to 25 percent over working pressure. This is a safe figure because the system test pressure is 50 percent over working pressure. Typical relief vent piping is illustrated in Fig. C16.4.

Flow Limit Shutoff Valve

A flow limit shutoff valve automatically shuts off the flow from a cylinder if that flow rate exceeds a predetermined limit, usually about 10 times the highest expected

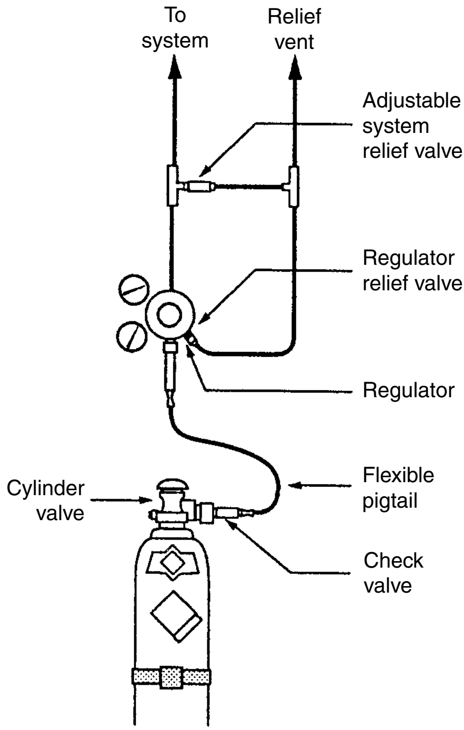


FIGURE C16.4 Typical relief vent arrangement.

flow rate. This valve must be manually reset after operation. A typical flow limit valve location is shown in Fig. C16.3.

Flash Arresters

Flash arresters are required when the gas being used is flammable, particularly hydrogen and acetylene. They are mounted in-line to prevent any flame from going back into the tank in the event that gas in the delivery piping system has ignited. It is standard procedure that a check valve be made an integral part of a flash arrester. A typical flash arrester location is shown in Fig. C16.3.

Manifold and Regulator Purge Devices

The replacement of cylinders introduces unwanted room air into the piping manifold assembly and the connecting cylinder pigtails. When maintaining high purity is necessary, purge valves are installed to run system gas through the contaminated parts of the system to replace all such air. The purge valve outlet should be vented outside the building. If the gas is suitable and low enough in volume, and the storage room is large enough and well ventilated, it could discharge into the room since the purge volume used is generally quite small. The regulator often requires special purging techniques recommended by the manufacturer.

Flow Measurement Devices

Flow rates are measured by two types of meters; *mechanical* or *electronic*. The mechanical type is called a *variable area type,* and uses a small ball as an indicator in a variable-area vertical tube.

The electronic meters are often called *mass flow* meters. They operate by using the difference in temperature that gas creates when flowing over a heated element.

Gas Warmers

On occasion, some gas in cylinders is withdrawn so fast that the temperature is lowered, causing the regulator to ice up because of the sudden change in temperature. To prevent this, an electrically heated gas warmer is available that is installed in-line, and which heats the gas leaving cylinder before it reaches the regulator. If a gas is subject to ice-up, a warmer should be considered if the flow rate exceeds 35 acfm (16.5 nl/s). The actual figure should be based on experience with the specific type of gas being used. Ask the supplier what their experience has been. Carbon dioxide is of particular concern.

Low-Temperature Cutoff

On occassion, the temperature of the delivered gas is a critical factor. If low temperature could harm instruments or interfere with procedures being conducted, a low-temperature cutoff should be installed with a solenoid valve to stop the flow of gas. If this happens often, a gas warmer might be required.

Alarms

Alarms are necessary for the user to be made aware of immediate or potential trouble as well as normal operation. They could be visible and/or audible. Usual alarms are *high system pressure, low system pressure, secondary bank in use, reserve in use,* and *reserve pressure low*. Low cylinder pressure is usually set at 500 to 600 psig (34.5 to 40.8 bar) for 2500 psig (170 bar) cylinders. In some installations, a normal light is also desirable. Other alarms could be provided that will indicate high-pressure loss at filters, low gas temperature, purifiers at limit of capacity, and flow limit valve operation. These alarms are usually installed in an alarm panel. The panel could be mounted in the room where the gases are stored, in a constantly occupied location such as a maintenance shop or receptionist area, or in the laboratory itself, depending on the availability and level of maintenance. Often multiple locations are desirable if continued supply of gas is critical.

Various in-line devices must be placed in the system for these alarms to function, such as a pressure switches, transducers, and auxiliary contacts to transmit the alarm signal to the alarm panel.

Toxic and Flammable Gas Monitors

If there is the possibility for toxic or flammable gas to accumulate in an enclosed area or room, a gas monitor shall be installed to activate if the percentage of gas rises above a predetermined limit considered harmful or dangerous. This should be 50 percent of either the lower flammability limit (LFL) or the concentration that may cause ill effects or breathing problems. The oxygen concentration of ambient air should never be allowed to fall below 19.5 percent. In addition, much lower levels should also be alarmed to indicate that a problem exists well before evacuation of an area is required. Refer to Table C16.9 for the flammability limits and specific gravity of some of the more common gases.

Gas Mixers

Gas mixers are used to accurately combine different gases in various proportions. The accuracy of the mixture, flow rates of the various gases, and the compatibility of the piping materials with the gases are considerations in the selection of the mixer.

DISTRIBUTION NETWORK

System Pressure

It is generally accepted practice to have an initial pressure of 50 to 55 psig (345 to 379.5 kPa) set by the line pressure regulator in the piping distribution system after all source devices. The lowest pressure available at the most remote outlet or use point is generally in a range of 40 to 45 psig (276 to 310.5 kPa). Generally accepted practice is to allow approximately 10 percent of initial pressure for friction loss in the entire piping system. This figure should be adjusted for specific conditions or special systems if necessary.

Pipe Material Selection

The piping material must be compatible with the specific gas, capable of delivering the desired gas purity for anticipated usage, and capable of being cleaned and/or sterilized often, if required. For compatibility of various piping materials for various gases, refer to the gas producer or the supplier of the gas.

The pipe most often used to maintain the highest purity is grade 304L or 316L stainless steel tubing conforming to ASTM A270. The interior should be electropolished to a minimum of 150 grit, and the exterior mill-finished in concealed spaces. In exposed locations and where the pipe exterior will be sterilized or cleaned, the pipe exterior should have a No. 4 finish in conformance with the American Iron and Steel Institute (AISI) publication "Finishes for Stainless Steel." The pipe is joined by orbital welding. It is recommended that tube to be welded have a minimum wall thickness of 0.065 in (1.65 mm) in order to be easily welded. Thinner walls could be used if recommended by the orbital welding equipment manufacturer. Stainless steel pipe is capable of withstanding repeated sterilization by steam and a variety of chemicals. When welding is not required, a tube wall thickness of 0.028

in (0.7 mm) is commonly used. The total installed cost of welded stainless steel is often less than that of cleaned copper tube in the smaller sizes.

In many laboratory applications, maintaining ultrahigh purity of a gas from storage tank to the outlet is not a requirement. For this type of service, ASTM B819 copper tube and fittings that have been cleaned for oxygen service and joined by brazing often have the least initial cost and are the material of choice. The following grades of copper pipe are used:

1. ASTM B88, Copper Water Tube. Standard water tube where high purity is not an important consideration.
2. ASTM B819, Copper Tube for Medical Gas Systems. Standard water tube cleaned for medical gas use.
3. ASTM B75, Seamless Copper Tube. Used for capillary tubing.
4. ASTM B280, Seamless Copper Tube for Air Conditioning and Refrigeration Field Service. Nonstandard size, cleaned for air-conditioning and refrigeration service. This is often referred to as ACR tubing.

Another pipe material often used for compatibility reasons is aluminum tubing, ASTM B210, Alloy 6061, T4 or T6 tempers. This tubing is most commonly joined using the patented flare joint.

Valves

The valves used in laboratory systems are not required to conform to any specific code. Compatability, pressure limits, cost, and suitability for their intended purpose are the only criteria used for the selection of the most appropriate valves. Check valves shall have a soft seat in order to prevent leakage during backflow conditions.

The most often used shutoff-type valves are ball valves. Three-piece ball valves are the most desired ones because the body can be separated from the end connections when being installed and serviced, and removed during installation to prevent burning of the seals. For control and modulating purposes, needle valves are used because of the precise level of control permitted. The materials of the valve and seals must be compatible with the gas used.

For specialty applications, there are diffusion-resistant valves, which reduce or prevent unwanted gases from entering the system through the packing. Where purity is a major consideration, packless and bellows-sealed diaphragm valves are available.

Swing-type check valves with soft seats are used to prevent the reverse flow of gas. A typical installation detail showing check valve location is shown in Figs. C16.3 and C16.4.

Joints

The most often used joints for copper tubing are brazed. No flux is permitted and only cast copper fittings conforming to ASTM B16.18 should be used, which require no flux. The interior of the joint shall be purged with an inert gas, such as argon or carbon dioxide, to eliminate generation of copper oxide and particlulates into the gas stream during the brazing process. For stainless steel pipe, orbital welding leaves the smoothest effectiveness interior.

Another type of joint, used mostly on small size pipe because of its cost effectiveness, is the patented flared joint. In addition, the flared joint is popular because it can be made up by unskilled workman using only a saw and some wrenches. When copper tubing is used with a flared joint, the pipe shall not have embossed identification stamped into the pipe because it causes leaks at the joint. There is no ASTM designation for the patented flare type joints, but they are acceptable for all applications as long as the allowable pressure ratings are not exceeded.

Maintaining Cleanliness and Purity During Construction

Copper fittings and various valve types specifically cleaned for medical service can be purchased from manufacturers and delivered to the job site capped and bagged to maintain cleanliness. If a fitting becomes dirty prior to being installed, it should be cleaned in accordance with NFPA99 requirements, Standard for Health Care Facilities, before being made part of the system. During construction, the greatest threat to cleanliness is dirt and dust entering the pipe during construction because it has not been capped to keep it out.

When brazing joints, the cleanliness of the copper piping system shall be maintained by not using flux and having the joint continuously purged with oil-free, dry nitrogen, thereby preventing the heat of the brazing process from generating copper oxide and depositing it on the inside of the joint. The flow of purge gas shall be continued until the joint is cool to the touch.

Another concern in maintaining high purity of the gas is *outgasing*. This is a phenomenon where a gas under pressure is absorbed into any porous material. This occurs primarily in elastomers used as gaskets or seals, and to some lesser extent into metallic and plastic pipe and tubing materials. When the pressure is reduced or eliminated, such as when changing cylinder banks or during maintenance, the absorbed gases are spontaneously given off, adding impurities into the gas piping system.

Pipe Sizing

Following is a recommended system sizing procedure:

1. Locate the gas storage area and lay out the cylinders, manifold, and so forth.
2. Lay out the piping system from the storage area to the farthest outlet or use point. Measure the actual distance along the run of pipe to the most remote terminal and then add 50 percent of the distance to the measured run for a fitting allowance. This is called the *equivalent run of pipe*.
3. Select all of the filters, purifiers, and so forth necessary for system purity in order to establish a combined allowable pressure drop through each of them and the assembly as a whole.
4. Establish the gas pressure required at the farthest outlet. This determines the initial system pressure after the cylinder regulator. Calculate the appropriate friction loss allowance for the system.
5. Divide the total run of pipe (in 100s of ft or 30 m) by the allowable friction loss to calculate the allowable friction loss in psig (kPa) per 100 ft (30 m) of pipe. This is to allow the use of the correct sizing chart. If other methods are used to find friction loss in the piping system, calculate the loss for that specific method.
6. Determine the total connected flow rate of gas for all parts of the system. For

general laboratory use, a figure of 1 scfm (0.5 nl/s) for each outlet is used. Calculate the scfm (nl/s) of gas through each branch, from the farthest outlet back to the source (or main). For specific equipment, use the flow rate recommended by the manufacturer.

7. Determine the diversity factor for the facility when sizing pipe in order to allow for the fact that not all outlets will be used at once. This will result in the actual, or weighed, flow rate. For specific specialty gas use, equipment, and areas, the diversity factor must be determined from the end-user.
8. With all the above information available, the pipe can now be sized by using the appropriate tables and figures. Starting from the most remote point on the branch, proceeding forward to the main, calculate the actual flow rate using the diversity factor at each design point where new connections to the piping is made.

TABLE C16.11 Laboratory Use Factors for Compressed Air

No. of outlets	% use factor
1–2	100
3–5	80
6–10	66
11–20	30
21–over	20

Discussion

1. The diversity (or simultaneous use) factor, which determines the maximum number of outlets in use at any one time, has a major influence in the sizing of the piping system. It has no exact method of being determined and is arrived at purely by judgment. Table C16.11 and Fig. C16.5 (calculated from Table

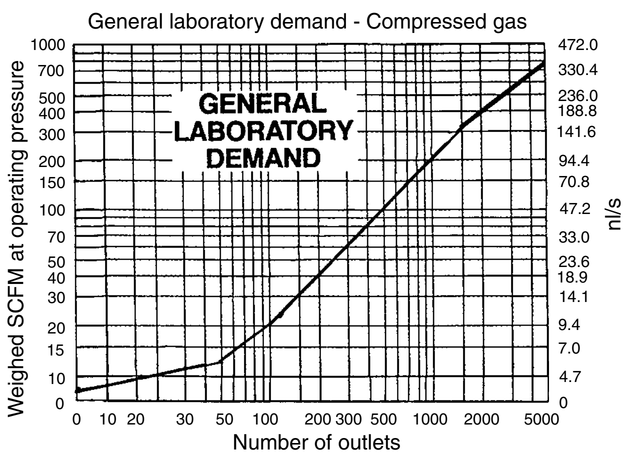


FIGURE C16.5 Direct-reading compressed gas flow rate for laboratories.

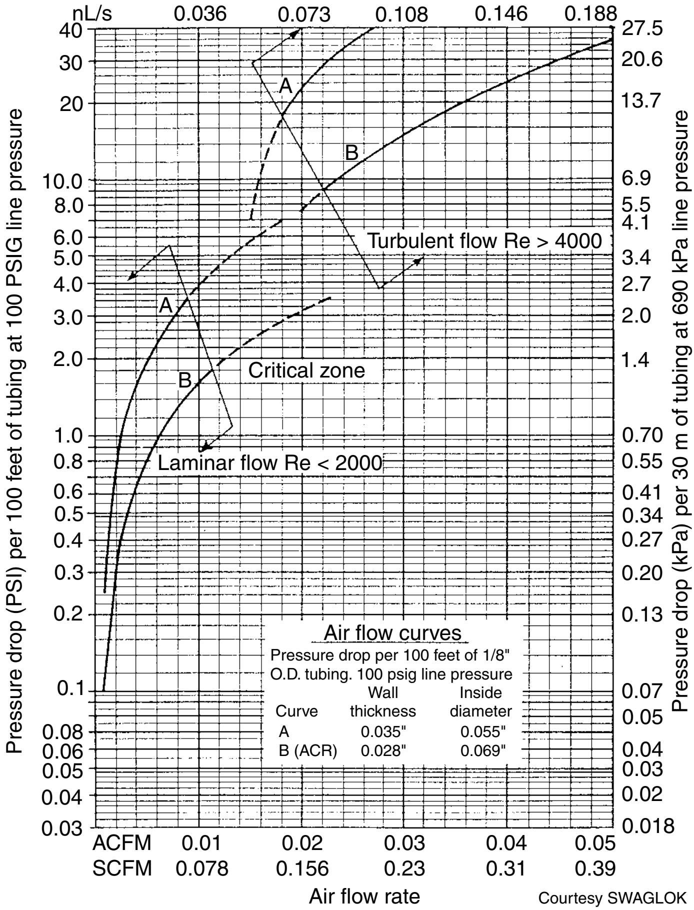


FIGURE C16.6 Compressed-air sizing chart. ⅛ in (3 mm) copper tubing 100 psig [700 kPa].

C16.11) have been developed for general laboratory use and are based on many years of experience.

2. A selection of charts and tables are presented for sizing compressed air pipe. Figures C16.6 and C16.7 are charts for small-sized capillary tubing often used to connect individual pieces of equipment to a branch pipe. Figure C16.6 is used to size ⅛ in (3 mm) tubing, and Fig. C16.7 is for ¼ in (6 mm) tubing. Table C16.12 is a sizing chart used for ½ in (13 mm) tubing and larger. Table C16.12 has been calculated using the Colebrook variation of the Darcy-Weisbach formula specifically for use with compressed air, type "L" copper pipe, and an initial pressure of 55 psig (380 kPa). Enter the table with the actual flow rate and the allowable friction loss. Find the flow rate in the table and then read across to find a friction loss figure that is equal to or less than the allowable friction loss. Read up the column up to find the size. In some cases, the diversity factor for

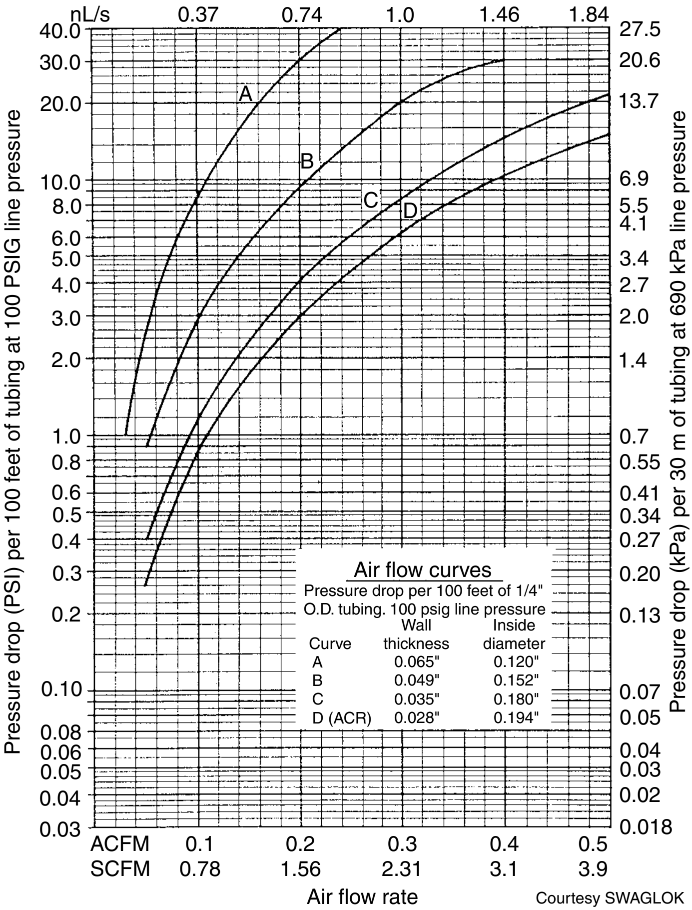


FIGURE C16.7 Compressed-air sizing chart. ¼ in [6mm] copper tube, 100 psig line pressure [700 kPa].

the next highest range of outlets may result in a smaller size pipe than the range previously calculated. If this occurs, do not reduce the size of the pipe—keep the larger size previously determined. In order to use this chart for other gases, pipe materials, and pressures, the following conversions will be necessary:

a. When any gas with a specific gravity other than air (1.00) is used, an adjustment to the scfm (nl/s) will be required. Equation C16.7 shall be used to calculate a factor that will convert scfm (nl/s) in Table C16.12 from compressed air to the equivalent of any other gas or combination of gases. Multiply the calculated factor by the compressed air flow rate to obtain the new flow rate for the gas under consideration.

$$f = \frac{1}{g} \qquad \text{(C16.7)}$$

TABLE C16.12 Pressure Drop (psi) per 100 ft in 55 psi (380 KPa) Copper Tubing Type L

SCFM	N L/S	ACFM	IN. ½	¾	1	1¼	1½	2	2½	3	4
5	2.36	1.1	0.15	0.04	0.01						
10	4.72	2.2	0.51	0.13	0.04	0.01					
15	7.0	3.3	1.04	0.27	0.09	0.02	0.01				
20	9.5	4.3		0.45	0.14	0.04	0.02				
25	11.8	5.4		0.67	0.21	0.06	0.03	0.01			
30	14.1	6.5		0.93	0.29	0.08	0.04	0.01			
35	16.5	7.6			0.39	0.10	0.05	0.02	0.01		
40	18.9	8.7			0.49	0.13	0.06	0.02	0.01		
45	21.2	9.8			0.60	0.16	0.08	0.02	0.01		
50	23.6	10.9			0.73	0.20	0.09	0.03	0.01		
60	28.3	13.0			1.01	0.27	0.13	0.04	0.02	0.01	
70	33.0	15.2				0.36	0.17	0.05	0.02	0.01	
80	37.7	17.4				0.45	0.22	0.07	0.03	0.01	
90	42.5	19.5				0.56	0.27	0.08	0.03	0.01	
100	47.2	21.7				0.68	0.32	0.10	0.04	0.02	0.00
110	52	23.9				0.81	0.38	0.12	0.05	0.02	0.01
120	57	26.0				0.94	0.45	0.14	0.06	0.02	0.01
130	61	28.2				1.09	0.52	0.16	0.07	0.02	0.01
140	66	30.4					0.59	0.18	0.08	0.03	0.01
150	71	32.6					0.67	0.20	0.09	0.03	0.01
175	83	38.0					0.89	0.27	0.11	0.04	0.01
200	55	43.4					1.13	0.34	0.14	0.05	0.01
225	106	48.8						0.42	0.18	0.06	0.02
250	118	54.3						0.51	0.22	0.08	0.02
275	130	59.7						0.60	0.26	0.09	0.02
300	142	65.1						0.71	0.30	0.11	0.03
325	153	70.5						0.82	0.35	0.12	0.03
350	165	76.0						0.94	0.40	0.14	0.04
375	177	81.4						1.06	0.45	0.16	0.04
400	189	86.8							0.51	0.18	0.05
450	212	97.7							0.63	0.22	0.06
500	236	108.5							0.76	0.27	0.07
550	260	119.4							0.90	0.32	0.09
600	283	130.2							1.06	0.37	0.10
650	307	141.1								0.43	0.12
700	330	151.9								0.49	0.13
750	354	162.8								0.56	0.15
800	378	173.6								0.63	0.17
850	401	184.5								0.70	0.19
900	425	195.3								0.78	0.21
950	448	206.2									0.23
1000	472	217.0									0.25
1100	519	238.7									0.30
1200	566	260.4									0.35
1300	613	282.1									0.41
1400	661	303.8									0.47
1500	708	325.5									0.53

Notes
a. Values in table are for flows not exceding 4000 fpm 20 m/s vel.
b. 1 PSI = 6.89 KPa
c. Refer to App. E3M for metric tubing sizes or ASTM B88.

To calculate the specific gravity of any gas, divide the molecular weight of the gas in question by 29, which is the composite molecular weight of air.

b. For flow of any compressed gas in steel pipe, use Table C16.12 and decrease flow by 5 percent.

c. For pressures other than 55 psig, use the following formula for IP units:

$$PDa = \frac{P1 + 14.7}{P2 + 14.7} \times PDr \qquad \text{(C16.8)}$$

d. For IP units, when there are temperatures other than 60°F, use the following formula to calculate a factor that, when multiplied by the flow rate, will give the revised flow rate at the new temperature:

$$f = \frac{460 + t}{520} \qquad \text{(C16.9)}$$

where $P1$ = 55 (referenced table pressure, in psig)
$P2$ = actual service pressure, in psig
PDr = reference pressure drop found in chart for flow rate in table, psi/100 ft.
PDa = adjusted pressure drop for actual pressure, psi/100 ft.
g = specific gravity of gas
t = temperature in °F for conditions under consideration.
f = factor

Another method for sizing mains and branches with average use and where the piping network is closer to the source (where the pressure is higher and therefore is less critical than the most remote outlets), is to use a prepared chart based on the number of outlets with the actual friction loss through the pipe not considered. The flow rate and diversity of use is taken into consideration in the sizing chart and assumes that the system pressure is adequate. This method provides a sufficient degree of accuracy and speed of calculation. Table C16.13 is such a chart for various compressed gas systems found in laboratories.

Pressure Tests

Bulk storage tanks and dewers are required to be rated in accordance with ASME Section VIII, Pressure Vessels, and therefore are tested to this Code at the factory before shipment. They are not tested after installation. For the same reason, cylinders are not tested. The code requires that only the distribution system, from the cylinder valve to the outlets, be subject to pressure tests.

Testing is done by pressurizing the system to the test pressure with an inert, oil-free and dry gas, or with the system gas to be used. Nitrogen is often used because of its low cost and availability. For systems supplied from cylinders with a working pressure up to 200 psig (1380 kPa), the entire piping system, including the cylinder manifold, is tested to 300 psig (2070 kPa) for one hour, with no leakage permitted. If a higher working pressure than 200 psig (1380 kPa) is required, the system is tested at 150 percent of the system design pressure. This pressure testing should be done in increments of 100 psig (690 kPa), starting with 100 psig (690 kPa). This is done to avoid damage due to a catastrophic failure. Leaks are repaired after each increment.

TABLE C16.13 Laboratory Branch Sizing Table

No. of conn.	Air	Gas	Vac.	Oxy.	Nit.
1	½″	½″	½″	½″	½″
2	½″	½″	½″	½″	½″
3	½″	½″	¾″	½″	½″
4	½″	½″	¾″	½″	½″
5	½″	¾″	¾″	½″	½″
6	½″	¾″	1″	½″	½″
7	½″	¾″	1″	½″	½″
8	½″	¾″	1″	½″	½″
9	½″	¾″	1″	½″	½″
10	½″	¾″	1″	½″	½″
11–20	¾″	1″	1¼″	¾″	¾″
21 & over	1″	1¼″	1½″	1″ (21–30) 1¼ (30–50) 1½″–over 50	1″

After final testing, it is recommended that the piping be left pressurized at system working pressure.

System Pressure Relief Valve (PRV) Settings

In order to prevent damage to equipment and personnel resulting from overpressure, it is required that a *pressure relief valve* (PRV) be provided for the system. For systems using cylinders, the PRV should be placed at the source. If there is special equipment with a lower pressure threshold, a separate PRV shall be placed on the branch line only to that piece of equipment. For a 50 psig (345 kPa) system the setting should be 75 psig (518 kPa).

Flushing, Testing, and Purging the Distribution System

After the system is completely installed and before it is placed in service, the piping system must first be flushed (blown out) to remove any loose debris, then tested, and finally purged with the intended system gas to assure purity.

An accepted flushing method is to flow two to five times the design volume for the branch or main through each respective part of the system. This is done by connecting the flushing gas under pressure to the piping system, and then opening and closing all outlets and valves starting from the closest and working to the most remote.

Tests of the gas at the farthest outlet shall be taken to ensure that the gas is the desired purity. This test could be done either by the end-user if they have the necessary instruments, or by a testing service. To test for particulates use a minimum flow rate of 27 scfm (100 l/m) discharging into a clean white cloth and observe for any particles on the cloth.

Finally, the system must be capable of providing the desired purity when actually placed in operation. Since flushing and testing may leave the piping system filled with inert or other gas, these must be removed, or purged. This is accomplished by allowing the system gas to flow through all parts of the piping system, opening all of the valves, and testing the gas purity at various points of the system until the desired purity level is reached. A purging arrangement for the piping distribution system is illustrated in Fig. C16.8.

For high-purity gases, a laboratory specializing in testing for the purity level required should be used unless the facility is capable of performing the test.

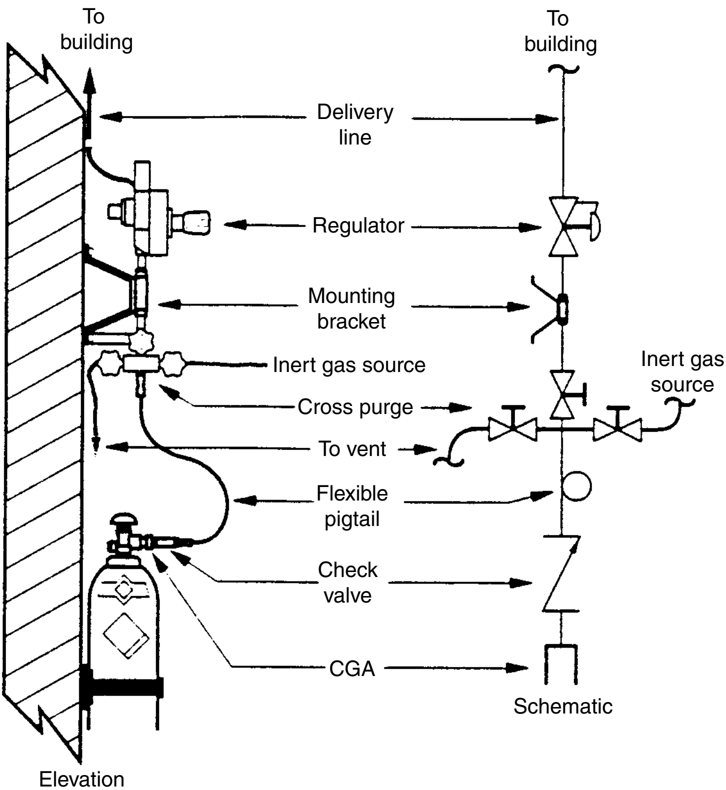


FIGURE C16.8 Typical cylinder valve purging arrangement.

LABORATORY VACUUM SYSTEM DESCRIPTION

The vacuum in the laboratory system is provided by single or multiple vacuum pumps drawing air from vacuum inlets or equipment connected to the pump(s) by a piping network. Vacuum pumps are generally connected to a receiver from which air is withdrawn to produce the vacuum. The piping distribution system is also connected to the receiver. The receiver provides a reserve capacity to allow the periodic shut-down of the pumps and also serves as a tank to intercept and drain off liquids that accidentally find their way into the piping network.

LABORATORY VACUUM SYSTEM CODES AND STANDARDS

Laboratories conducting biological work where airborne pathogens could be released are required to follow one of the appropriate biological level criteria (BL-1, BL-2, BL-3, and BL-4) established by the National Institutes of Health (NIH). For most biological installations it is recommended that check valves be installed in each vacuum branch line to every room or area to prevent any cross discharge. In addition, the vacuum pump exhaust shall be provided with duplex 0.02μ absolute filters to eliminate the release of any pathogenic particulates.

Air exhausted from the system must be discharged to the atmosphere by means of an exhaust piping system. The pipe size shall be large enough so as not to restrict operation of the vacuum pump.

LABORATORY VACUUM SYSTEM COMPONENTS

Vacuum Pumps

The vacuum source usually consists of two or more pumps which operate as system demand requires, a receiver used to provide a vacuum reservoir and to separate liquids from the vacuum airstream, the interconnecting piping, and alarms. A duplex or triplex pump arrangement is usually selected if the system is critical to the operation of the laboratory. In some smaller installations where the vacuum system is not critical, it may be acceptable to have a single vacuum pump. The pumps selected should be oil-free.

The two most often used pump types are *liquid ring* and *rotary vane.* Rotary vane pumps are usually the smallest in physical size, have low starting and running torque, and are relatively vibration-free. The typical rotary vane pump is capable of achieving a higher vacuum pressure than the typical liquid ring pump. Both pumps are available oil-free. Oil-free vacuum pumps using no seal fluids are also available.

Seal Liquids. For liquid ring pumps, a circulating liquid, commonly water or oil, is used in the pump casing and is an integral part of the pump operation. This liquid is commonly known as *seal liquid* and should not be confused with shaft or any other sealing method.

Vacuum Pressure Gauges

There are four commonly used types of gauges: (1) Bourdon, (2) diaphragm, (3) capacitance, and (4) strain.

The *Bourdon gauge* is mechanical and measures the difference between relative pressure between the system and local barometric pressure. This the most widely used type of gauge. The *diaphragm gauge* measures the pressure difference by sensing the deflection of a thin metal diaphragm or capsular element. An *electronic (capacitance) gauge* uses a change in a variable-capacitance sensor to detect changes in pressure. A *strain gauge* uses the deflection of a diaphragm to produce a change in electrical resistance.

Ancillary Equipment. A coalescing or oil mist filter should be used on the exhaust of any pump that uses oil to prevent the discharge of that oil into the atmosphere. It can also be used to recover solvents from the discharge airstream.

An automatic air bleed valve will lower the vacuum pressure in a piping system.

Receivers

Receivers are installed primarily to prevent excessive cycling of the pumps, by providing a vacuum reserve. Since the majority of vacuum pumps are furnished as a prepiped assembly that includes the pump, receiver, interconnecting pipe, valves, and so forth, the manufacturer selects the size of the receiver based on previous acceptable performance with the size of the pump selected. The receiver shall be rated in accordance with ASME Section VIII, Pressure Vessels.

Since there is a possibility that fluid may enter the receiver, a suitable draining method shall be provided. This can be done either manually or automatically.

The manual method requires a valved drain line from the bottom of the receiver. In order to drain the receiver, it must be isolated and brought to atmospheric pressure. This procedure removes the receiver from service for a limited time. The drain valve is then opened and the liquid discharged into a floor drain. A sight glass shall be provided to observe the level of accumulated liquid in the receiver.

Automatic methods are rarely used because of the higher initial cost, but their use will permit uninterrupted use of the receiver. This requires the installation of a separate, smaller drain tank with a level switch inside. The drain tank is installed adjacent to and lower than the receiver. A drain line, installed at the bottom of the receiver and controlled by a solenoid valve, shall connect the receiver to the drain tank. The drain tank shall be capable of being isolated from the receiver by means of a solenoid valve. The drain line also shall have a solenoid valve. All valves shall be set to operate in the correct sequence when the level of liquid in the drain tank reaches its set point and sends a signal to each solenoid valve. The effluent is then discharged to a floor drain.

Separators

When vacuum pumps use a constant flow of seal water, a separator is often necessary to remove water from the exhaust airstream. The effluent is commonly discharged to a floor drain. The equipment manufacturer will provide this information

If the facility will constantly introduce liquids into the normal vacuum piping, a separator shall be installed between the last outlet before connecting to the receiver. The receiver is not intended to be a separator, although a small amount of liquid is expected.

Interconnecting Piping

The interconnecting piping at the source between the vacuum pumps and devices of the central supply system shall be corrosion-resistant pipe such as copper (ASTM B88), brass (ASTM B43), stainless steel (ASTM A270), and galvanized steel pipe (ASTM A53).

PIPING DISTRIBUTION NETWORK

Pipe Material and Joints

Piping for the distribution system shall be a corrosion-resistant material such as copper tube, ASTM 88, Type K or L, stainless steel ASTM A270, or galvanized steel pipe, usually schedule 40 ASTM A53. Copper tube above ground is generally type ''L'' hard temper. When installed underground, type ''K'' soft temper should be used. Although cost has a major influence on the selection of the piping material, the most commonly used is copper tube type ''L'', ASTM B88 up to 4 in (100 mm) in size, with soldered joints. Pipe NPS 5 (DN 125) and larger and vacuum pump exhaust piping are usually ASTM A53, schedule 40 galvanized steel pipe with threaded joints. Fittings shall be long-turn drainage pattern so as not to impede the flow of fluids in the pipe.

Valves

The most often used control valves are *ball* and *butterfly* valves. They are selected on their suitability for vacuum service and the possibility of resisting any specific gases introduced into the piping system. Check valves shall be of the soft-seat type.

PIPING DISTRIBUTION NETWORK SIZING CRITERIA

Number of Inlets

There are no code or other mandated requirements for specific locations of laboratory vacuum inlets. The number of inlets is determined by the user, based on a program of requirements for all rooms, areas, and equipment used in the facility. Inlets for laboratory stations, fume hoods, and so forth shall be appropriate for the intended use, based on requirements of the end user.

Flow Rate. The basic flow rate from each laboratory inlet shall be 1.0 scfm (0.47 nl/s). This is an arbitrary number based on experience. This flow rate is used in conjunction with the diversity factor.

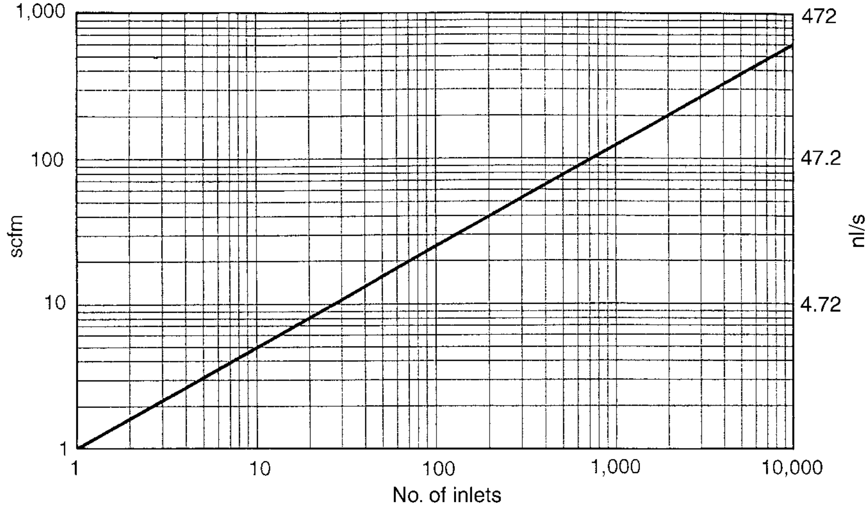


FIGURE C16.9 Direct-reading vacuum flow rate for laboratories.

Diversity Factor. The diversity factor established for general laboratories is based on experience. Refer to Fig. C16.9 for a direct-reading chart to determine the adjusted general laboratory vacuum flow rate using the number of connected inlets.

For the design of classrooms, the diversity factor for one and two classrooms on one branch is 100 percent. For more than two classrooms, use a diversity factor double for that found in Fig. C16.9. Since these flow rates and diversity factors are arbitrary, they must be used with judgment and modified if necessary to adjust for special conditions and owner requirements. Always consult the user for definitive information regarding the maximum probable simultaneous usage.

Allowable Friction Loss. A generally accepted figure used to size a piping system is to allow a total friction loss of 3 in (75 mm) Hg for the entire distribution system after the source assembly piping is taken into consideration. For smaller systems, use a figure of 1 in (25 mm) Hg for each 100 ft (30 m) of pipe.

Recommended Velocity. A generally accepted maximum velocity is 5,000 feet per minute (fpm) or 25 meters per second (m/s). If noise is a problem, use 4,000 fpm (20 m/s).

PIPING DISTRIBUTION NETWORK SIZING

Establishing System Design Criteria

There are two figures needed to size the piping network. The first is the *allowable pressure drop* (which includes friction loss in the piping system, exhaust pipe losses, and losses through in-line devices such as filters, traps, and so forth) for the entire network, in inches of Hg per 100 ft of pipe (kPa/30 m). This is found by dividing the allowable pressure loss into the total equivalent length of pipe, in 100s of ft (30 m). The second is the *adjusted scfm* (nl/s) (connected scfm or nl/s, multiplied by a diversity factor) at the design point of the piping network.

To find the allowable friction loss for the network, first find the equivalent length of pipe. This is the actual measured run of pipe, in feet, added to a distance, also in feet, that allows for the additional friction loss through fittings, valves, and so forth. The most commonly used method of finding the equivalent run is to add 50 percent to the actual run. If the measured run is 300 ft (90 m), add 150 ft (45 m) to obtain the equivalent run, which is 450 ft (135 m). The most accurate method is to use Fig. C13.1 (''Plumbing Systems'') giving the equivalent straight run for each size of fitting and valve.

Friction loss allowance is a matter of judgment. For most systems, and for ease of calculations, it is generally accepted practice to allow a total friction loss of 3 to 4 in Hg (10.1 to 13.5 kPa) for the piping system, using any remaining pressure loss available as an allowance to compensate for in-line devices and vacuum pump source interconnecting piping.

TABLE C16.14 Vacuum Air Sizing Table

Max. velocity: 5000 fpm (25 m/s)

Pipe material: ''L'' copper tubing (ASTM B88)
Pressure drop: Hg/100 ft

		Tube size							
nl/s	scfm	NPS ¾	1	1¼	1½	2	2½	3	4
0.472	1	.08							
0.944	2	.27	.08						
1.41	3	.53	.15						
1.9	4	.88	.25	.09					
2.36	5	1.3	.36	.14					
2.83	6	1.8	.50	.19					
3.30	7		.65	.24	.11				
3.77	8		.82	.30	.13				
4.25	9		1.01	.37	.16				
4.72	10		1.22	.45	.20				
7.0	15			.91	.40	.11			
9.5	20				.66	.18			
11.8	25					.26	.09		
14.1	30					.36	.13		
16.5	35					.47	.17		
18.9	40						.21	.09	
21.2	45						.26	.11	
23.6	50						.32	.14	
28.3	60						.44	.19	
33.0	70							.25	.06
37.7	80							.31	.08
42.5	90								.10
47.2	100								.12
59.0	125								.18
71.0	150								.25

a. 1 in Hg = 3.37 KPa
b. Refer to App. E3M for metric sizes of tubing (ASTM B88).

Using the previous equivalent run of 450 ft (137.2m), and a total friction loss of 3 in (75 mm) Hg, the friction loss for the piping system is calculated by dividing 4.5 (450 ft divided by 100 because the chart uses loss/100 ft) by 3 (in Hg). This gives a figure of 0.66 in Hg per 100 foot of pipe as the allowable friction loss for the piping network.

Pipe-Sizing Procedure

The piping distribution network is sized starting from the most remote point and working forward to the source.

Starting at the most remote inlet on each branch, add together the connected load from all inlets, starting with the last inlet and continuing toward the source. Every new connection is a design point. At each design point, calculate the total connected load in scfm (nl/s). Then enter Fig. C16.9 with the total connected load and read the adjusted scfm (nl/s). This is continued separately at each design point to connection with the submain and finally the main.

TABLE C16.15 Vacuum Air Sizing Table

Max. velocity: 5000 FPM (25 m/s)

Pipe material: Sched. 40 steel ASTM A53
Pressure drop: Hg/100 ft[a]

		Pipe diameter							
nl/s	scfm	DN 20 NPS ¾	25 1	32 1¼	40 1½	50 2	65 2½	80 3	100 4
0.472	1	.07							
0.944	2	.22	.07						
1.41	3	.45	.14						
1.9	4	.75	.24	.06					
2.36	5	1.1	.35	.09					
2.83	6	1.56	.48	.13					
3.30	7		.63	.17	.08				
3.77	8		.81	.21	.10				
4.25	9		1.00	.26	.13				
4.72	10		1.21	.32	.15				
7.0	15			.66	.31	.09			
9.5	20				.52	.15			
11.8	25				.78	.23	.10		
14.1	30					.32	.14		
16.5	35					.42	.18		
18.9	40					.54	.23	.08	
21.2	45						.28	.10	
23.6	50						.34	.12	
28.3	60						.47	.16	
33.0	70							.22	.06
37.7	80							.28	.07
42.5	90							.34	.09
47.2	100								.11
59.0	125								.17
71.0	150								.23

[a] 1 in Hg = 3.37 KPa

To find the pipe size, enter Table C16.14 or Table C16.15 (depending on the pipe material used) with the adjusted scfm; find a friction loss figure that is equal to or less than the allowable figure calculated; then read up to find the pipe size at the top of the column. This chart is based on an initial vacuum pressure of 20 in Hg (34 kPa abs), which is a commonly used and generally accepted value. To find pressure losses for values other than 20 in Hg (34 kPa abs), use Eq. C16.5.

Piping Network Testing

1. During construction, each 200 ft (60 m) section of pipe shall be pressure tested to a pressure of 150 psig (1035 kPa) with compressed air for 1 hour with no loss of pressure allowed as work progresses prior to installation of inlets. Each joint shall be tested with soapy water.
2. After the inlets are installed, a second pressure test using air as above shall be conducted at the same pressure for 1 hour.
3. A final test using 22 in Hg (27 kPa abs) or 10 percent higher than system design vacuum shall be conducted for 24 hours with no loss of pressure allowed.

General Design Considerations

There are several basic recommendations regarding the sizing of a system that shall be followed when sizing a complete network.

1. Because of the use of the diversity factor table, it may be possible for a branch line to have a greater size than the main it feeds from. Always use the largest pipe size calculated at any junction.

TABLE C16.16 Vacuum Pump Exhaust Pipe Sizing

nl/s	Total vacuum plant capacity all pumps (scfm)	Equivalent pipe length						
		ft 50 m 15.2	100 30.4	150 45.6	200 60.8	300 91.2	400 121.6	500 152
4.72	10	2.00″	2.00″	2.00″	2.00″	2.00″	2.00″	2.00″
23.6	50	2.00″	2.50″	3.00″	3.00″	3.00″	3.00″	3.00″
47.2	100	3.00″	3.00″	3.00″	4.00″	4.00″	5.00″	5.00″
71	150	3.00″	4.00″	4.00″	4.00″	5.00″	5.00″	5.00″
55	200	4.00″	4.00″	4.00″	5.00″	5.00″	5.00″	5.00″
142	300	4.00″	5.00″	5.00″	5.00″	6.00″	6.00″	6.00″
189	400	5.00″	5.00″	6.00″	6.00″	6.00″	8.00″	8.00″
236	500	5.00″	6.00″	6.00″	6.00″	8.00″	8.00″	8.00″

1 in = 25.4 mm

2. The smallest size tube to any individual inlet shall be ½ in (13 mm) tubing. Use ¾ in (19 mm) as a minimum size for any branch and 1 in (25 mm) size minimum for any main or riser. This will allow for future changes.
3. It is common practice in laboratory vacuum system design to have the source pumps sized for 20 in Hg (34 kPa abs), using an allowable friction loss of 3 in (75 mm) Hg. This leaves 2 in Hg for the remaining loss at the pump assembly.
4. Provide for future expansion and alterations by having adequate minimum-size main lines and branches, or deliberately oversize the lines by one size when future expansion is likely.

Vacuum Pump Exhaust Sizing

The vacuum pump exhausts may be manifolded together, provided individual exhausts are isolated. Exhaust piping shall be sloped back to the pump. The minimum size of the exhaust pipe should be at least the same size as the vacuum pump exhaust port. The exhaust piping assembly shall be sized to limit the pressure loss to 1 psi (6.9 kPa) or less. The exhaust should have an in-line muffler to lessen the noise, and the exhaust line shall be routed outside the facility. The exhaust line end shall have a louver and screen to prevent rain and insects from entering. Systems that serve research laboratories and patient treatment areas shall have a duplex filter on the exhaust. The pressure drop through this filter shall be added to the friction loss through the exhaust pipe in order to calculate total friction loss through the line. For sizing the exhaust pipe, refer to Table C16.16.