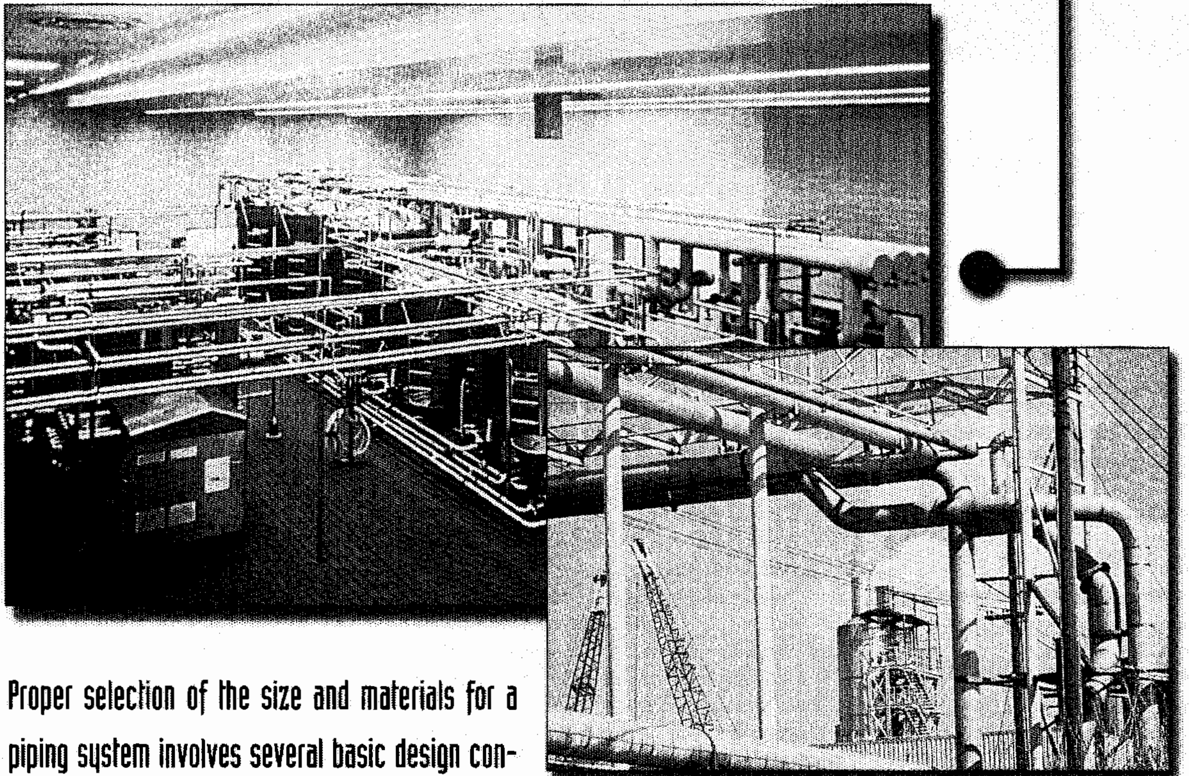
ESSENTIALS OF PIPING SYSTEM DESIGN:

Sizing and Materials Selection



Proper selection of the size and materials for a piping system involves several basic design considerations. The first step involves determining whether to use piping or tubing. The next step is to establish the size of the pipe or tube, then to select the proper wall thickness, the surface roughness and finally the alloy selection based on the environment both inside and outside the tube.

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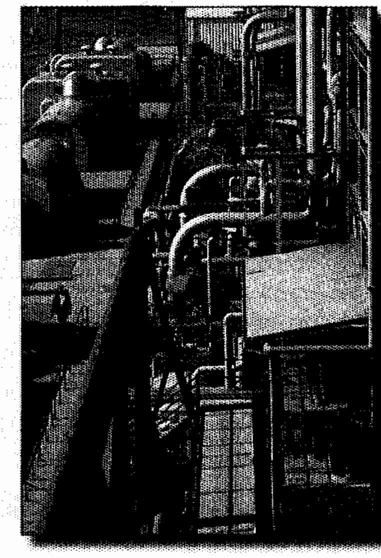

Table 1

COMPARISON OF PIPE AND TUBE TOLERANCES

	Pipe	Tube
ASTM Ref. Specification	A-312	A-249
Outside Diameter	+ 0.015 up to +0.093" - 0.031" (Pipe Size to 12")	± 0.004 up to ± 0.015" (Tube size to 4")
Wall Thickness	- 12%, No Maximum	± 10%, Minimum Wall Avail.

Proper design of the piping system is fundamental to any fluid handling system. Some systems have operated trouble-free for years, then there are others. The more unique the fluid being transported the more critical the selection of materials and the design criteria. Of course, everyone wants a trouble-free system, but that usually comes at a higher cost. If cost is a constraint, then the system usually is designed with the lowest cost materials with no considerations made for corrosion resistance. For the long-term this may be false economy.

The selection process involves a number of individual steps:

1. Use of a pipe or a tube.
2 Determination of hydraulic diameter.
3. Determination of fluid velocity — the second step in alloy selection.
6. Determination of system pressure drop — the third step in alloy selection.
7. Selection of alloy based on corrosive conditions.

A PIPE OR A TUBE?

What is the difference between a pipe and a tube? They look very similar, but there are some critical differences.

Simply stated, the difference is dimensions and specifications. Pipe is made to wide tolerances and tube is made to close tolerances as shown in Table 1. Pipe size is the theoretical inside diameter, even though each size is made to a fixed outside diameter. Tube size is the outside diameter. Pipe wall thickness is referred to as "schedule" and tubing is the actual wall thickness or "gage."

Pipe is described according to diameter and schedule as indicated in Table 2 which gives comparative dimensions for some representative sizes. A 1" schedule 40 pipe has approximately a 1" inside diameter (ID). Its outside diameter (OD) is always 1.315", but the ID changes with the schedule. Then there is the problem with tolerances as illustrated in Table 1. Outside diameter tolerances are quite generous and the wall thickness even more so. And pipe is always made to the bottom of the wall tolerance, so if the design is critical, pipe is not the best choice.

Before the introduction of schedules, pipe was referred to as "standard", "extra strong", and "double extra strong." In 1939 the American Standards Association introduced the "schedule" designation to provide a more rational approach to pipe selection. Very few diameters have the same wall thickness even though they may have the same schedule number. Actually, there is some logic in this since the same schedule for the different diameters will have essentially the same pressure rating. Schedule numbers are based on the relationship:

Schedule Number = 1000 P/S

Where

P = internal pressure in psi

S = allowable fiber stress in psi

Schedule 40 pipe is the same as the old "standard" designation, and Schedule 80 the same as "extra strong" in the most common diameters. Stainless steel sizes are designated with an "S" following the schedule number, and include smaller schedules, namely 5S and 10S.

Tubing is made to much tighter OD tolerances and it is possible to buy a minimum wall. Each tube size is specified individually according to wall thickness. There is no commonality for the various sizes with regard to pressure rating. But the sizes are predictable and the design is "cleaner." Sometimes tube wall thickness is referred to as "gage." This is Birmingham Wire Gage (BWG), and is a carryover from the early days of the Industrial Revolution in England. For example, a 1.000-inch OD 18 GA tube is 1.000-inch OD with a 0.049-inch wall thickness. A correlation between Gage and thickness is given in Table 3.

With the looser tolerances comes a lower price tag for the pipe. Tubing with its tighter tolerances and higher level of inspection required by the specifications is more expensive.

Selection of a tube size over a pipe size depends on the design of the system. If the design is rather "loose," then pipe may be the way to go. If the design is "tight" and attributes like surface finish are critical, then a tube is the way to go. In this paper we will use the term "tube" as synonymous with "pipe."

SIZING FOR FLOW

The next step is to determine the hydraulic diameter, or flow diameter, of the tube. This is the first step in material selection since different alloys have different critical velocities for erosion of the tube wall. In general, the erosion resistance of the metal is proportional to the hardness of the metal. Soft metals erode at low velocities; hard metals erode at high velocities.

The governing formula[1] is:

Q = AV

Where

Q = the quantity of fluid to be moved in units like ft^3/sec

A = the cross sectional hydraulic area, or the ID of the tube in units like ft^2

V = the velocity of the fluid in units like ft/sec

There is a critical velocity for each allo[illegible]t metals like aluminum have low critical [illegible]ties, in the range of 5 fps. Hard metals like stainless steel have critical velocities in the range of 40 fps. Therefore, the velocity should be within the limits of the tube alloy selected. These values are not absolute; they are determined in water at ambient temperatures. If solids are suspended in the water the critical velocities will be much lower. The same is true for gas bubbles in the water. Generally, as the temperature increases to where the strength of the alloy begins to drop, the erosion rates likewise increase. Fortunately, this occurs at the higher temperatures for most metals so this does not apply in most cases.

OPERATING TEMPERATURE

Temperature is usually dictated by the process, but in general, the closer it can be kept to ambient temperatures the better. The one exception to this is moving corrosive gasses where it is better to keep the gas above the dew point to prevent condensation and corrosion of the tube wall. The main advantage to ambient temperature is constancy of the mechanical properties and, again in general, to minimize tube creep.

DETERMINATION OF WALL THICKNESS

Wall thickness is based on the burst pre[illegible]ure of the tube, and its companion, safe op[illegible]g pressure. System pressure usually is determined by the pump, flow requirements and the system head. Enough excess pressure must be added to compensate for the head loss of the system and still maintain the velocity.

[illegible]he most common formula for calculating the burst pressure is Barlow's Formula:
$P = 2St/D$
Where
P = burst pressure
S = ultimate (tensile) strength of the alloy
T = wall thickness of the tube
D = outside diameter of the tube (or pipe)

When using this formula always use the minimum strength values from the ASTM standards. Also, use the minimum wall thickness that is at the bottom of the tolerance, and the maximum diameter, at the top of the tolerance. This formula is reasonably accurate and should represent the minimum pressure at which the tube will burst. However, keep in mind that material defects or mechanical damage can change the tube wall so that burst will occur at lower pressures.

Substitution of the ultimate strength in the formula with the ASME allowable stress, from the ASME Boiler and Pressure Vessel Code, Section II, Part D, changes the pressure to the "safe working pressure." For estimation purposes the ASME allowable stress is approximately 25 percent of the ASTM minimum tensile strength, so if it is not possible to have access to the Code, you can substitute 25 percent of the ASTM values. Operating temperature is very important here. At temperatures below 200°F it is not a [illegible]r concern. But as the temperature increases, especially for the weaker alloys, the allowable stresses will drop. And with the drop in allowable stress the wall thickness must increase.

Section VIII of the Code[2] uses a modification of Barlow's formula:
$T = PR/(S-0.6P)$
Where
T = tube wall thickness
P = system pressure
R = inside radius of the tube
S = ASME allowable stress

This is somewhat more accurate, but is still subject to the same precautions about material defects and mechanical damage.

Corrosion allowance must be added to the calculated wall thickness. These values can be obtained from corrosion data for various media with different alloys. The values are expressed in mpy, or mils per year. A corrosion rate of 10 mpy is 0.010 inches per year. If the system is designed for a 10 year lifetime then one must add 10 x 0.010 inch = 0.100 inch. If the calculated tube wall at the safe operating pressure is 0.090 inch, then the wall with the corrosion allowance will be 0.190 inch. At this point it may be less expensive to use an alloy with a lower corrosion rate. Some alloys like stainless steel and titanium will not list corrosion rates in water [illegible] they are not susceptible to general corros[illegible] in water.

PRESSURE DROP

Pressure drop, or head loss, is a measure of fluid friction as the fluid flows through the tube. Each fitting, valve, reducer or anything that causes a change in flow direction also adds to the friction. This pressure drop is much greater than any surface friction arising from surface roughness. And this pressure drop directly affects the pump motor size. The major cause of friction in the tubing comes from the surface roughness. The smoother the surface, the lower the friction loss. Corrosion has a direct bearing on the head loss over time because surfaces become rougher with corrosion. Therefore, a more corrosion-resistant material will have a more constant head loss during its lifetime.

Many formulae have been developed over the years, but the most accepted[3] is:
$\Delta p = (4.52Q^{1.85}/(C^{1.85}D^{4.87})$
Where
Δp = friction loss in psi/ft
Q = flow rate in gpm
C = Hazen-Williams Coefficient
D = inside diameter of tube in inches

The Hazen-Williams Coefficient is a function of the surface roughness of the tube and its corrosion resistance. A more complete discussion and actual values are given elsewhere[4]. Materials like electropolished stainless steel have the same C value as glass and hard plastic, whereas heavily corroded iron pipe will have 25 percent of the value. Because the "C" factor is in the denominator, the lower value causes the pressure drop to rapidly increase. So corrosion resistance and initial surface smoothness have a direct bearing on operating cost and long term performance.

CORROSION RESISTANCE

Selection of materials is critical for long term trouble free operation. There are five types of corrosion[5] that can affect a system:

1. general or uniform corrosion
2. galvanic corrosion which includes
   a. pitting corrosion
   b. crevice corrosion
3. stress corrosion cracking
4. intergranular corrosion
5. Microbiologically Influenced Corrosion

General corrosion is the uniform attack of a material (metal, plastic, ceramic or glass) by the environment. Not all media attack materials at the same rate, and the attack is very temperature- and concentration-dependent. During general corrosion the thickness decreases, the length shortens and the width narrows with a corresponding decrease in weight. Normally general corrosion is expressed as thickness loss per year. Using this value it is possible to design a system for a given lifetime. Some materials have very low general corrosion rates such as stainless steel or titanium in water. Others are very high such as aluminum in hot caustic.

The second type of corrosion is galvanic corrosion. Usually it is caused by electrically coupling two different metals in an electrically conductive solution such as carbon steel and stainless in a weak sulfuric acid solution. The carbon steel dissolves and the stainless steel is as fresh as the day it was installed. In this example the carbon steel became the sacrificial anode for the stainless steel. If the carbon steel had been installed electrically from the stainless steel and protected from the "throwing power" of the stainless steel, then corrosion of the carbon steel would have been far less.

Two subsets of galvanic corrosion are pitting and crevice corrosion. These are examples of localized corrosion. The bulk of the tubing system will be untouched, but pits or holes will develop randomly, causing failure. Pitting is alloy- and environment-specific, while crevice corrosion is localized under a crevice former. Crevice formers are everything from gaskets to dirt to paint to bolt heads. The tighter the crevice the worse the condition.

All metal systems are subject to stress corrosion cracking. Three conditions are required for this to occur: tensile stress, environment and alloy. Residual stress is extremely important, but more so is the presence of stress concentrators. A stress concentrator will increase a residual stress

Table 2
SELECTED PIPE DIMENSIONS

Pipe Size	Schedule	Outside Diameter	Nominal Wall Thickness	Minimum Wall Thickness	Nominal Inside Diameter	Inside Diameter at Minimum Wall
1 inch	5S	1.315	0.065	0.057	1.185	1.201
	10S		0.109	0.095	1.097	1.125
	40S		0.133	0.116	1.049	1.083
	80S		0.179	0.157	0.957	1.001
2 inch	5S	2.375	0.065	0.057	2.245	2.261
	10S		0.109	0.095	2.157	2.185
	40S		0.154	0.135	2.067	2.105
	80S		0.218	0.191	1.939	1.993
3 inch	5S	3.500	0.083	0.073	3.334	3.354
	10S		0.120	0.105	3.260	3.290
	40S		0.216	0.189	3.068	3.122
	80S		0.300	0.263	2.900	2.974
4 inch	5S	4.500	0.083	0.073	4.334	4354
	10S		0.120	0.105	4.260	4.290
	40S		0.237	0.207	4.026	4.086
	80S		0.337	0.295	3.826	3.910

Table 3
CONVERSION OF BWG TO INCHES

BWG	Inches	BWG	Inches
9	0.148	17	0.058
10	0.134	18	0.049
11	0.120	19	0.042
12	0.109	20	0.035
13	0.095	21	0.032
14	0.083	22	0.028
15	0.072	23	0.025
16	0.065	24	0.022

to a value far greater than the tensile stress of the metal. The presence of a pit with a small radius is sufficient to increase the residual stress by several times — resulting in tensile failure. Compressive stresses do not result in stress corrosion failure, therefore shot peening is sometimes used as a means of placing a surface in compression. Another method is to change the means of tube straightening from circumferential to longitudinal direction which is a harder direction for the stresses to cause cracking.

Intergranular corrosion likewise occurs in nearly every metal system. Usually associated with grain boundary precipitates, corrosives will attack the alloy-depleted zone and cause corrosion along the grain boundaries. It is a combination of general and galvanic corrosion, resulting in the grains dropping out like so many pieces of rusty sand. In stainless steel it usually is associated with the welding of the higher carbon grades and can be minimized by the use of the "L" grades. Also, it can develop over time by exposure of the alloy to high temperatures or chemicals that cause constituents to precipitate or attack of the grain boundaries. It can lead to stress corrosion cracking.

Microbiologically Influenced Corrosion is the newest mechanism to be identified. Technically it is not a specific corrosion mechanism, but rather one in which the bacteria, by means of their metabolism, create chemicals that attack the metal in the vicinity of their colony. There are four basic types of bacteria: sulfate reducing which produce sulfurous acid; sulfur fixing which produce sulfuric acid; nitric acid producing; and manganese/iron fixing bacteria. In each case the bacteria produce a metabolic byproduct that is harmful to the metals, or in the case of the manganese fixing bacteria, a product that reacts with environment to produce a corrosive condition. The preventative action is to use a biocide to prevent the colonies from forming or to use an alloy that is immu[illegible] the byproducts. An example is the attack of the carbon steel serv-ice water piping in several coastal nuclear power plants. Sulfate-reducing bacteria caused the pipe to tuberculate to a point that it restricted the flow of water. The solution was to replace the carbon steel with a 6 percent molybdenum superaustenitic stainless steel.

CONCLUSIONS

A properly designed fluid conveying system will include the following elements:

1. Proper diameter of tube to convey the fluid at a velocity such that erosion won't occur.
2. A wall thickness that is sufficient to provide safe operating conditions, but not so thick as to increase the cost unnecessarily.
3. A surface smoothness on the fluid side of the tube that will minimize head loss.
4. Proper selection of an alloy that will have adequate corrosion resistance for the life of the system.

Special care must be taken in the alloy selection to take the corrosive nature of the environment into account. Since there are five corrosion mechanisms that can attack the tubing it is important that each be considered. Because bacteria are ever present they must be designed against, or bactericide injection must be designed into the system.

Alloys are available that will provide long life, smooth surfaces and resistance to corrosion. Many times their use will be far less expensive than a less expensive alloy that is prone to corrosive attack or deterioration over time — resulting in higher operating costs.

About the Author

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