Calculating and Accommodating Pipe Line Thermal Growth

All materials, including pipe, machinery, structures and buildings experience dimension changes as a result of changes in temperatures. This report covers considerations for accommodating thermal expansion and contraction. Movement due to other causes (e.g.: seismic, etc.) must be added to pipe line thermal growth. Pipe subjected to temperature changes will be placed in a condition of stress, exerting potentially damaging reactive forces and moments on components or equipment.

Three common methods of accommodating this pipe movement are to 1) provide an expansion joint; 2) allow the system to “free-float” whereby the pipe would be allowed to move in a desired direction through the use of anchoring and/or guidance, if necessary, taking into account the capability of branch connection or changes in direction which may have resultant harmful bending moments; or 3) utilize the linear movement/deflection capabilities of flexible grooved couplings.

The selection of either of these methods is dependent on the type of piping system and the designer's preference. Since it is impossible to predict all system designs, it is the intent here to call attention to the mechanical advantages of the grooved piping method and how it can be used to the piping system designer's benefit. These examples are presented to stimulate thought and should not be considered as recommendations for a specific system.

The first step in accommodating thermal movement is to compute the exact change in the linear length of the piping system over the distance of interest, along with a suitable safety factor. The actual expansion of 100-foot pipe lengths has been computed at different temperatures for the most common piping materials (carbon steel, stainless steel and copper tubing) and are shown in Table 1. These values should not be applied to pipe of alternate materials as they will vary. Expansion coefficients may vary 5% or more when obtained from different sources and should be taken into account. An example illustrating the use of Table 1 follows:

Given: 240-foot long carbon steel pipe
Maximum operating temperature = 220°F (104°C)
Minimum operating temperature = 40°F (4°C)
Temperature at time of installation = 80°F (26°C)

Note: To assure the maximum life for the service intended, proper gasket selection is essential. Reference should always be made to the latest Victaulic Gasket Selection Guide for recommendations.

Calculation: From Table 1, carbon steel pipe expansion

220°F (104°C)	1.680"	per 100 ft. of carbon steel pipe
40°F (4°C)	0.300"	per 100 ft. of carbon steel pipe
Difference:	1.380"	per 100 ft. of carbon steel pipe for temperatures 40°F to 220°F

Therefore, 240-feet of pipe = $\frac{240}{100}(1.380) = 3.312"$

This 3.312" of movement should have a suitable safety factor applied, which varies as determined by the system designer, to account for any errors in predicting operating extremes, etc. These examples were calculated without a safety factor applied.

To determine the positioning of the expansion joint at the time of installation:

Installation to cold condition (80°F to 40°F)

80°F (26°C)	0.580" per 100 ft.
40°F (4°C)	0.300" per 100 ft.
Difference:	0.280" per 100 ft. or 0.672" per 240 ft.

Installation to hot condition (80°F to 220°F)

220°F(104°C)	1.680" per 100 ft.
80°F(26°C)	0.580" per 100 ft.
Difference:	1.100" per 100 ft. or 2.640" per 240 ft.

Therefore, the expansion joint is to be set up with at least the capability to allow 0.672" of pipe contraction and at least 2.640" of pipe expansion when installed at 80°F (26°C).

TABLE 1 26.02-1A

Temp. °F/°C	Thermal Expansion of Pipe Inches per 100 ft. mm per 100 meters: Carbon Steel	Copper	Stain. Steel	Temp. °F/°C	Thermal Expansion of Pipe Inches per 100 ft. mm per 100 meters: Carbon Steel	Copper	Stain. Steel
–40 –40	–0.288 –24.0	–0.421 –35.1	–0.461 –38.4	180 82	1.360 113.2	2.051 170.9	2.074 172.9
–20 –28	–0.145 –12.1	–0.210 –17.4	– 0.230 –19.0	200 93	1.520 126.6	2.296 191.3	2.304 191.9
0 –17	0 0	0 0	0 0	212 100	1.610 134.2	2.428 202.4	2.442 203.4
20 –6	0.148 12.5	0.238 19.7	0.230 19.0	220 104	1.680 140.1	2.516 209.7	2.534 211.3
32 0	0.230 19.0	0.366 30.5	0.369 30.8	230 110	1.760 146.7	2.636 219.8	2.650 220.8
40 4	0.300 24.9	0.451 37.7	0.461 38.4	260 126	2.020 168.3	— —	— —
60 15	0.448 37.4	0.684 57.1	0.691 57.7	280 137	2.180 181.8	— —	— —
80 26	0.580 48.2	0.896 74.8	0.922 76.8	300 148	2.350 195.9	— —	— —
100 37	0.753 62.7	1.134 94.5	1.152 96.1	320 160	2.530 211.0	— —	— —
120 48	0.910 75.8	1.366 113.9	1.382 115.2	340 171	2.700 225.1	— —	— —
140 60	1.064 88.6	1.590 132.6	1.613 134.5	350 176	2.790 232.6	— —	— —
160 71	1.200 100.1	1.804 150.3	1.843 153.6				

The data provided is intended for use as an aid to qualified designers when products are installed in accordance with the latest available Victaulic product data.

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ACCOMMODATING PIPE THERMAL GROWTH

Victaulic offers the designer basic methods for accommodating pipe movement due to contraction and/or expansion.

1. Victaulic Style 150 Mover® Expansion Joint
2. Free-Floating System
3. Victaulic flexible grooved couplings utilizing their linear movement and deflection capabilities.
4. Expansion loops utilizing Victaulic flexible couplings and fittings.

These devices offer economical and attractive solutions to problems of thermal movements. The following sections provide product information and suggestions which show the mechanical advantages of the grooved piping method. **Since it is impossible to predict all system designs, it should be noted that these suggestions are not considered as recommendations for a specific system.**

1. Victaulic Style 150 Mover® Expansion Joint

The Victaulic Style 150 Mover Expansion Joint is a slip-type expansion joint which can provide up to 3" (76 mm) axial movement, accommodating pipe expansion and/or contraction. (See 09.04)

As with all types of expansion joints, the designer should guard against damaging conditions for which these devices cannot accommodate, such as temperatures or pressures outside the product recommended range or motions which exceed the product's capability.

For proper operation of the expansion joint, the piping system should be divided into separate expansion/contraction sections with suitable supports, guides and anchors to direct axial pipe movement.

Anchors can be classified as main or intermediate for the purpose of force analysis. Main anchors are installed at terminal points, major branch connections, or changes of piping direction. The forces acting on a main anchor will be due to pressure thrust, velocity flow and friction of alignment guides and weight support devices.

Intermediate anchors are installed in long runs to divide them into smaller expanding sections to facilitate using less complex expansion joints. The force acting on the intermediate anchor is due to friction at guides, weight of supports or hangers, and the activation force required to compress or expand an expansion joint.

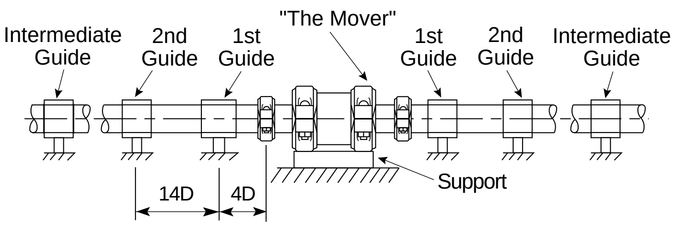
Pipe alignment guides are essential to ensure axial movement of the expansion joint. Whenever possible, the expansion joint should be located adjacent to an anchor within four (4) pipe diameters. The first and second alignment guides on the opposite side of the expansion joint should be located a maximum distance of four (4) and fourteen (14) pipe diameters, respectively. Additional intermediate guides may be required throughout the system for pipe alignment. If the expansion joint cannot be located adjacent to an anchor, install guides on both sides of the unit, as mentioned.

THE DATA PROVIDED IS INTENDED FOR USE AS AN AID TO QUALIFIED DESIGNERS WHEN PRODUCTS ARE INSTALLED IN ACCORDANCE WITH THE LATEST AVAILABLE VICTAULIC PRODUCT DATA.

TABLE 2 26.02-2A

RECOMMENDED PIPE ALIGNMENT GUIDE SPACING

Nominal Pipe Size Inches/mm	Maximum Distance to 1st Guide or Anchor Inches/mm	Approximate Distance Between 1st to 2nd Guide Inches/mm
1 25	4" 101.6	1' - 4" 406.4
1¼ 32	5" 127.0	1' - 5" 431.8
1½ 40	6" 152.4	1' - 9" 533.4
2 50	8" 203.2	2' - 4" 711.2
2½ 65	10" 254.0	2' - 11" 889.0
3 80	1' - 0" 304.8	3' - 6" 1066.8
3½ 90	1' - 2" 355.6	4' - 1" 1244.6
4 100	1' - 4" 406.4	4' - 8" 1422.4
5 125	1' - 8" 508.0	5' - 8" 1727.2
6 150	2' - 0" 609.6	7' - 0" 2133.6
8 200	2' - 8" 812.8	9' - 4" 2844.8
10 250	3' - 4" 1016.0	11' - 8" 3556.0
12 300	4' - 0" 1219.2	14' - 0" 4267.2
14 350	4' - 8" 1422.4	16' - 4" 4978.4
16 400	5' - 4" 1625.6	18' - 8" 5689.6
18 450	6' - 0" 1828.8	21' - 0" 6400.8
20 500	6' - 8" 2032.0	23' - 4" 7112.0
24 600	8' - 0" 2438.4	28' - 0" 8534.4



In addition, where long length, low pressure applications may require few intermediate alignment guides, the pipe weight, including any liquid contents, must be adequately supported. Recommended spacings are shown in the Victaulic I-100 Pocket Handbook and in the Design Data Section 26.01 of the General Catalog.

Figure 1 illustrates a typical application of expansion joints, anchors, and guides.

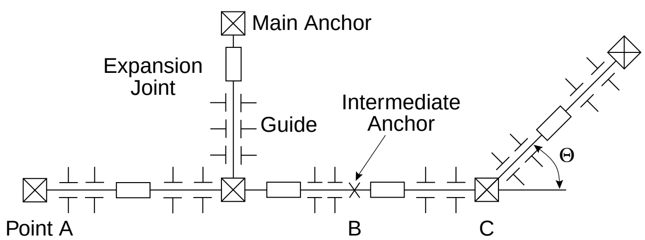


Figure 1

When installed, the “Mover” can provide compensation for 3" (76 mm) of axial pipe movement. This movement may be set to compensate for pipe expansion, contraction, or some combination as directed by the system requirements. Additionally, the movement caused by installation at a temperature other than the minimum or maximum operating temperature should be accounted for by adjusting the expansion joint’s installed length.

The activation forces required to fully compress Victaulic expansion joints are equivalent to the forces required to overcome approximately 15 PSI (103 kPa) internal pressure. The forces required will be similar for both the Style 150 Mover Expansion Joint and Style 155 Expansion Joint and are tabulated in Table 3 according to size.

In pipe sizes where the Mover is not available, Victaulic offers our Style 155 Expansion Joints. Style 155 Expansion Joints are a combination of couplings and short nipples, joined in tandem to provide increased expansion. The nipples are precisely grooved to provide full linear allowance at each joint.

The standard units are prepared with Style 77 or Style 75 couplings and are assembled with nipples in the full open position for full expansion. Also standard units provide up to 1.88" (47.752 mm) (¾ - 3"/20 - 80 mm sizes) or 1.75" (44.45 mm) (4 - 24"/100 - 600 mm sizes) of axial movement. Style 155 Expansion Joints with more or less axial movement capability are available simply by adding or removing coupling and nipple units. For contraction services, units are fully compressed. Where expansion and contraction allowances are needed, the spacing will be set proportionally to the installation temperature and the temperature extremes (according to customer specifications).

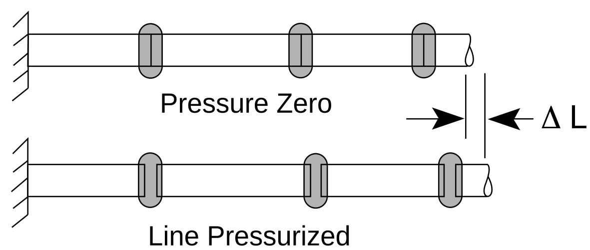
Victaulic Style 155 Expansion Joints may be used as flexible connectors; **however**, they will not simultaneously provide full expansion and full deflection. Expansion Joints installed horizontally require independent support to prevent deflection which will reduce the available expansion.

TABLE 3 26.02-3B

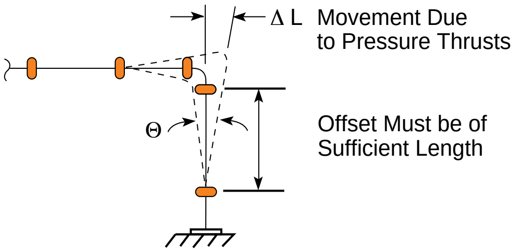
Nominal Pipe Size Inches mm	Activation Force Lbs. N
1 25	20 89
1½ 40	45 200
2 50	70 312
3 80	145 645
4 100	240 1068
6 150	520 2314
8 200	880 3916
10 250	1365 6074
12 300	1915 8522
14 350	2310 10280
16 400	3015 13417
18 450	3820 16999
20 500	4715 20982
24 600	6785 30193

2. Free-Floating System

Free-floating systems are piping systems which are allowed to thermally expand/contract without the use of expansion joints, provided that this movement does not cause bending moment stresses at branch connections, or is not harmful to joints and changes in direction, or to parts of structures or other equipment. This can be accomplished by randomly installing joints or, if desired, by installing guides to control the direction of movement. The effects of pressure thrusts must be taken into account when utilizing flexible grooved couplings as the pipe will be moved to the full extent of the available pipe end gaps when allowed to float.



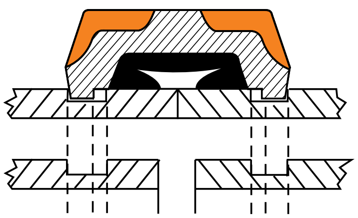
Ensure that branch connections and offsets are sufficiently long so that the maximum angular deflection of the coupling (shown in Performance Data for each coupling style) is never exceeded and that it can accommodate the anticipated total movement of the pipes. Otherwise, anchor the system and direct movements. Also ensure that adjacent pipes can move freely to provide anticipated movements.



3. Victaulic Flexible Grooved Couplings Utilizing Their Linear Movement and Deflection Capabilities.

When designing piping joined with flexible mechanical grooved type couplings, it is necessary to give consideration to certain characteristics of these couplings. These characteristics distinguish flexible groove type couplings from other types and methods of pipe joining. When this is understood, the designer can utilize the many advantages that these couplings provide.

Linear movement available at flexible grooved pipe joints is published under performance data for each Victaulic coupling style. These values are MAXIMUMS. For design and illustration purposes, these figures should be reduced by the following factors to allow for pipe groove tolerances.



LINEAR MOVEMENT TOLERANCE

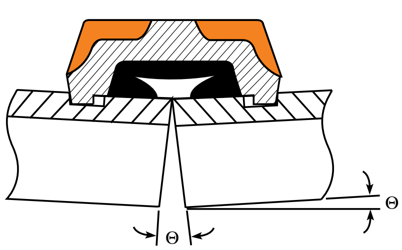
¾ - 3½" (20 - 90 mm) – Reduce published figures by 50%
4" (100 mm) and larger – Reduce published figures by 25%

Standard roll grooved pipe will provide one-half the expansion/contraction or deflection capabilities of the same size standard cut groove pipe.

Where full linear movement is required, the Victaulic Style 155 Expansion Joint can be used with special, precisely grooved nipples. Refer to Section 09.05 for additional information.

Angular deflection available at flexible grooved pipe joints is published under Performance Data for each Victaulic coupling style. These values are MAXIMUMS. For design and illustration purposes, these figures should be reduced by the following factors to allow for pipe grooving tolerances.

Θ = Maximum angular deflection between center lines as shown under Performance Data.

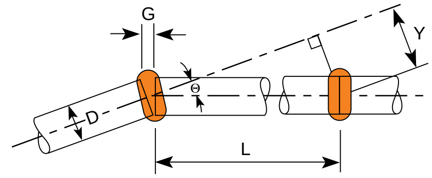


ANGULAR MOVEMENT TOLERANCE

¾ - 3½" (20 - 90 mm) – Reduce published figures by 50%
4" (100 mm) and larger – Reduce published figures by 25%

Standard cut grooved pipe will provide double the expansion/contraction or deflection capabilities of the same size standard roll groove pipe.

The angular deflection available at a Victaulic flexible grooved pipe joint is useful in simplifying and speeding installation.



$$Y = L \sin \Theta$$

$$\Theta = \sin^{-1} \frac{G}{D}$$

$$Y = \frac{G \times L}{D}$$

Y = Misalignment (Inches)

G = Maximum Allowable Pipe End Movement (Inches) as shown under performance data (published value to be reduced by Design Tolerance).

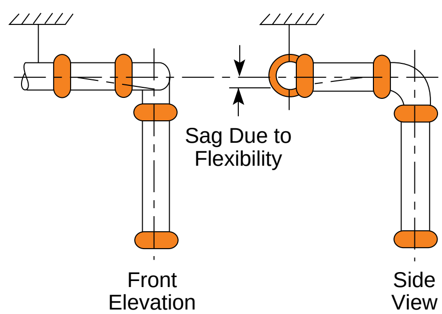
Θ = Maximum Deflection (Degrees) from Center Line as shown under performance data (published value to be reduced by Design Tolerance).

D = Pipe Outside Diameter (Inches)

L = Pipe Length (Inches)

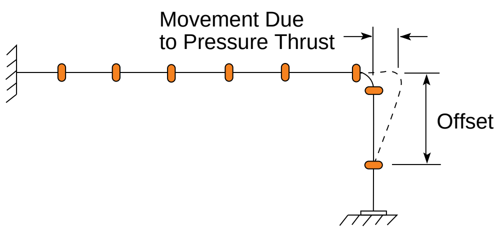
NOTE: Joints which are fully deflected can no longer provide linear movement. Partially deflected joints will provide some portion of linear movement.

Flexible grooved type couplings allow angular flexibility and rotational movement to take place at joints. These features provide advantages in installing and engineering piping systems, but must be considered when determining hanger and support spacing.



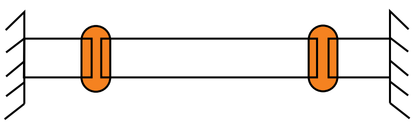
As illustrated above, it is obvious that this system would require further hangers (or use of Zero-Flex® rigid couplings) to eliminate the drooping of the pipes that would occur. Hanger positions must be considered in relation to the angular and rotational movement that will occur at joints.

Flexible couplings allow linear movement, therefore, consideration must be given to pressure thrusts which would allow the pipe ends to move to the maximum extent allowed by the coupling, which would accumulate at the end of the system, if the joints had been installed butted or only partially opened when pressurized.

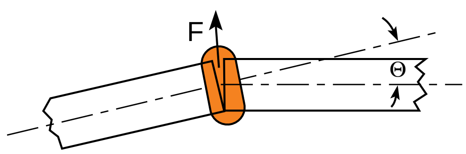


Offsets have to be capable of deflecting sufficiently to prevent harmful bending moments which would be induced at the joints of the offset. Note, if the pipes were to expand due to thermal changes, then further growth of the pipes would also take place at the ends.

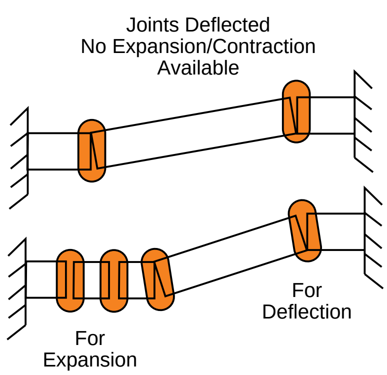
Angular deflection at butted or fully spaced joints is not possible unless the ends of the pipes can shorten and grow as required.



Unrestrained deflected joints will straighten up under the action of axial pressure thrusts or other forces acting to pull pipes apart. If joints are to be maintained deflected, then lines must be anchored to restrain pressure thrusts and end pull forces, otherwise sufficient lateral force must be exerted to keep joint deflected.

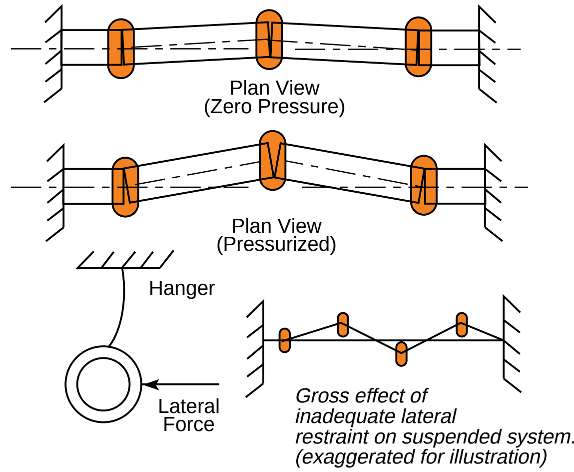


Lateral forces (F) will always act on deflected joints due to internal pressure. A fully deflected joint will no longer be capable of providing the full linear movement normally available at the joint.

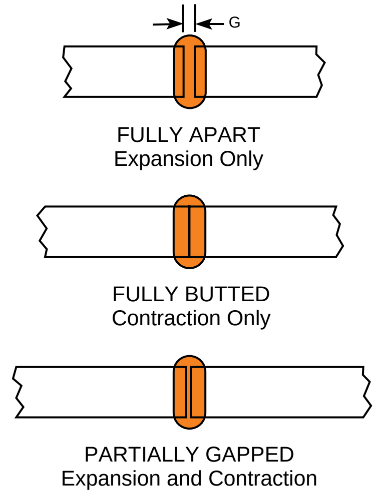


The grooved piping method will not allow both maximum linear movement and maximum angular movement simultaneously at the same joint. If both are expected simultaneously, systems should be designed with sufficient joints to accommodate both, including allowance for recommended tolerances.

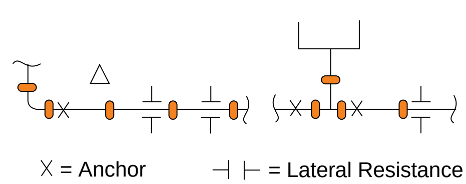
For anchored systems, where pressure thrusts do not act to hold the joints in tension, or in systems where the joints have been intentionally deflected (e.g., curves), provide lateral restraint to prevent movement of the pipes due to pressure thrusts acting at deflections. Lightweight hangers are not adequate in preventing sideways movement of pipes. It should be anticipated that small deflections will occur in all straight lines and side thrusts will be exerted on the joints.



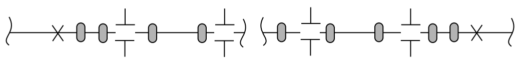
Flexible couplings do not automatically provide for expansion or contraction of piping. Always consider best setting for pipe end gaps. In anchored systems, gaps must be set to handle combinations of expansion and contraction. In free floating systems, offsets of sufficient length must be used to accommodate movement without over-deflecting joints.



Ensure anchorage and support is adequate. Use anchors to direct movement away from or to protect critical changes in direction, branch connections and structure. Spacing and types of supports should be considered in accommodating anticipated pipe movements. (Refer to the Victaulic I-100 Pocket Handbook or Section 26.01 of the General Catalog for suggested hanger spacing.)



Movement in piping systems due to thermal changes can be accommodated with the grooved piping method. Sufficient flexible joints must be available to accommodate anticipated movement, including Movement Tolerance. If anticipated movement will be greater than provided by the total number of joints in the system, additional expansion in the form of a Victaulic Style 150 Mover or Style 155 Expansion Joint should be used (Refer to Section 09.04 or 09.05).



Example 1

EXAMPLE: 400-foot (122 m) long, straight piping system; 6" (150 mm); 20-foot (6 m) random lengths; installed at 60° F (+16°C) (also lowest operating temperature); maximum operating temperature of 180° F (+82°C). Standard expansion tables show this system will give 3.7" (94 mm) total anticipated movement. (Refer to Section 26.02).

20	Joints between anchor points
X ¼"	Movement per coupling
	(cut grooved Style 77 Performance Data)
5"	Available Movement
– 25%	Movement Tolerance
3.75"	

In the above example, Style 07 Zero-Flex Rigid Couplings could have been used and the expansion and/or contraction requirement be made up with additional flexible couplings and/or Style 150, 155 Expansion Joints as needed.

4. Expansion Loops Utilizing Victaulic Flexible Couplings and Fittings

Victaulic offers the designer the advantage of using Victaulic flexible couplings and fittings in expansion loops without inducing stresses in the pipes, elbows or joints. The deflection capability of flexible couplings allows for thermal growth/contraction to be absorbed within the couplings at the elbows as the thermal forces induce deflection. Also, it is important that rigid couplings (Victaulic Style 07, HP-70) are not used on expansion loops as these couplings are not designed to accommodate angular deflection.

A total of eight (8) Victaulic flexible couplings, four (4) Victaulic grooved 90° elbows and three (3) pipe spools are required to complete each expansion loop. Their orientation is as shown in Figure A. As system temperatures lower and the pipe run contracts (see Figure B), the loop expands and the deflection capability of the couplings accommodate this movement. As system temperatures increase (see Figure C), the opposite effect occurs as the pipe run expands and the loop contracts with the couplings accommodating the deflection in the opposite direction.

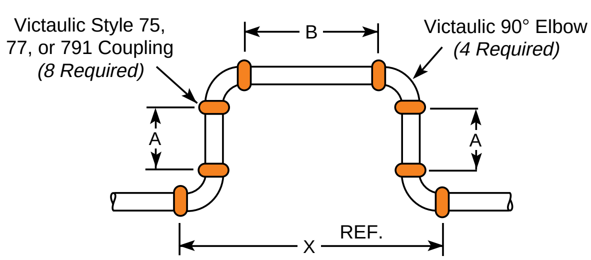


FIGURE A
Expansion Loop

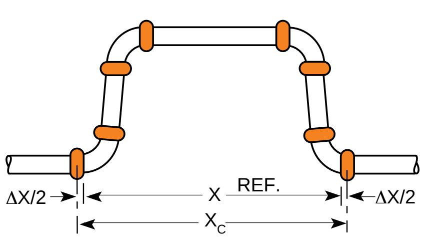


FIGURE B
Thermal Contraction
Pipeline Shrinks – Loop Expands

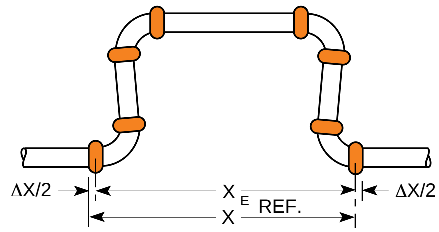


FIGURE C
Thermal Expansion
Pipeline Grows into Loop – Loop Contracts

The amount of thermal expansion/contraction, ΔX, should be determined by the system designer based on the length of pipe run between anchors and the anticipated temperatures change from the installation temperature (see Table 1 for details). The angular deflection available at each coupling is a design characteristic inherent to the coupling size and style and the type of groove (cut or roll grooved). The length of the perpendicular branches of the loop (Dimension A) is determined by the amount of expected pipeline expansion/contraction (ΔX) and the deflection available per joint. Dimension A should be the same on both sides of the loop. The length of the parallel branch of the expansion loop (Dimension B) is determined by ΔX, and it must be sufficiently long enough to prevent the elbows at the pipe run from butting during thermal expansion. It is recommended that Dimension B be at least 2" (50.8 mm) larger than ΔX.

The designer can use Figures D and E titled "Expansion Loop Design Utilizing Victaulic Flexible Couplings and Fittings" to aid in the design of expansion. These loops incorporate all of the design information for each size Victaulic Flexible Coupling including the angular movement tolerance as shown in Section 3. The nominal pipe size and either the design thermal expansion (ΔX) or the length of perpendicular branches (A) must be known and the other can be determined. It is essential for a properly functioning expansion loop that it be installed without any coupling deflection and that the pipeline be properly anchored and guided. Whenever possible, the expansion loop should be located adjacent to an anchor within four (4) pipe diameters. The first and second alignment guides on the opposite side of the expansion loop should be located a maximum distance of four (4) and fourteen (14) pipe diameters, respectively. Additional intermediate guides may be required throughout the system for pipe alignment. If the expansion loop cannot be located adjacent to an anchor, install guides on both sides of the unit, as mentioned.

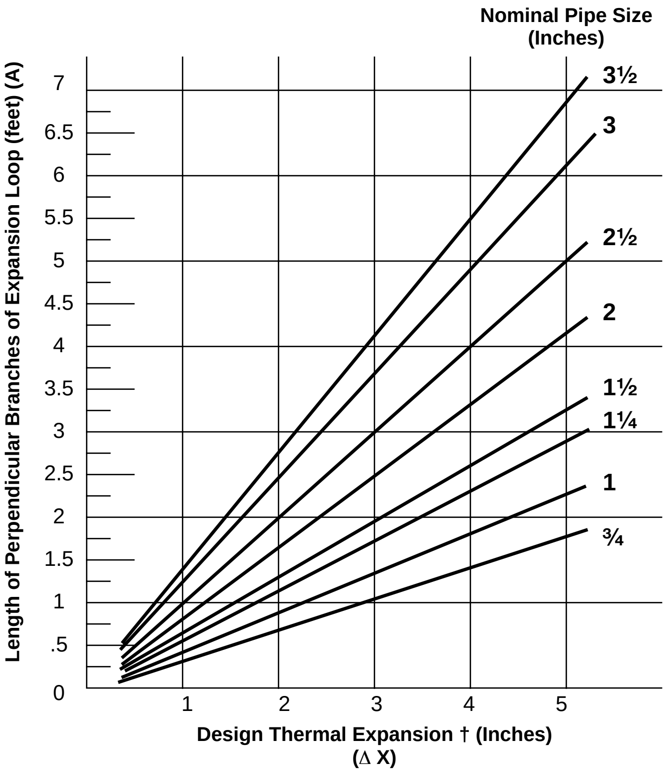
Example: Using the parameters established in the previous section's example problem, 6" (150 mm) nominal pipe size and 3.75" (95.2 mm) of total anticipated movement, refer to Figures D and E to determine the length of perpendicular loop branches for both cut and roll groove pipe.

ΔX = 3.75" (95.2 mm)
Nominal Pipe Size = 6" (150 mm)

For Cut Groove Pipe (Figure D)
A = 2.7 Ft. (0.82 m) Minimum

For Roll Groove Pipe (Figure E)
A = 5.4 Ft. (1.65 m) Minimum

Figure D
Expansion Loop Design Utilizing Victaulic Flexible Couplings and Fittings*
VICTAULIC CUT GROOVED PIPE



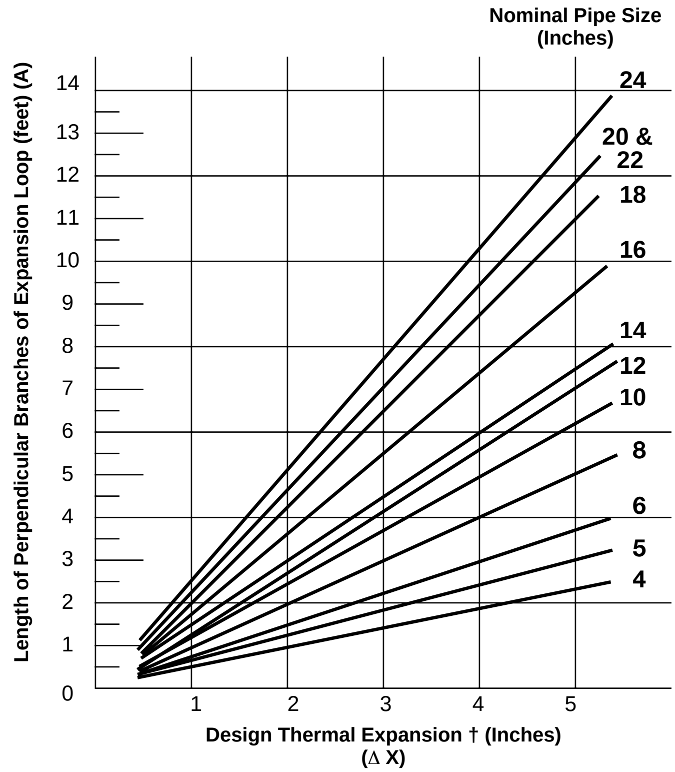
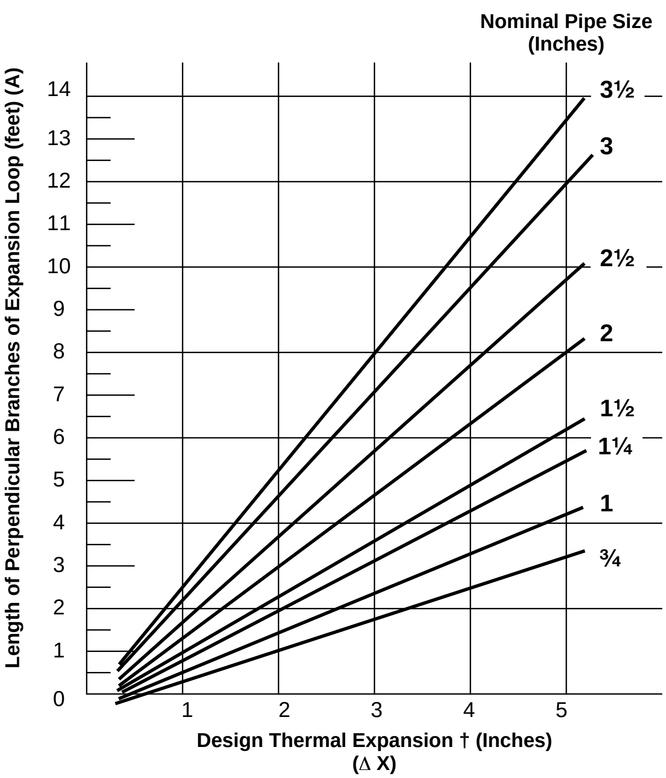
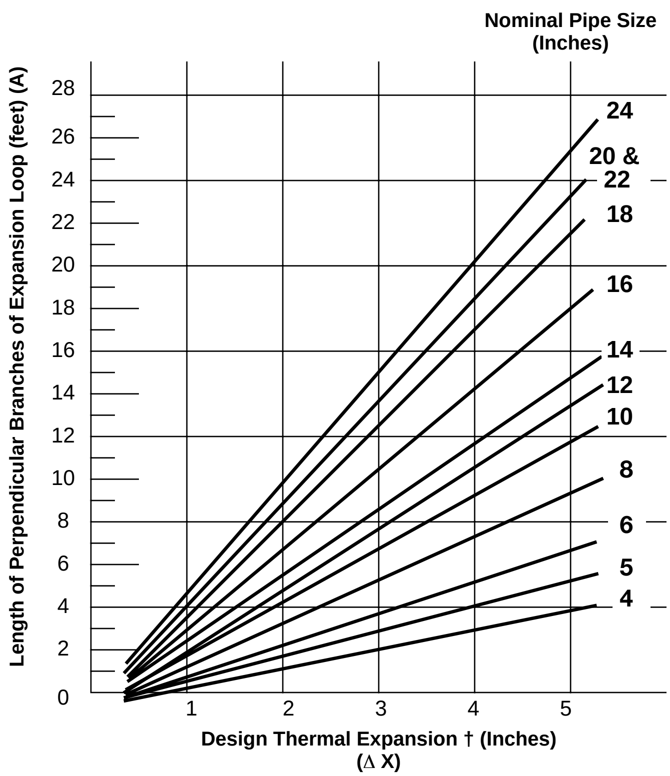


Figure E
Expansion Loop Design Utilizing Victaulic Flexible Couplings and Fittings*
VICTAULIC ROLL GROOVED PIPE





* Based on pipe grooved in accordance with Victaulic specifications.

† Valves include design tolerances: 50% reduction for sizes below 4"/25% reduction for sizes 4" and larger.

To provide an expansion loop for the described system, the two branches must be a minimum of 2.7 (0.82 m) feet and 5.4 (1.65 m) feet long for cut and roll groove pipe, respectively. The parallel branch of the expansion loop must be at least 2" (50.8 mm) larger than ΔX.

B = ΔX + 2

B = 3.75" + 2" = 5.75" Minimum (95 mm + 54 = 4845 mm)

In this case, a standard Victaulic No. 43 grooved x grooved adapter nipple with a 6" (152.4 mm) end-to-end dimension can be utilized as the parallel branch for either cut or roll groove pipe.

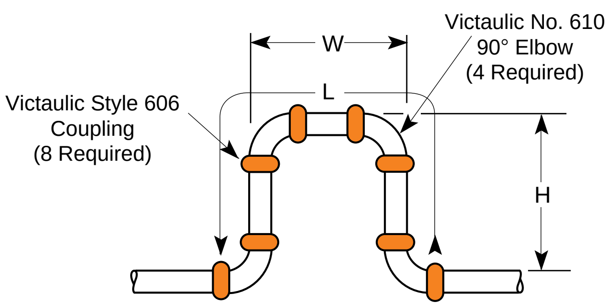
5. Expansion Loops for Joining Copper Tubing with Victaulic Copper Connection Products

Expansion loops or "U" bends are frequently used to accommodate the expansion and/or contraction of pipe lines due to thermal changes. Copper tube, as does all piping material, expands and contracts with these temperature changes. Table 1 in Section 26.02 shows the actual expansion of 100-foot (30.5 m) pipe lengths for copper tubing. Calculations for the anticipated expansion/contraction can be obtained from the example shown in 26.02.

The necessary length of copper tube expansion loop can be calculated from the following formulas (1) (2):

$$L = \sqrt{\frac{3EDe}{S}}$$

L = Loop length, in inches, as shown in the figure below:



E = modulus of elasticity of copper in PSI = 15,600,000 PSI (107 546 400 kPa)

S = allowable stress of material in flexure, in PSI = 6000 PSI (41 364 kPa)

D = outside diameter of copper tubing in inches

e = amount of expansion to be absorbed, in inches

Simplifying the formula:

$$L = 88.32\sqrt{De}$$

Calculated Loop lengths for various expansions are shown in the table below:

TABLE 4 26.02-4A

Expansion Inches/mm	Loop Length "L", Inches/mm for Tube Sizes Shown				
	2½ 63.5	3 76.2	4 101.6	5 127.0	6 152.4
½ 12.7	102 2590.8	111 2819.4	127 3225.8	142 3606.8	155 3937.0
1 25.4	144 3657.6	157 3987.8	180 4572.0	200 5080.0	219 5562.6
1½ 38.1	176 4470.4	192 4876.8	220 5588.0	245 6223.0	268 6807.2
2 50.8	203 5156.2	221 5613.4	254 6451.6	283 7188.2	310 7874.0
2½ 63.5	227 5765.8	247 6273.8	284 7213.6	317 8051.8	346 8788.4
3 76.2	248 6299.2	271 6883.4	311 7899.4	347 8813.8	379 9626.6

NOTE: Expansion Loop should be located between two anchors and the pipe should be guided so as to direct the movement into the loop.

References:

(1) Copper/Brass/Bronze Product Handbook, Copper Development Association, Inc.

(2) Source book on Copper and Copper Alloys, American Society for Metals.