

Thermal Expansion and Contraction in Plastics Piping Systems

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Foreword

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The purpose of this technical report is to provide information on thermal expansion and contraction in plastic piping systems.

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1. INTRODUCTION

Expansion and contraction of piping systems due to temperature changes is not unique to plastics. Changes in temperature tend to cause a change in dimensions of any matter. But, the amount of dimensional change for a given temperature change can vary significantly depending on the material characteristics. Thermoplastic materials exhibit a relatively high tendency to expand and contract when subjected to a temperature change – as much as about ten times that which is exhibited by metals. Accordingly, the design and installation of plastics piping often requires that special attention be paid to this characteristic.

As elaborated later in this report, the restraining of the tendency of a piping system to expand/contract can result in significant stress reactions in pipe and fittings, or between the piping and its supporting structure. The allowing of a moderate change in length of an installed piping system as a consequence of a temperature change is generally beneficial, regardless of the piping material, in that it tends to reduce and redistribute the stresses that are generated should the tendency for a dimensional change be fully restrained. Thus, allowing controlled expansion/contraction to take place in one part of a piping system is an accepted means to prevent added stresses to rise to levels in other parts of the system that could compromise the performance of, or cause damage to the structural integrity of a piping component, or to the structure which supports the piping. Everyone is familiar with the typical expansion loops that are periodically placed in long pipelines subject to wide temperature changes, such as steam lines and the Alaska oil pipeline. These loops absorb changes in pipe length and thereby mute and redistribute the large stresses that would result if pipe thermal movements had been physically restrained. Similar measures for safely absorbing thermal expansion/contraction reactions need to be taken with thermoplastic piping systems.

In installations, such as in buried piping systems, where loops or other means for absorbing thermal expansion/contraction forces are either not an option nor practical, other measures can be used to safely isolate pipe joints, fittings and other piping components from excessive forces.

This report discusses thermal expansion/contraction effects in thermoplastics piping and presents general recommendations for ensuring that these effects are adequately compensated both during design and installation. As demonstrated by laboratory tests and extensive field experience, the potential expansion/contraction problems in plastics piping systems are not as great as their larger tendency to expand and contract due to changes in temperature might suggest. Potential problems can readily be mitigated by the exercise of relatively simple measures that may be taken during piping system design and installation.

The potential consequences of larger expansion/contraction coefficients are greatly offset by plastics' lower stiffness as well as by their capacity to gradually reduce stress reactions through the phenomenon of stress-relaxation. These qualities of plastics piping result in considerably lower ultimate reaction loads than those that result in metal piping for an equal temperature change. Notwithstanding these beneficial features, design and installation should always be conducted with the objective in mind of the avoiding, or adequately compensating, potentially adverse effects of expansion/contraction. Some situations that require special attention include the following: when unconstrained pipe contraction can

risk the pull-out of a pipe from a fitting; when pipe expansion/contraction can create excessive thrust or bending moments on fittings, particularly on fabricated fittings, flanges and other piping components that are more vulnerable than pipe to such forces; when repetitive expansion/contraction can induce material fatigue at some stress-riser in the piping, typically at some point in a change-of-direction fitting; and when expansion of above ground piping can result in excessive sag.

The information presented herein is intended to serve as a general guide for the identifying and mitigating of potential expansion/contraction problems in the more common applications of plastic piping systems. It should be recognized that a piping system is subject to stresses generated by other reactions than just to temperature variations. For example, in pressure applications the stresses resulting from internal pressure can be a major contributor. Other significant contributions to total stress can come from the weight of the pipe and its contents, from inertial reactions to sudden changes in velocity, and from externally applied loads. For more complex piping systems, especially in which relatively severe service and installation conditions could be encountered, appropriate engineering references should be consulted for more comprehensive guidance for piping system stress/strain analysis and for methods of reducing operating stresses/strains to acceptable values.

2. LINEAR COEFFICIENTS OF THERMAL EXPANSION

The change in length with temperature for a solid material relative to its original length is generally expressed by the parameter *linear coefficient of thermal expansion*. This parameter has units of reciprocal temperature $[(^{\circ}\text{C})^{-1} \text{ or } (^{\circ}\text{F})^{-1}]$. Linear thermal expansion/contraction coefficients for commonly used thermoplastics piping materials are presented in Table A-1. The values for plastic materials have been established in accordance with method ASTM D696. Of course, heating or cooling affects all dimensions in a body, with a resultant change in volume. For materials, such as thermoplastics, for which for most practical purposes thermal expansion may be assumed to be isotropic the volumetric coefficient of thermal expansion is approximately three times the linear coefficient.

The values in Table A-1 are for the convenient temperature range of approximately -30°C (-22°F) to $+30^{\circ}\text{C}$ (86°F). The magnitude of the coefficient tends to somewhat increase with increasing temperature. The samples on which the coefficients are established have to be prepared so as to minimize any possible anisotropy and residual stress. In reality, some anisotropy in thermoplastics pipe and fittings always present because of the way in which they are produced – for example, a pipe may have a slightly different coefficient of expansion in the extrusion (i.e., axial) direction as compared to that in its diametrical direction. However, for purposes of design this relatively small degree of anisotropy can generally be neglected. Method of processing could also result in a residual manufacturing stress that can produce some irreversible dimensional change upon the first few temperature change cycles.

It should also be considered that the values in Table A-1 are for fully unrestrained specimens, which is not always the case in actual practice as some restraint against

completely free pipe movement is frequently present. Furthermore, the coefficients given in this table represent typical values for a family of materials. The actual value for a particular commercial plastic may be slightly greater or smaller depending on the material's specific formulation; that is, the kind and amount of other ingredients (i.e., additives) that may have been used in addition to the base polymer. Notwithstanding these limitations, the values in Table A-I are considered sufficiently reasonable approximations for adequately estimating the effects of expansion/contraction for most cases of plastic piping design and installation.

3. THERMAL EXPANSION/CONTRACTION REACTIONS IN PLASTICS PIPING SYSTEMS

The total stress and total strain that occurs at any point in a piping system, as well as the principal direction in which it acts (i.e., circumferential, axial or radial) depends on the combined effect of several possible reactions. Unless muted by proper design and installation, thermal stress can be a major contributor to the net stress acting in the axial direction. As explained in the introduction, this report only addresses effects of thermal expansion/contraction. The reader should keep in mind that the pipe and each of the other components in a piping system will also be subjected to other stress/strain reactions than those that just arise from thermal expansion/contraction.

Changes in Length – When a pipe is anchored at one end but can otherwise freely move in the axial direction, as is illustrated by Figure 1, an increase in temperature causes the pipe to increase in overall length. A decrease in temperature would cause an opposite change. The following expression predicts the net expansion/contraction in the length of a fully unrestrained pipe that occurs in consequence of a given change in temperature:

$$\Delta L = \alpha \cdot L \cdot \Delta T \quad \text{(Equation 1)}$$

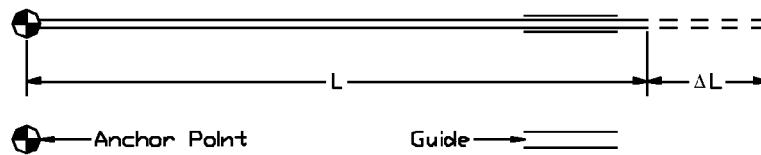
Where:

ΔL	=	change in pipe length, in
L	=	initial pipe length, in
ΔT	=	change in pipe temperature, °F
α	=	coefficient of linear expansion/contraction, in/in °F

As indicated by the last column in Table A-1, the relatively large coefficient of thermal expansion/contraction of plastics pipe results in a change in length for the same temperature change that is almost ten times greater than that for metal pipe.

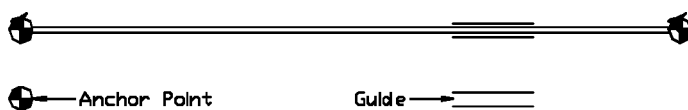
The actual change in pipe length occasioned by a temperature change will more often than not somewhat less than calculated by the above equation because installed pipe generally experiences some restraint against freely moving in the axial direction. The restraint may be relatively minor, such as the small frictional drag of guides and supports in the case of above ground installations; or it may be major, as when a pipe is continuously constrained by surrounding soil.

Figure 1



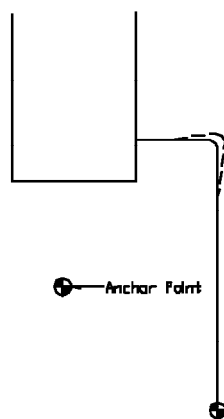
A pipe anchored at one end will expand in length when subjected to a higher temperature.

Figure 2



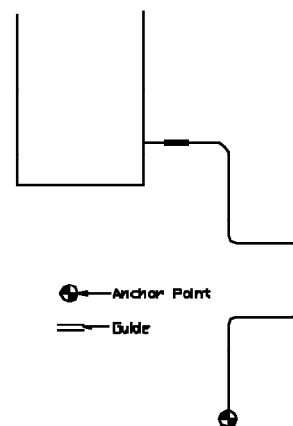
A pipe restrained from shortening or lengthening will react to temperature changes by generating compressive or tensile forces that act in the axial direction.

Figure 3



In this layout, thermal expansion of the longer vertical run results in the development of high bending stresses in the shorter horizontal run.

Figure 4



Two techniques for isolating a short branch from excessive bending are shown by the use of a loop, which safely absorbs the vertical expansion, and by the placement of a guide, or support, in the short horizontal run to protect it against bending.

Thermally Induced Loads When Pipe is Fully Restrained – In the case of a pipe length which is restrained against lengthening or shortening, a change in pipe temperature results in the development of an axial compressive or tensile stress. This stress is resisted by a compressive or tensile force that acts on the pipe ends, or at any point in the pipe at which it may be anchored. Should this reaction stress and resultant force be sufficiently large it could lead to performance problems in, or damage to a piping component, or to the supporting structure.

The primary concern with plastics pipe in above ground installations is the same as for metal pipe; it is the possibility that an excessively large thrust may be transmitted to a piping components or, to the supporting structure. However, as already pointed out the thermal reaction thrust in plastics piping is generally of much lower magnitude than that which is generated in a metal piping systems for the same temperature differential. Also, because plastic pipe is more flexible than metal pipe – due to the significantly lower elastic modulus of plastic materials – when placed in compression it can more easily deform laterally and when allowed to do so it is somewhat less likely to fully transmit compressive loads onto external restraints than does metal pipe.

The magnitude of the tensile or compressive axial stress that can be generated in a pipe that is constrained both against axial and lateral deformation (See Figure 2) may be computed using the same equation, as follows, as is used with metal pipe:

$$S = E \cdot \alpha \cdot \Delta T \quad (\text{Equation 2})$$

Where:

- S = tensile or compressive stress in axial direction, psi
- E = modulus of elasticity (*effective* modulus in the case of plastics), psi
- α = coefficient of expansion/contraction, in / in °F
- ΔT = temperature differential, °F

There is however, one essential difference in the manner this equation is used with plastics pipe: the *effective* modulus is used with plastics, whereas with metals the *elastic* modulus is employed. The term *elastic* denotes a proportionality between stress and strain that remains constant independent of stress and duration of stress application. While for metals this assumption of elastic stress/strain response is sufficiently accurate for most design purposes it is not applicable to plastics. Plastics are viscoelastic materials – meaning that they behave as a composite of an elastic solid and a highly viscous liquid. Viscoelastic materials exhibit a stress/strain relationship that is dependent on the magnitude of the applied stress and that is also profoundly affected by duration of loading and by temperature. As a result, plastics do not have a true modulus of elasticity. Upon the application of a stress a plastics material undergoes an initial resultant deformation which upon increased duration of loading grows – but at a gradually decreasing rate – into an ever larger deformation. This continuing, but steadily slowing down deformation under continuous loading is called *creep*.

When subjected to constant deformation there is an analogous response called *stress-relaxation*. The stress required to maintain a certain initial deformation tends to diminish, or relax, with time. As in the case of creep, stress-relaxation is fairly rapid at first, but as time increases the rate of stress-relaxation decreases and asymptotically approaches a

final value. Both rate of creep and rate of stress-relaxation in thermoplastics are greatly affected by temperature.

Even though the stress/strain relationship of viscoelastic material is much more complex than that of elastic materials the same equations which have been developed for the latter can be used with the former by means of the concept of *effective* modulus. Effective modulus (sometimes also referred to as the *creep-modulus*) is the approximate ratio of stress to strain that results under a particular combination of conditions (e. g., magnitude of load, duration of loading, temperature and environment). Consequently, whenever a value of effective modulus is reported the applicable conditions (e.g., 50-years under continuous loading at 73°F) are also stated. Often times the effective modulus is expressed as a percentage of the material's *short-term modulus* which has been determined by means of a standard short duration tensile strength test that takes only minutes to complete. Approximate values of the ambient temperature short-term moduli of various piping material are presented in Table A-2. Also included in this table are multipliers by which these values may be reduced to approximate values of effective modulus for certain time periods of continuous loading. These multipliers may also be used as an index of the rate at which stress-relaxation occurs under the condition of constant deformation.

Approximate temperature multipliers by which the values in Table A-2 may be adjusted to other temperatures are shown in Table A-3.

An often used convention for the estimating of the initial (i.e., maximum) axial stress that can result by constraining pipe expansion/contraction is to conduct the calculation under two generally very conservative assumptions: the temperature change occurs very quickly, meaning that the short-term modulus should be used; and the material stiffness for the lower temperature is the primary determinant of the magnitude of the generated stress, meaning that the short-term modulus for the lowest temperature should be used. Because the effective modulus in fact decreases with increasing temperature and because the change in temperature seldom occurs very quickly, both these assumptions lead to an estimate of that is somewhat larger than actual.

For an example of the application of Equation 2 let us assume that a PE 3408 pipe, which because it has been laying above ground in direct exposure to the sun is at a temperature of 120°F, is being lowered into the shaded bottom of a trench that has been excavated in -term modulus for this pipe material of 130,000 psi for 50°F (interpolated from the values given in Table A-3) and using the expansion contraction coefficient of 9.0×10^{-5} in/in x °F (from Table A-I) the estimated maximum initial axial tensile stress than can occur in this pipe if it were restrained against contraction immediately after placement in the cooler trench (by say, being connected to an anchored fitting) is as follows:

$$\begin{aligned} S &= E \cdot \alpha \cdot \Delta T \\ S &= 130,000 \text{ psi} \cdot 9.0 \times 10^{-5} (\text{°F})^{-1} \cdot (120 - 50) \text{ °F} \\ S &= 819 \text{ psi} \end{aligned}$$

As pointed out above, the actual initially developed stress will be somewhat lower. However, even this overstated value is well within both the short-term strength and the long-term strength capabilities of PE 3408 materials which, respectively, are about 3,200 and