Thermal Stresses in HDPE Water Pipes

Final Report

Submitted to:

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DISCLAIMER

This report presents pipe stresses caused only by temperature changes. The effect of other factors, such as stresses due to soil overburden, internal pipe pressures, external loadings, and ground movement are outside the scope of this report.

EXECUTIVE SUMMARY

This report presents methods to evaluate the stresses in high-density polyethylene caused by temperature changes. The report presents the HDPE thermo-mechanical properties used in a viscoelastic approach for evaluating stresses. The methodology requires that the time and temperature conditions be defined when determining the stresses, and the report makes recommendations for these. The HDPE material properties needed for determining stress changes are introduced and recommendations are given for selecting particular values. Where possible, checks are made for consistency with current PPI recommendations.

A straight-forward linear viscoelastic model for evaluating stresses in buried HDPE is presented. The mathematical model and equations can be used for exact calculation of stresses, which includes stress superposition for multiple time-temperature loading conditions. An alternate approximate method based on the exact solutions also is proposed. This alternate method allows practitioners to estimate pipe stresses without using the detailed equations presented.

Recommendations are made for temperature changes for a) installation, b) a relaxation period following installation, and c) seasonal variations in different geographical zones. The proposed temperature changes account for:

1) The temperatures at the beginning and end of an activity,
2) The amount of time over which the temperature change occurs, referred to as the load duration,
3) The amount of relaxation time between temperature changes, and
4) The range of seasonal temperature changes for different geographical temperature zones.

Pipeline installation temperatures, or temperatures at hook-up, are given for two types of construction. *Typical* conditions are those that do not intentionally minimize installation temperatures and stresses. *Best Practices* are based on allowing the pipe to cool to the prevailing ground temperature prior to hook-up as discussed in Section 6, minimizing the installation stresses. These temperatures for the three temperature zones and the two types of construction practices are given below.

Installation Temperatures

Temperature Zone (see Fig. 3.3)	Installation (Hook-up) Temperature	
	Typical	Best Practices
Warm	100°F	70°F
Moderate	90°F	65°F
Cold	80°F	60°F

°C = (°F-32)×5/9

The range of seasonal temperature changes have been evaluated across the US and Canada. The stresses for the recommended minimum temperatures in cold, warm, and moderate temperature zones in the U.S. and Canada are given in the table below. The soil temperatures and hook-up temperatures used for example calculations in the table were developed with the PPI task group based on a review of the information in Section 3.

Temperatures and stresses for representative design considerations

Construction	Temperature zone (See Fig. 3.3)	Installation (2 days)	Relaxation (0 to 30 days)	Seasonal cooling (90 days)
		Temperature Phase and Temperatures		
Typical	Warm	100 to 70°F	70°F	70 to 50°F
	Moderate	90 to 65°F	65°F	65 to 40°F
	Cold	80 to 60°F	60°F	60 to 33°F
		Stresses (rounded to nearest 5 psi)		
	Warm	175	175	255
	Moderate	155	155	290
	Cold	130	130	300
		Temperature Phase and Temperatures		
Best Practices	Warm	Pipe and soil both at 70°F		70 to 50°F
	Moderate	Pipe and soil both at 65°F		65 to 40°F
	Cold	Pipe and soil both at 60°F		60 to 33°F
		Stresses (rounded to nearest 5 psi)		
	Warm	0		110
	Moderate	0		150
	Cold	0		180

°C = (°F-32)×5/9

Installation: Load duration = 2 days

Relaxation after installation: Load duration = 0 to 30 days

Seasonal cooling: Load duration = 90 days

Notes:

1. The values in the table are for illustrative purposes only. The designer should select the soil temperatures and ramp durations based on local conditions.
2. Soil temperatures are based on depths of cover associated with watermain installations in the applicable temperature zone.
3. Additional relaxation (not shown for clarity) will occur during the winter period.

With *typical* construction practice the installation temperature changes about 25 to 30ºF (14 to 17ºC) in 2 days depending on the temperature zone. A conservative choice is that there is no relaxation time after installation prior to the seasonal temperature change. The seasonal temperature change, again depending on the temperature zone, is about 20 to 30ºF (11 to 17ºC) in 90 days. The stresses caused by these temperature changes given are relatively small. For *typical* construction practices the stresses range from 255 to 300 psi (1.75 to 2.07 MPa). These stresses are less than 10% of a HDPE yield stress of $\sigma_{yield} \approx$ 3,500 psi (24 MPa).

Best Practices reduces the overall stresses during installation. Anything that can be done to reduce the temperature difference between the newly installed and existing pipeline will reduce the HDPE thermal stresses. Simply by backfilling the newly installed piping and waiting overnight after a hydrostatic pressure test prior to hook-up (*Best Practices*) can reduce these stresses to about 110 to 180 psi (0.76 to 1.24 MPa), about 3 to 6% of the HDPE yield stress. This is a significant reduction in stresses.

The methods and recommendations provided in this report are based on HDPE material properties, a survey of temperature changes and minimum temperatures in the U.S. and Canada, and judgement regarding practical design scenarios. This report is intended to provide guidance and insight into the main factors that influence thermal stresses in HDPE water pipelines.

Appendix A provides detailed example calculations for three representative design scenarios. These step-by-step examples can be used as templates for performing design calculations for different cases.

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LIST OF SYMBOLS

°C	Celsius degrees temperature
°F	Fahrenheit degrees temperature
E_p	pipe Young's modulus
E_{ref}	reference pipe Young's modulus
E(T)	temperature dependent Young's modulus
E(T, t)	temperature and time dependent Young's modulus
E_0	initial modulus
n	relaxation exponent
t_{start}	starting time
t_{finish}	finishing time
t_1	time at the end of the first ramp loading
t_2	time at the end of relaxation phase
t_3	time at the end of the second ramp loading
T_{start}	starting temperature
T_{finish}	finishing temperature
T_1	temperature at the beginning of installation phase
T_2	temperature at the end of installation and during relaxation phases
T_3	temperature at the end of seasonal cooling phase
ΔT	temperature change
α_T	coefficient of thermal expansion/contraction
ε_{0i}	i^{th} strain increment
ε_0	initial strain
ν	Poisson's ratio
σ_{allow}	allowable stress
$\sigma(t)$	stress at time t
$\sigma(T, t)$	stress at temperature T and time t
σ_{yield}	yield stress
σ_0	instantaneous stress
τ_i	time when i^t strain increment is applied

Section 1

Introduction

1.1. Organization

This report provides guidance on evaluating stresses in high-density polyethylene (HDPE) piping resulting from temperature changes. Section 1 provides introductory comments and presents the report organization. Section 1 also presents some of the basic terminology used in the report. Section 2 summarizes the relevant material properties used for HDPE 4XXX. These properties are consistent with those developed from laboratory testing at Cornell University and values presented in the PPI Handbook for Polyethylene Pipe (PPI, 2008). Section 3 addresses seasonal ground temperatures within the U.S. and southern Canada for the range of typical installation depths. These temperatures can be used by a design engineer to develop the range of thermal stresses expected to occur in the pipe. Section 3 also presents water temperatures received following a request from PPI to several water companies to monitor water temperatures and provide typical temperature ranges within their systems. Section 4 presents the methodology to determine thermal stresses in restrained PE pipe due to temperature changes. The methodology accounts for the viscoelastic effects of the PE and can superimpose stresses resulting from several loading scenarios. The effects of near-instantaneous temperature changes due to a rapid influx of cold water are included in the methodology.

In Section 5 several implications of the approach are presented in an alternate design format. Stresses are summarized in tables and figures allowing the engineer to select stresses based on the appropriate temperature changes for their application. There are many temperature scenarios to consider, and this report presents several scenarios that should be considered. A recommended approach for evaluating temperature changes is presented, and examples are given. Section 6 presents best practices for the control of thermal stresses. These are provided to guide a designer in minimizing the effects of the thermal stresses. The conclusions drawn from the report are summarized in Section 7.

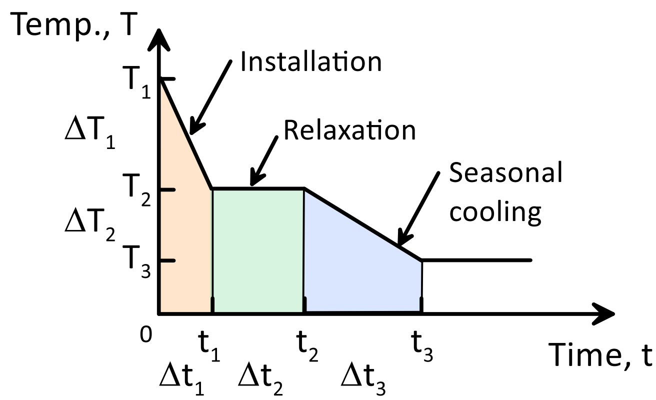


Figure 1.1. Time and temperature terminology

1.2. Terminology

This report uses conventional terminology and symbols for most variables, such as E for Young's modulus, σ for stress, and sign conventions of positive for tensile forces and stresses and negative for compressive forces and stresses. In the sections dealing with stress relaxation there are several times, temperatures, and temperature changes that are important to note. Figure 1.1 shows schematically the times and temperatures used in this report. The main times and temperatures are:

1) Connection of a new pipe section to an existing pipe is referred to as hook-up. This is shown as the "Installation" zone in Figure 1.1. The temperature change during hook-up is from T_1 to T_2 and occurs between t = 0 and t_1. The temperature change is ΔT_1.

2) Stresses relax between t_1 and t_2. The temperature at this relaxation stage is constant at T_2. This is the "Relaxation" zone in Figure 1.1.

3) At t_2 the seasonal cooling begins and the temperature is reduced to T_3. The "Seasonal Cooling" stops at t_3 and the temperature then remains constant at T_3 as shown in Figure 1.1, and further relaxation of pipe stresses occurs. Generally, the stress at the end of the seasonal cooling ramp is the largest.

4) Additional stress changes can occur because of a rapid influx of cold water. The water temperature will likely change as the water moves into the pipeline, which is at ground temperature. The cold water temperature is between 33 and 40°F (1 and 4°C). This cold-water influx can occur at any time the line is in service, i.e., at $t > t_1$. If during a rapid water

influx, the pipe is at or near the seasonal minimum, then there is not much effect because the pipe is already cold.

This report frequently refers to the *instantaneous* modulus of the plastic pipe as E_0. E_0 is the modulus at the end of an applied temperature change that occurs over a load duration time of t_1. Young's modulus of HDPE varies with temperature, and in the viscoelastic model used to describe the PE behavior, the temperature changes with time. When a temperature change occurs, the value of E_0 is the modulus at that temperature. This also is referred to as E(T). Figure 1.2 shows schematically how the time and temperature contribute to the instantaneous modulus. The "instantaneous" strain, ε_0 is given by:

$$\varepsilon_0 = \alpha_T \Delta T \tag{1.1}$$

where

α_T = coefficient of thermal expansion/contraction, and

ΔT = temperature change.

The instantaneous stress, is given by:

$$\sigma_0 = \varepsilon_0 E_0 = \alpha_T \Delta T E_0 \tag{1.2}$$

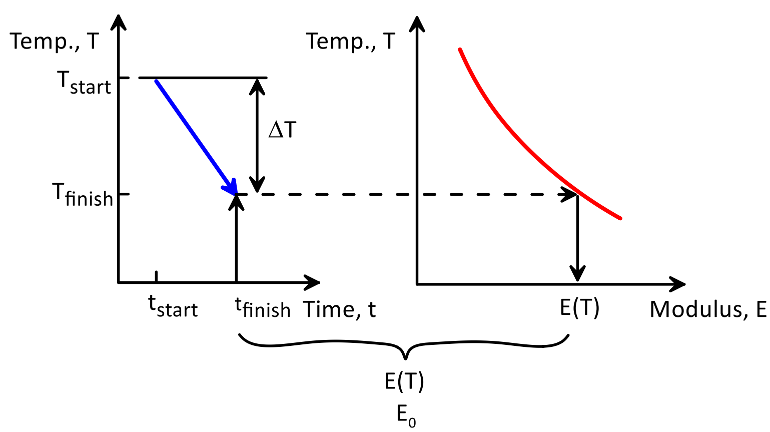


Figure 1.2. Definition of instantaneous modulus, E_0.

Section 2

HDPE Material Properties

2.1. Introduction

This section presents general aspects of PE viscoelastic behavior and the relevant material properties used in the stress and displacement evaluations of high-density polyethylene PE 4XXX used in this report. The material properties are, in general, temperature, time, and strain-rate related. This section is not intended to be a comprehensive evaluation of all PE properties. The material properties presented in this section are based on a combination of experimental results and generally accepted properties such as those presented in the Chapter 3 and its appendices of the Handbook of Polyethylene Pipe (PPI, 2008).

Polyethylene has highly time- and temperature-dependent properties. The mechanical properties of polyethylene can change significantly even within the range of temperatures found in typical civil engineering applications, e.g., the modulus can change by a factor of two between 32 and 120°F (0 and ~50°C). Under a constant strain rate, higher temperatures decrease the material modulus and increase material ductility. When the temperature is held constant during mechanical testing, strain rate has a significant effect on material properties. With a higher strain rate, molecular chains have less time to deform under load, leading to a stiffer response.

In a viscoelastic material such as polyethylene, the stress generally is a function of both time and applied strain. Linear viscoelasticity can be applied to polyethylene when the stresses are less than about 60% of the yield stress (Moore 1994) or when the strains are less than 0.01 (Moore and Hu 1995; Moore and Zhang 1995). When the thermal stresses in polyethylene pipes are concerned, a 1% strain would be caused by a temperature change of approximately 125°F (~70°C) considering a typical axial coefficient of thermal expansion/contraction for PE4XXX polyethylene pipe. The temperature changes in buried polyethylene pipes are expected to be substantially less than this so the strains due to a thermal loading is expected to be less than 1%, and linear viscoelasticity is used in this report.

2.2. Relaxation Rate

Viscoelastic relaxation rates can be obtained by applying an initial deformation to a test specimen and then measuring the time-dependent decrease in load at predetermined time intervals. When the strains are applied instantly, the time-dependent stress obtained from a stress-relaxation test can be modeled by the following power law relationship.

$$\sigma(t) = \sigma_0 \, t^{-n} \tag{2.1}$$

where

σ_0 = *instantaneous* pipe stress,

t = time, and

n = power law exponent.

The instantaneous pipe stress for temperature loading is given by:

$$\sigma_0 = [E(T) = E_0] \, \alpha_T \, \Delta T \tag{2.2}$$

where

E(T) = modulus at the final temperature,

α_T = coefficient of thermal expansion, and

ΔT = instantaneous temperature change.

The exponential relaxation is shown in Figure 2.1. A reference time, t, of 1 minute typically is used when describing stress relaxation. Table 2.1 lists the power law exponent, n, for stress relaxation tests performed by several researchers. Higher values of n indicate more rapid relaxations. The relaxation rates for PE often are taken as $n \approx 0.1 \pm 0.02$. The methodology used in this report consistently uses an exponent of n = 0.085, and near the lower bound of the general range of reported observations. This is a conservative approach for estimating field relaxations and pipe stresses.

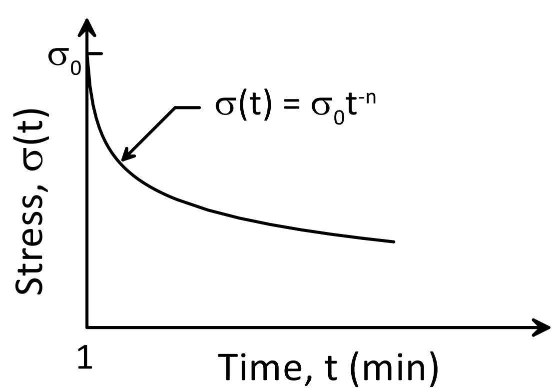


Figure 2.1. Exponential variation in stress with time

Table 2.1. Relaxation power law exponents for PE piping

Source	Material	Nominal Temperature	Power Law Exponent, n
Chua and Lytton (1989)	HDPE	70°F (21°C)	0.098
Hashash (1991)	HDPE	70°F (21°C)	0.086
Husted and Thompson (1985)	MDPE	70°F (21°C)	0.105
Janson (1985)	HDPE MDPE	70°F (21°C)	0.088 0.081
Keeney (1999)	MDPE	20 to 120°F (-7 to 49°C)	0.085 ± 0.01

2.3. Young's Modulus, E

Young's modulus, E, for PE is temperature-, time-, and strain rate-dependent. In this report strain-rate dependency is not considered. This section presents the moduli used to evaluate pipe stresses and displacements.

2.3.1. Modulus, E(T)

Figure 2.2 shows the recommended Young's modulus, E(T), used for relatively rapid loading of HDPE. This modulus represents the stress-strain response of the pipe material at a given temperature. The recommended curve, and the associated equations, are based on experimental data from both stress- and strain-controlled testing. The "PPI" curve is based on the value of E(T) = 130 ksi (896 MPa) at T = 73°F (23°C) and temperature modification factors given in Table B.1.2 in Chapter 3 of the PPI PE Handbook (PPI, 2008). Table 2.2 provides the tabulated data for the moduli used in this report. Note that the modulus in Table 2.2 at T = 73°F (23°C) is 127 ksi (876 MPa), and not 130 ksi (896 MPa). This is due to the curve fitting parameters in Eqn. 2.3 that were used in the calculations. Equations are given so the calculations can be done in spreadsheets or other numerical approaches. This difference is not significant and well within the range of uncertainty in material properties. For the extreme temperature range encountered in routine practice, say 32 to 120°F (0 to 50°C), the two curves shown in Figure 2.2 are in excellent agreement. The equations for the recommended data in Figure 2.2 are given by:

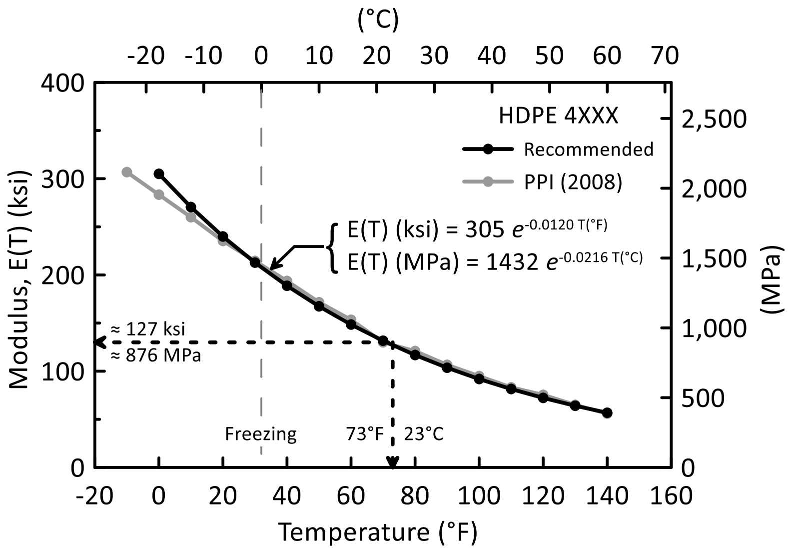


Figure 2.2. Modulus vs. temperature for HDPE

$$\mathrm{E(T)\,(ksi)} = 305e^{-0.0120\,\mathrm{T(^oF)}}$$
$$\mathrm{E(T)\,(MPa)} = 1432e^{-0.0216\,\mathrm{T(^oC)}} \tag{2.3}$$

Table 2.2. Modulus vs. temperature for HDPE pipe

T (°F)	E(T) (ksi)	T (°F)	E(T) (ksi)
-20	387.7	70	131.7
-10	343.9	73	127.0
0	305.0	80	116.8
10	270.5	90	103.6
20	239.9	100	91.9
30	212.8	110	81.5
32	207.7	120	72.3
40	188.7	130	64.1
50	167.4	140	56.8
60	148.5	150	50.4

T (°C)	E(T) (MPa)	T (°C)	E(T) (MPa)
-30	2738	20	930
-25	2457	25	834
-20	2206	30	749
-15	1980	35	672
-10	1777	40	604
-5	1595	45	542
0	1432	50	486
5	1285	55	437
10	1154	60	392
15	1036	65	352

2.3.2. Apparent Young's Modulus, E(T, t)

Frequently in viscoelastic evaluations, an "apparent modulus" is used to account for stress relaxation with time. This apparent modulus is the relaxed stress at some time, t, relative to the initial applied thermal strain. The method described in Section 3 of this report continuously varies the modulus according to Eqn. 2.3 as the temperature changes. Methods used for stress relaxation accounts for a) variations in modulus with temperature as given in Figure 2.2, b) stresses caused by temperature changes occurring over a specific loading time, c) stress relaxation, and d) superposition of stress changes added at various times in the design sequence for an HDPE pipeline. The apparent modulus is not required in any of the calculations presented in this report.

2.4. Coefficient of Thermal Expansion (CTE), α_T

The coefficient of thermal expansion, or CTE, for PE pipe depends greatly on the molecular structure of the material. Because of the manufacturing process there is a difference between the CTE in the axial (longitudinal) direction and hoop (circumferential) directions. Experimental observations have indicated that the hoop CTE is roughly 65 to 70% of the axial CTE. Reported values for the axial CTE are α_T = 100, 90, and 80×10^{-6} per °F (180, 162, and 144×10^{-6} per °C) for PE2XXX, PE3XXX, and PE4XXX, respectively. The value used in this report for PE4XXX is α_T = 80×10^{-6} per °F (144×10^{-6} per °C). Unless specifically noted, the CTE in the hoop direction will be 65% of the axial value.

2.5. Poisson's Ratio

Poisson's ratio for many types of PE has been found to increase linearly from about $\nu = 0.42$ at 20°F (-7°C) to about $\nu = 0.49$ at 120°F (49°C) [Stewart, et al., (1999)]. Figure 2.3 shows this variation for MDPE, which has similar Poisson's ratio as HDPE. Poisson's ratio used at T = 73°F (23°C) is $\nu = 0.45$. This is the same value given in the Chapter 3 of the PPI PE Handbook (PPI, 2008).

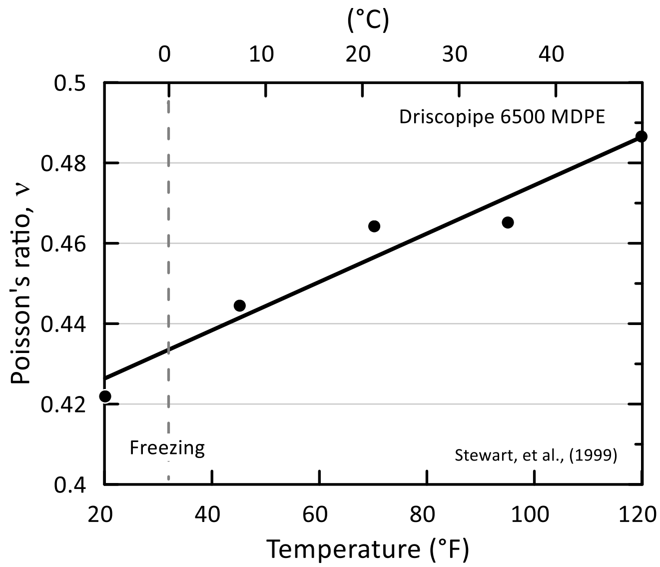


Figure 2.3. Poisson's ratio vs. temperature for PE

2.6. Summary

HDPE is a viscoelastic material with temperature- and time-dependent material properties. This section identified the primary properties used in the evaluations presented in later sections. The main PE 4XXX properties required for the evaluation of pipeline stresses and displacements are:

1) The variation in Young's modulus with temperature, E(T). The values used are:

$$\mathrm{E(T)\,(ksi)} = 305e^{-0.0120\ \mathrm{T(^oF)}}$$
$$\mathrm{E(T)\,(MPa)} = 1432e^{-0.0216\ \mathrm{T(^oC)}}$$

2) The coefficient of thermal expansion, CTE in the axial direction is as $\alpha_T = 80\times10^{-6}/^oF$ ($144\times10^{-6}/^oC$). The CTE in the hoop direction will be taken as 65% of the axial CTE.

3) The stress relaxation rate is n = 0.085. This is a conservative estimate for HDPE.

4) Poisson's ratio is taken as v = 0.45 in both the axial and hoop directions.

Section 3

Temperature Changes

3.1. Introduction

Thermal loads in buried piping are a direct result of temperature changes. This section presents data from measured ground temperatures at pipeline depths in the United States to develop seasonal design temperature ranges. In addition, ground and water temperature measurements reported by several water utilities about the operational conditions within their system are presented. Design scenarios are identified that represent reasonable situations for the range of HDPE piping temperatures.

3.2. Seasonal Temperature Variations

Figure 3.1 illustrates ground temperature data for several locations within the northeastern United States as reported by Keeney (1999). These data were collected at soil depths between 3 to 4 ft (0.9 to 1.2 m). Ground temperatures fluctuate between 70 and 20°F (21 and -7°C) over a period of 6 to 7 months. More typically, the data show that ground temperatures fluctuate between 70 and 30°F (21 and -1°C). Figure 3.2 presents data gathered from the National Resources and Conservation Services (NRCS) at a depth of 40 in. (1.2 m). The contours shown in Figure 3.2 are extreme frost penetration depths across the United States provided by NAVFAC (1986). The lower bound ground temperature at this depth is on the order of 32°F (0ºC), and the upper bound is about 60°F (16ºC).

Figure 3.3 presents a map of lower Canada and the U.S. with three temperature zones: *cold*, *moderate*, and *warm*. The temperature zones shown in Figure 3.3 have been selected based on an interpretation of the information presented in the measured data and judgement regarding rational temperatures and temperature changes.

Figure 3.4 shows the recommended design temperature ranges for the three zones shown on Figure 3.3. In Figure 3.4, the starting ground temperature is shown as 70°F (21°C) and the time over which the seasonal temperature drop occurs, Δt_3, is 90 days or about 3 months. The difference in stresses for a ramp time from 1 to 3 months is small, because the stress relaxation occurs quite rapidly and after a month the stresses have relaxed substantially.

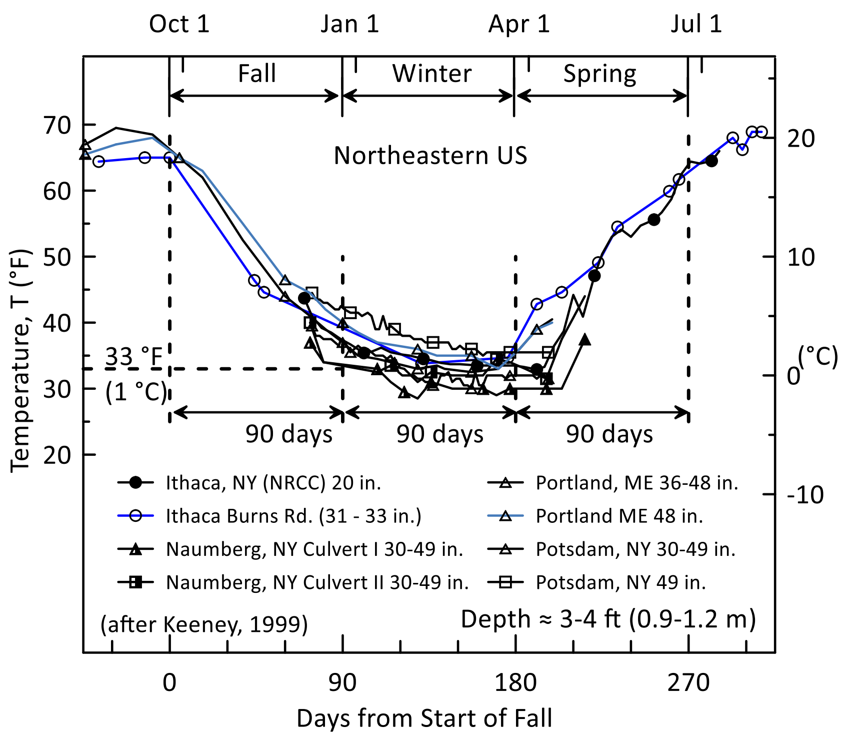


Figure 3.1. Measured ground temperatures in northeastern United States

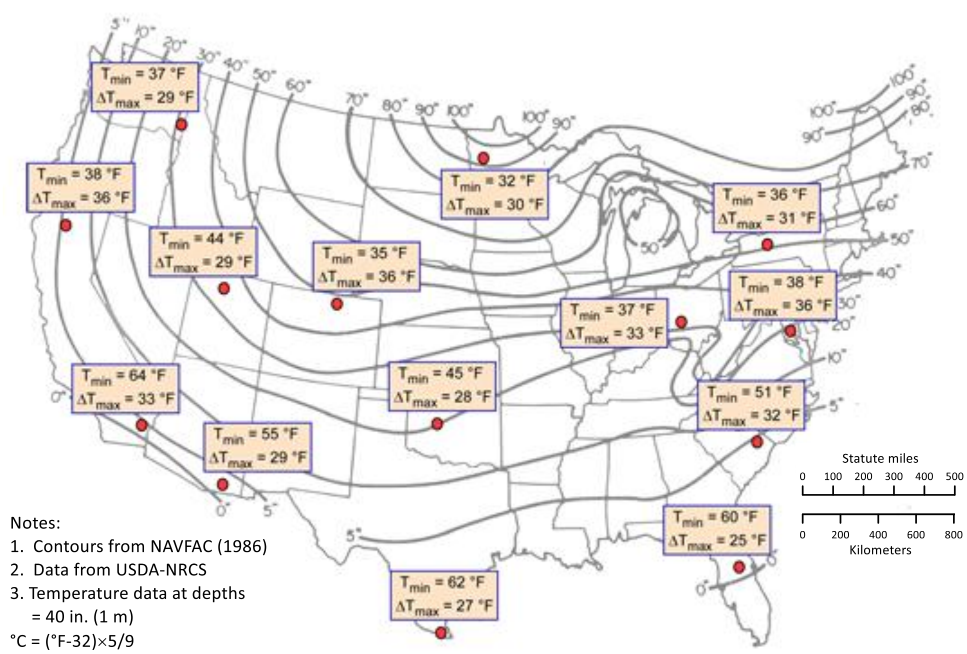


Figure 3.2. Typical minimum ground temperatures across U.S. (after NRCS & NAVFAC)

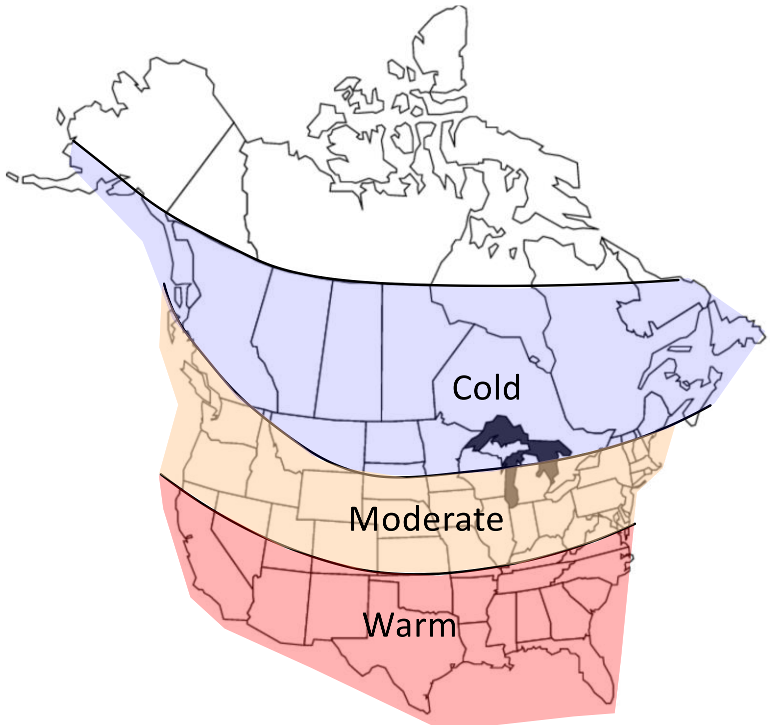


Figure 3.3. Temperature zones in lower Canada and U.S.

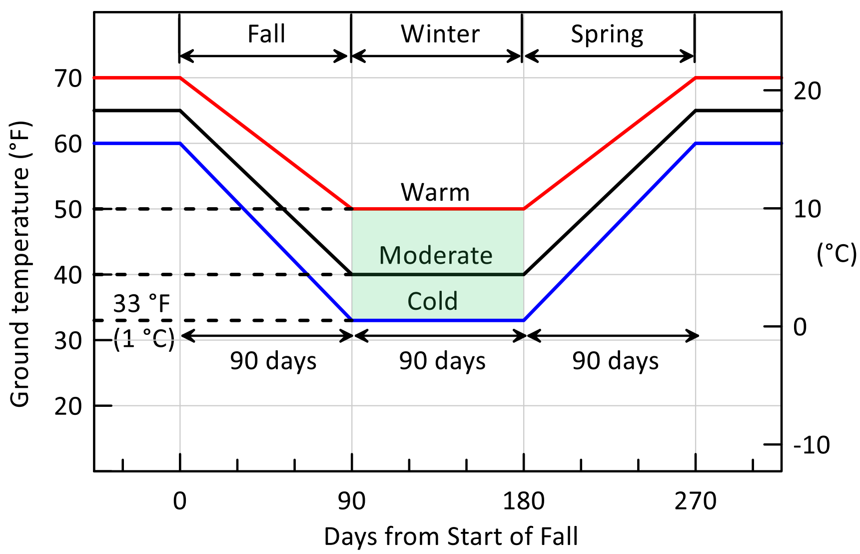


Figure 3.4. Design temperature ranges for pipelines in different temperature zones

Typically pipe burial depths are below the frost line and the coldest water temperature reported by water industry personnel was about 33°F (1°C), so a *lowest* temperature just above freezing is reasonable. Thus, the *maximum* design temperature change due to seasonal variations in ground temperature is about ΔT = 37 to 40°F (21 to 22°C) within the northeastern U.S. and other "cold" temperature zones.

3.3. Reported Temperature Ranges

In January 2020, PPI requested that several water utilities provide information about the operational conditions within their system. Two utilities, from Minnesota (MN) and Colorado (CO) have responded. The questions and responses were:

1. Ground temperature data at buried pipe depths.

   MN: At typical burial depths of 5 to 8 ft (1.5 to 2.4 m) the ground temperature would be about 50°F (10°C) in the summer and could be as low as 33°F (1°C) in a cold winter.

2. Water temperature data (minimum / maximum).

   CO: In a distribution system, the water temperature extremes would run as low of about 40°F (4°C) in the winter and a high of 72°F (22°C) in the summer. The average temperature in the system is 54°F (12°C).

   MN: Duluth's water supply from Lake Superior is typically in the 40s°F (single digit °Cs) all summer. In the winter the water it comes in at 33 to 35°F (1 to 2°C).

3. Comments on whether the company has experienced pipe pull-out.

   CO: No.

   MN: Absolutely none during normal operations.

4. Minimum temperature in above-ground water storage tanks and in other water sources.

   CO: The top couple inches freezes in the above ground tanks during winter months. The system does not have any elevated storage tanks.

   MN: 33°F (1°C). Ice layers in the tanks and recirculation pumps to keep them from freezing [at the depths from which the water is taken].

Critical information from the survey data is that the operational water temperature ranges from about 55°F (13°C) during warmer months to 33°F (1°C) in the winter. Additional considerations are that typically the water piping is buried below the frost depth, which can vary considerably throughout the U.S. and Canada. The typical range of ground temperatures at pipe depth is from 55 to 33°F (13 to 1°C).

3.4. Design Temperature Ranges

Temperatures for the evaluation of stresses resulting from temperature changes must consider:

1) The pipe temperature at the start of installation, T_1, the temperature at the end of installation, T_2, and the time interval over which the pipe cools during installation, Δt_1. These are referred to as the "Installation" changes, as was shown in Figure 1.1.

2) The constant temperature period, Δt_2, over which the pipe stresses can relax following installation. This is shown as the "Relaxation" phase in Figure 1.1.

3) The temperature drop to minimum seasonal temperature, T_3, and the time for this seasonal temperature change to occur, Δt_3. This is referred to as the "Seasonal cooling" zone in Figure 1.1.

The temperature and times for the three considerations above can cover wide ranges, depending on the utility location and construction periods. Consider that the pipe temperature at the start of installation ground temperature in the three zones could be between $T_1 \approx 100$ and 80°F (38 and 27°C). The high temperature of $T_1 = 100$°F (38°C) is a possible *upper* limit on this temperature. Reducing T_1 will greatly reduce the installation-related stresses. The pipe will cool to the ground temperature of between $T_2 \approx 70$ and 60°F (21and 16°C) in $\Delta t_1 = 2$ days. Two days is reasonable considering the time for backfill and pressure testing, prior to connection with the other pipe in the water system.

The "Relaxation" phase could be a *minimum* $\Delta t_2 = 0$ if the seasonal temperature change begins immediately after installation, with no time for stress relaxation. There also could be a few months of relaxation before the seasonal temperature change begins. Since the stress changes after about 1 month of relaxation are small, using a load duration of $\Delta t_2 = 30$ days as the *maximum* relaxation period is slightly conservative.

Figure 3.4 indicates seasonal minimum temperatures of T_3 = 50, 40 and 33°F (10, 4 and 1°C) for warm, moderate, and cold temperature zones, respectively, with a time of Δt_3 = 90 days for the seasonal change to occur.

Table 3.1 gives the temperature ranges for installation, relaxation, and seasonal cooling. In Table 3.1 conditions for *Typical* and *Best Practices* construction are identified. *Typical* conditions are those that do not intentionally minimize installation stresses. *Best Practices* are based on allowing the pipe to cool to the prevailing ground temperature prior to hook-up, minimizing the installation stresses. The load durations for these temperature changes also are given. Other temperatures – times can and should be used, depending on the situation. The ranges provided in Table 3.1 are intended to cover a substantial range of those encountered in routine practice.

Additional stress changes can occur because of a rapid influx of cold water. The water temperature will likely change as the water moves into the pipeline, which is at ground temperature. The cold water temperature ranges between 33 and 40°F (1 and 4°C). This cold-water influx can occur at any time the line is in service, i.e., at $t > t_1$. If during a rapid water influx, the pipe is at or near the seasonal minimum, then there is not much effect because the pipe is already cold. As the water flows into the pipeline, it likely will change temperature to that of the pipe, which would be from about 33 to 50°F (1 to 10°C).

3.5. Summary

Temperature and load durations were determined for the three phases of: 1) installation, 2) relaxation, and 3) seasonal changes, as well as 4) a rapid influx of cold water. Pipe installation temperatures could range from an initial temperature ranging from 100 to 80°F (38 to 27°C), with a final temperature at the end of installation of 70 to 60°F (21 to 16°C).

Seasonal ground temperature changes were evaluated based on several sources. Three simplified temperature zones for southern Canada and the U.S. were identified. These were zones of cold, moderate, and warm temperatures for general service conditions and seasonal pipe temperature changes. Three minimum temperatures were determined for the three zones. The possible minimum temperatures are T_2 = 50°F (10°C) for warm zones, T_2 = 40°F (4°C) for moderate zones, and T_2 = 33°F (1°C) for cold zones.

Table 3.1. Temperatures and stresses for representative conditions

Construction	Temperature zone (See Fig. 3.3)	Installation (2 days)	Relaxation (0 to 30 days)	Seasonal cooling (90 days)
		Temperature Phase and Temperatures		
Typical	Warm	100 to 70°F	70°F	70 to 50°F
	Moderate	90 to 65°F	65°F	65 to 40°F
	Cold	80 to 60°F	60°F	60 to 33°F
		Stresses (rounded to nearest 5 psi)		
	Warm	175	175	255
	Moderate	155	155	290
	Cold	130	130	300
		Temperature Phase and Temperatures		
Best Practices	Warm	Pipe and soil both at 70°F		70 to 50°F
	Moderate	Pipe and soil both at 65°F		65 to 40°F
	Cold	Pipe and soil both at 60°F		60 to 33°F
		Stresses (rounded to nearest 5 psi)		
	Warm	0		110
	Moderate	0		150
	Cold	0		180

°C = (°F-32)×5/9

Installation: Load duration = 2 days

Relaxation after installation: Load duration = 0 to 30 days

Seasonal cooling: Load duration = 90 days

Notes:

1. The values in the table are for illustrative purposes only. The designer should select the soil temperatures and ramp durations based on local conditions.
2. Soil temperatures are based on depths of cover associated with watermain installations in the applicable temperature zone.
3. Additional relaxation (not shown for clarity) will occur during the winter period.

Table 3.2. Temperature conditions for cold water influx

Temperature Zone (see Fig. 3.3)	T_{start}	T_{finish}	Load duration
Warm	70°F (21°C)	40°F (4°C)	One hour
Moderate	65°F (18°C)	40°F (4°C)	One hour
Cold	60°F (16°C)	33°F (1°C)	One hour

Section 4

Thermal Stresses in Restrained PE Pipe

4.1. Introduction

In this section a methodology is presented that uses a viscoelastic model for stress relaxation that accounts for a) variations in modulus with temperature, b) temperature changes (and the resulting stresses) occurring over a specific loading time, c) stress relaxation, and d) superposition of stress changes added at various times in the design sequence for an HDPE pipeline. The approach considers three possible phases of temperature change. They are:

1) Cooling from the temperature prior to connection to an existing pipe to the ambient ground temperature (i.e., hook-up conditions),
2) Seasonal temperature changes from summer to winter conditions, and the time span for the seasonal temperature change, and
3) Rapid changes in temperature due to a sudden influx of cold water.

The design engineer must select the values for the temperature changes and durations under consideration based on reasonable estimates within the service area. Figure 4.1 shows schematically the changes due to the hook-up temperature and the seasonal temperature changes. The hook-up temperature change is from T_1 to T_2 and occurs between $t = 0$ and t_1. Following this temperature change the stresses relax between time t_1 and t_2. The temperature at this relaxation stage is T_2. At t_2 the seasonal cooling begins, and the temperature is reduced to T_3. The seasonal cooling stops at t_3 and the temperature then remains constant at T_3 and further relaxation of pipe stresses occurs.

Additional stress changes due to a sudden influx of cold water can be evaluated readily. This sudden cold-water influx can occur at any time the line is in service, i.e., at $t > t_1$. Consequences of the time selection are given in a later section.

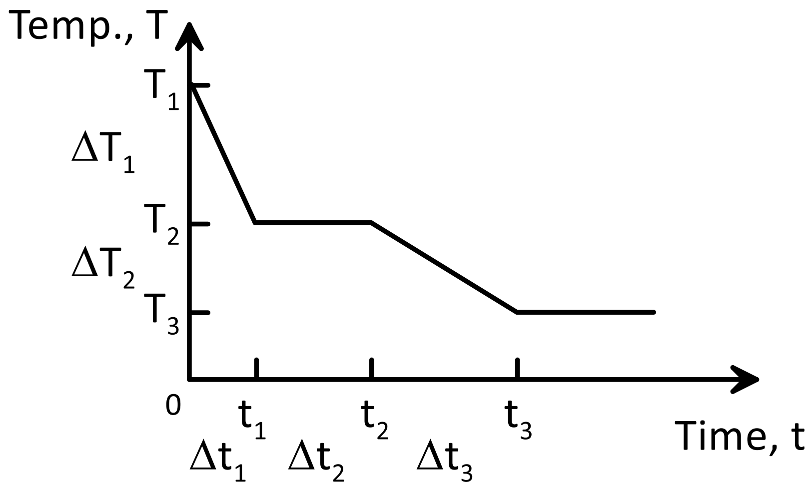


Figure 4.1. Schematic of multiple temperature changes

4.2. Viscoelastic Stress and Modulus

Viscoelastic behavior using a stress relaxation test is obtained by applying an initial deformation to a test specimen and then measuring the time-dependent decrease in load at predetermined time intervals. When the strains applied instantly, the time-dependent stress obtained from a stress-relaxation test can be modeled by the power law relationship given as:

$$\sigma(t) = \sigma_0 \, t^{-n} \tag{4.1}$$

where

σ_0 = instantaneous pipe stress,
t = time, and
n = power law exponent (= 0.085 for HDPE).

The instantaneous stress, σ_0, for a temperature loading is calculated as:

$$\sigma_0 = E(T)\, \varepsilon_0 = E(T)\, \alpha_T\, \Delta T \tag{4.2}$$

where

$E(T)$ = Young's modulus,
ε_0 = instantaneous stain caused by temperature change,
α_T = coefficient of expansion, CTE, and
ΔT = instantaneous temperature change.

Normalization of the stress in Eqn. 4.1 by the applied strain, ε_0, results in an equation in the form of a relaxation modulus, which, for sufficiently small deformations is independent of the strain for linearly viscoelastic materials, so that the relaxation modulus is:

$$E(t) = E_0\, t^{-n} \qquad (4.4)$$

The relaxation modulus can also be calculated by using the stresses obtained from relaxation tests as:

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} \qquad (4.4)$$

where

$\sigma(t)$ = time-dependent stress measured during the test and

ε_0 = constant strain applied during the test.

If the material obeys Eqn. 4.4 within the range of strains to which they are exposed, then that observation implies that the material behavior can be described by linearly viscoelastic theory. Since polyethylene behavior also is temperature dependent, an analytical model for linearly viscoelastic behavior must include time and temperature in the relaxation modulus as:

$$E(T,t) = \frac{\sigma(T,t)}{\varepsilon_0} \qquad (4.5)$$

where $\sigma(T, t)$ = temperature- and time-dependent stress.

Eqns. 4.1 through 4.5 evaluate relaxation from a deformation that is applied nearly instantaneously. When several strain increments are applied sequentially to a linearly viscoelastic material, each incremental response is *independent* and the resulting stress at a specific time equals the sum of all incremental stress responses relaxed to the time in question. The relaxation modulus follows the power law model prescribed in Eqn. 4.1, and for a series of *m* strain increments, the stress at time *t*, after the m^{th} increment, may be calculated by:

$$\sigma(t) = \sum_{i=1}^{m} \varepsilon_{0i} E_0 \left(t - \tau_i\right)^{-n} \qquad t \geq \tau_m^{+} \qquad (4.6)$$

where τ_i = time when i^{th} strain increment, ε_{0i}, applied. This principle of additive stresses given by Eqn. 4.6 which is known as the Boltzmann Superposition Principle.

4.3. Gradual Application of Strain (Ramp Loading)

In many of the equations that follow, the historical development used the symbol t_0 for the end time of the first temperature change. In the terminology used in this report, the time for the first loading change is from t = 0 to t_1, consistent with Figure 4.1. If the strain is applied gradually over a finite time interval, the summation in Eqn. 4.6 can be written in the form of the *convolution integral* as:

$$\sigma(t) = \int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{4.7}$$

If the relaxation modulus, E(t - τ), follows the power law model described by Eq. 4.4, and the strain is ramped at a constant rate up to a maximum strain, ε_0, over a time, t_1, then the stress may be calculated as:

$$\sigma(t) = \frac{E_0\varepsilon_0}{t_1}\int_0^t (t-\tau)^{-n}d\tau \tag{4.8}$$

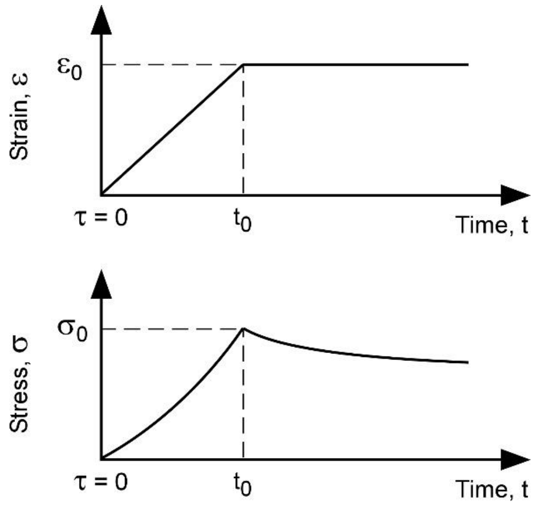
This equation can be divided into two parts and exact solutions can be obtained for each part. The first part corresponds to the strain ramp period ($t \le t_1$) and the second part corresponds to the times after the strain ramp ends ($t > t_1$). The stresses for these two periods, with Eqn. 4.4 in mind, are:

$$\sigma(t) = \frac{E_0\varepsilon_0}{t_1}\frac{t^{1-n}}{1-n} \qquad (t \le t_1) \tag{4.9a}$$

$$\sigma(t) = \frac{E_0\varepsilon_0}{t_1}\left[\frac{t^{1-n}-(t-t_1)^{1-n}}{1-n}\right] \qquad (t > t_1) \tag{4.9b}$$

The loading condition and stress described by Eqns. 4.9a and 4.9b are illustrated in Fig. 4.2. Figure 4.2 has a concave upward shape because of an assumed cooling temperature change.

The polyethylene modulus, E_0, is temperature dependent. If the strain, ε_0, is mechanically applied at a constant temperature then the modulus, E_0, is the instantaneous modulus at that temperature. However, if the stresses are due to a thermal loading then the modulus, E_0, changes throughout the loading time and it is the temperature-dependent pipe modulus at any time, t. A temperature change of ΔT will result in different stress relaxation curves depending on whether the temperature is decreasing and causing tensile stresses, or increasing thus causing compressive stresses, as shown



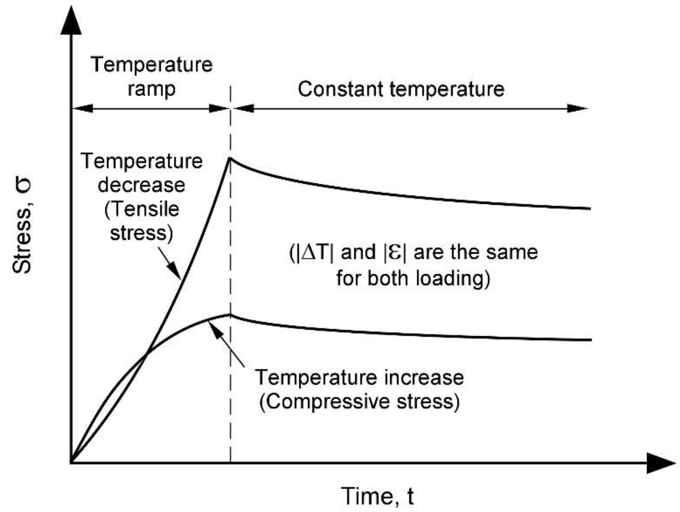


Figure 4.2. Schematic of stress relaxation during and after ramp loading

Figure 4.3. Effect of temperature decrease or increase on pipe stresses

in Figure 4.3. In Figure 4.3, the absolute value of the compressive stress is shown to demonstrate increasing and decreasing temperature changes on the same vertical axis.

In Figure 4.3, the stress resulting from a temperature cooling of $-\Delta T$ is higher than the stress for a warming $+\Delta T$ with the same absolute value. The explanation for this is given in Figure 4.4. Two temperature-time profiles are shown in Figure 4.4a). One for cooling for 90 to 40°F (32 to 4°C) and one for warming from 40 to 90°F (4 to 32°C). Each has the same $|\Delta T|$. Figure 4.4b) shows a portion of the modulus-temperature relationship used for the HDPE for this temperature range. For the cooling ΔT the modulus changes from 104 to 189 ksi (710 to 1300 MPa). For the warming ΔT the modulus changes from 189 to 104 ksi (1300 to 710 MPa). The incremental rate at which the modulus changes with temperature also is different for decreasing versus increasing temperature changes. For cooling, the rate change in modulus per degree is higher than the incremental slope of the modulus-temperature curve for warming. This is reflected in the curvature of the stress-time curves given in Figure 4.4c), which shows tensile (positive) stresses for cooling and compressive (negative) stresses for warming. In Figure 4.4d) the sign for the compressive stress is flipped to show the relative changes. These figures show the interactions between temperature, time, and stress for the viscoelastic parameters used in this report.

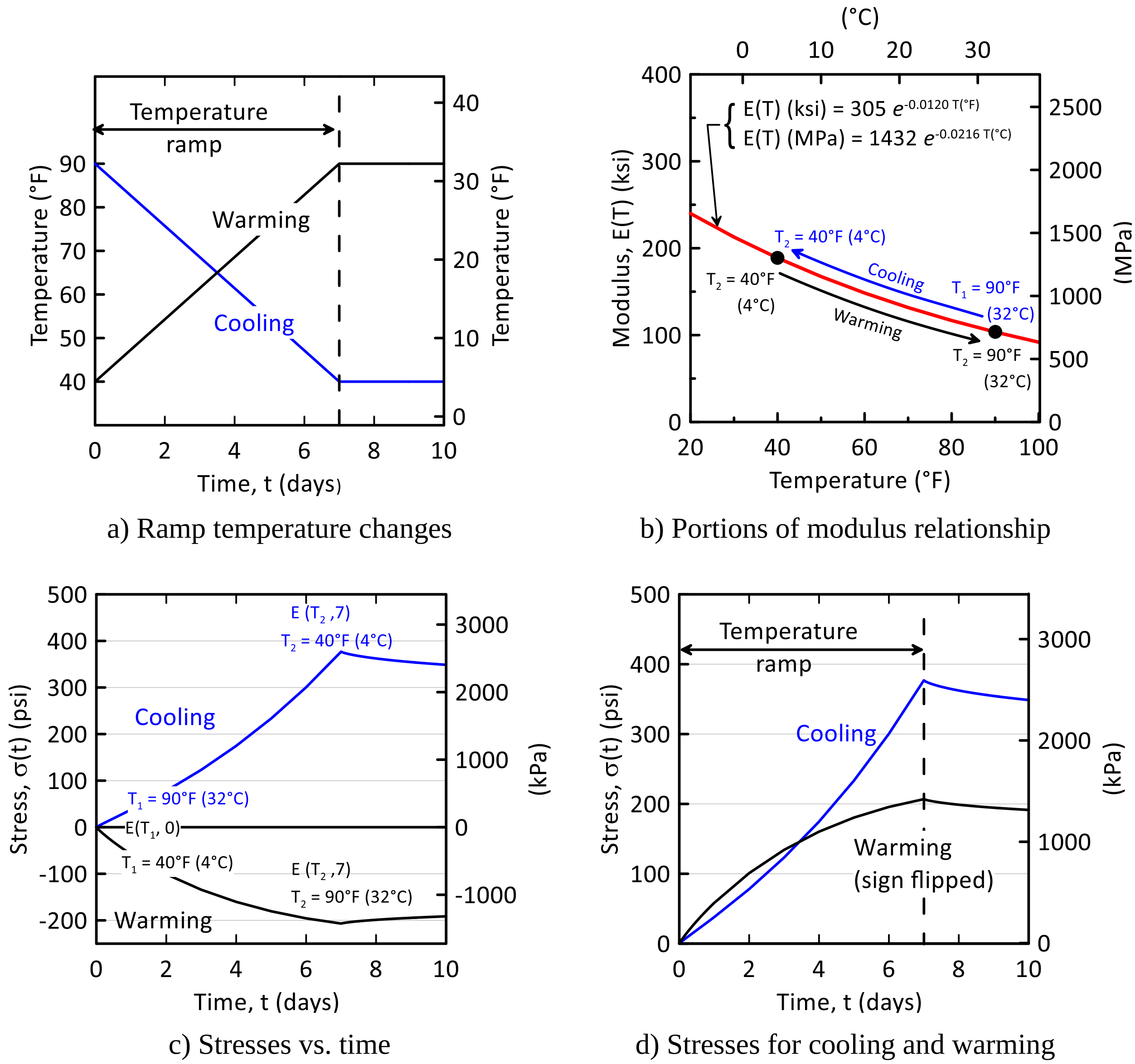


Figure 4.4. Explanation for different peak stresses for cooling and warming with comparable temperature changes

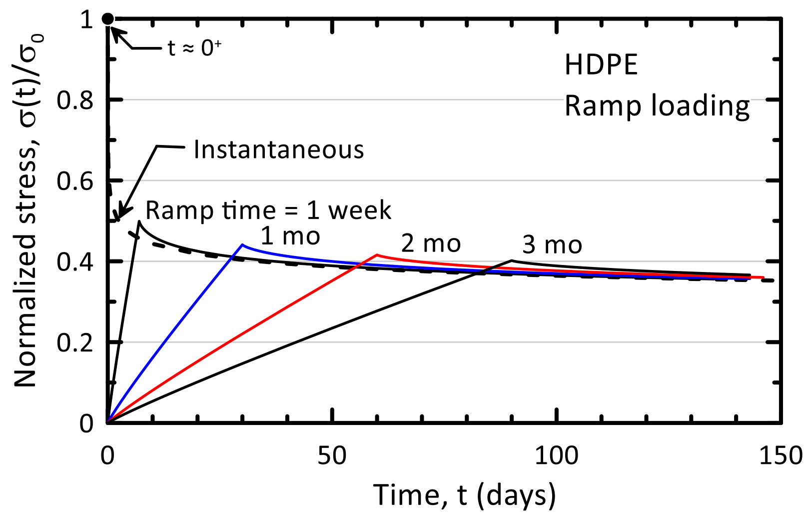


Figure 4.5. Effect of ramp loading time on viscoelastic material stresses

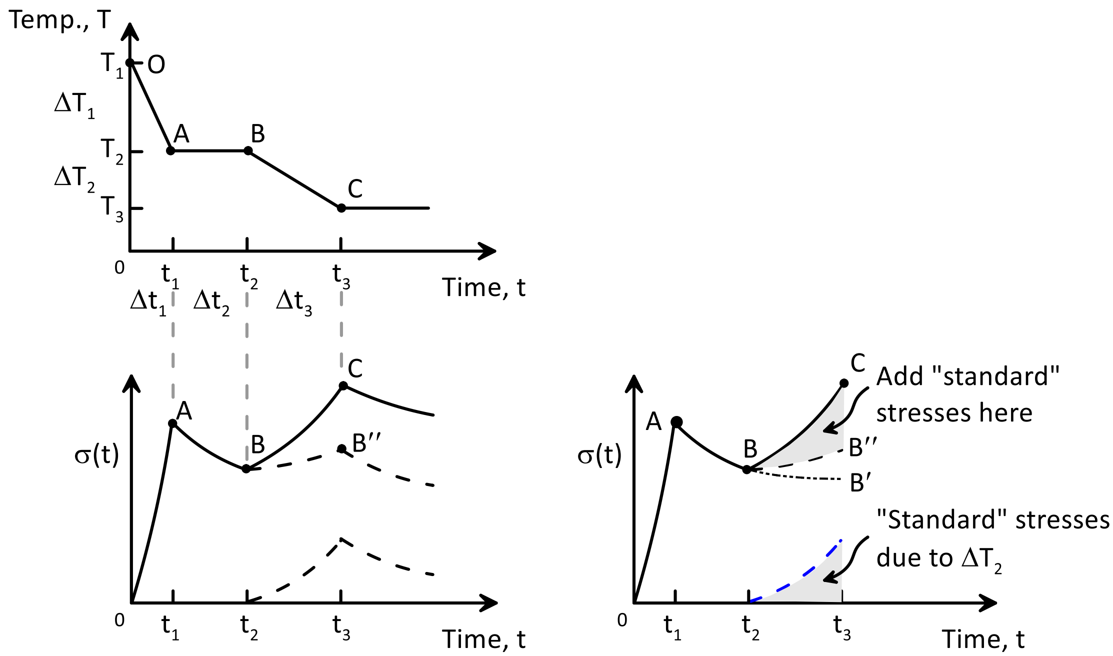
4.4. Effect of Ramp Loading Time

Figure 4.5 shows the stresses at the end of ramp loading normalized by the stress if the change in temperature occurred instantaneously. Several key points are observed in Figure 4.5. The stresses decrease very quickly with time. After about 1 week, the stresses are approximately 50% of the *instantaneous* stresses. The stresses at the ramp loading are slightly larger than the relaxed stresses for instantaneous loading. This slight overshooting is small. In the instantaneous loading, t_1 is zero, and the modulus used is that at the final temperature. The *instantaneous* stress is evaluated using E(T) at the final temperature for all times. The last major observation from Figure 4.5 is that the peak stresses for ramp times greater than about 1 month are about the same; slightly more than 40% of the *instantaneous* stress.

4.5. Stress Superposition

If the PE is stressed due to an initial temperature change which occurs over the time period of t = 0 to t_1 and now is relaxing, then the equations given above can be used to superimpose stresses resulting from and additional temperature change occurring over another later time interval.

Figure 4.6 is a schematic diagram for cooling. Temperature profile a) is for the full temperature range. The upper portion of Figure 4.6a) shows a temperature drop from T_1 to T_2 (ΔT_1) occurring over a time interval 0 to t_1. These are points O and A on the figure. The temperature now remains



a) Full temperature profile

b) Partial temperature profile

Figure 4.6. Schematic of multiple temperature changes and stress superposition

constant at T_2 from time t_1 to t_2, points A and B. At t_2 the temperature changes from T_2 to T_3 (ΔT_2) over a time period of $t_3 - t_2 = \Delta t_3$, points B and C, and then stays constant at T_3.

The solution to this stress superposition is broken down into several parts. The stress superposition steps are:

1) The stress due to ΔT_1 up to time t_2 has two parts.

a) The stress at time t_1 is determined using $E(T_2)$. The stress at the end of the first ramp is:

$$\sigma(t) = \frac{E(T_2)\alpha_T \Delta T_1}{t_1} \frac{t_1^{1-n}}{1-n} = E(T_2)\alpha_T \Delta T_1 \frac{t_1^{-n}}{1-n} \qquad (t = t_1) \tag{4.10}$$

b) The stress at the end of Δt_2 while the pipe is relaxing at T_2 is:

$$\sigma(t) = \frac{E(T_2)\alpha_T \Delta T_1}{t_1} \left[\frac{t_2^{1-n} - (t_2 - t_1)^{1-n}}{1-n} \right] \qquad (t = t_2) \tag{4.11}$$

2) The stress resulting from the second temperature change has two parts.

a) Stress relaxation from the first temperature change continues, but now using a modulus corresponding to $E(T_3)$. This is given by:

$$\sigma(t)=\frac{E(T_3)\alpha_T\Delta T_1}{t_1}\left[\frac{t_3^{1-n}-(t_3-t_1)^{1-n}}{1-n}\right]\qquad (t=t_3) \tag{4.12a}$$

b) The stress from ΔT_2 is evaluated using $E(T_3)$ with a time change of Δt_3.

$$\sigma(t)=\frac{E(T_3)\alpha_T\Delta T_2}{\Delta t_3}\frac{\Delta t_3^{1-n}}{1-n}=E(T_3)\alpha_T\Delta T_2\frac{\Delta t_3^{-n}}{1-n}\qquad (t=t_3) \tag{4.12b}$$

The stress at t_3 now is the sum of these two parts, i.e. Eqns 4.12a and 4.12b.

The design stress is the larger of the stresses determined by Step 1 and Step 2 above. This procedure for superposition will be used later in Section 5 to present summary figures for several temperature scenarios.

The temperature profile shown in Figure 4.6a) is for the full temperature range. The dashed line from point B to B″ represents further relaxation of the A-B line caused by O-A loading. It might be intuitive that the stresses should continue to go down. Figure 4.6.b) provides an explanation of why the dashed line, B-B″, for the stress relaxation goes up. Line B-B′ in Figure 4.6.c) might be the expected further relaxation from t_2 to t_3, which would occur at constant temperature T_2. However, the temperature starts to change at t_2, changing the modulus, so the PE is now relaxing at a changing modulus. Since the modulus goes up with further cooling, the relaxed stresses due the O-A loading increase. If it was relaxation from a *mechanical loading,* such as instantly applied strain, then the stress would keep decreasing (i.e. following line B-B′) because the temperature is constant and modulus does not change. But for the *temperature loading* case, the modulus at any time is a function of temperature which now is a function of time.

The "standard" stresses due to the ΔT_2 cooling (B to C) from times t_2 to t_3 are computed using Eqn. 4.12b. These stresses are added to line B-B″ to obtain the superimposed stresses for the B-C portion of the temperature profile.

4.6. Rapid Cold Water Influx

Cold water can suddenly be introduced into the pipeline. This water influx can occur any time when the line is in service. Additional stress changes due to a rapid influx of cold water can be evaluated readily. To do this, use a ΔT from the pre-influx pipe temperature to the temperature of the colder water. Select a time over which the ΔT will occur. This time would be short and would depend on the temperature differential between the pipe and water. The time may be a short as 1 hour. The shorter the time scale, the larger the water-induced stress. If during a rapid temperature change the pipe is at or near the seasonal minimum, then there is not much effect because the pipe is already cold. The stress due to this rapid influx would be determined using Eqn. 4.9a and would be added to the stress anywhere in the time-regime used. The most conservative approach would be to assume the rapid influx of cold water occurs at the end of pipe installation, t_1.

4.7. Summary

Linear viscoelasticity can be used to estimate thermal stresses in plastic pipelines. The Boltzmann superposition principle and the convolution integral method are used to do this. The necessary equations are developed of three possible phases of temperature change. They are:

1) Cooling from the temperature prior to connection to an existing pipe to the ambient ground temperature (i.e., hook-up conditions),
2) Seasonal temperature changes from summer to winter conditions, and the time span for the seasonal temperature change, and
3) Rapid changes in temperature due to a sudden influx of cold water.

A major observation of stress relaxation in the HDPE is that the stresses diminish rapidly with time. When temperature changes occur more slowly, even over a week or so, the stresses are about 50% of those if the stress was applied instantaneously. The peak stresses for ramp times greater than about 1 month are about the same; slightly more than 40% of the instantaneous stress.

Section 5

Alternate Design Procedures and Typical Stresses

5.1. Introduction

Earlier sections of this report have presented the primary material properties needed and calculation procedures for determining stresses and displacements in water piping systems resulting from temperature changes. This section uses this information to present tables and figures based on the exact procedures given earlier, rather than requiring the use of equations for every design situation. Also given are methods using alternatives to the exact solutions which may result in very slightly (less than a few percent) more conservative estimates of the stresses. This section presents a few figures used previously in the report, so all the relevant information is provided in this section. Example calculations for *typical* construction conditions are provided using several alternate procedures. *Typical* conditions are those that do not intentionally minimize installation stresses. *Best Practices* are based on allowing the pipe to cool to the prevailing ground temperature prior to hook-up, minimizing the installation stresses.

An important consideration is that the largest stress in HDPE water pipe under normal operating conditions is circumferential (hoop) stress caused by internal pressure. The Handbook for HDPE (PPI, 2008) states that other stresses are seldom greater than 300 to 400 psi (2.0 to 2.8 MPa), and generally this also is the case for temperature-induced stresses. Where practical, the predicted stresses in this section will be related to the allowable stress for HDPE of σ_{allow} = 1,000 psi (6.9 MPa) and $\sigma_{yield} \approx$ 3,500 psi (24 MPa), even though a yield point and yield stress are difficult to define in a nonlinear viscoelastic material.

Figure 5.1 is a re-presentation of the time-temperature terminology for the main loading considerations. Line OA represents the "installation" stage, line AB the "relaxation" stage, and line BC the "seasonal cooling" stage.

One of the most fundamental relationships used in this report is given in Equation 5.1 (Section 4's Eqn. 4.9a), which gives the stresses moving from point O to point A on Figure 5.1. The stresses are calculated using

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad (t \le t_1) \qquad (5.1)$$

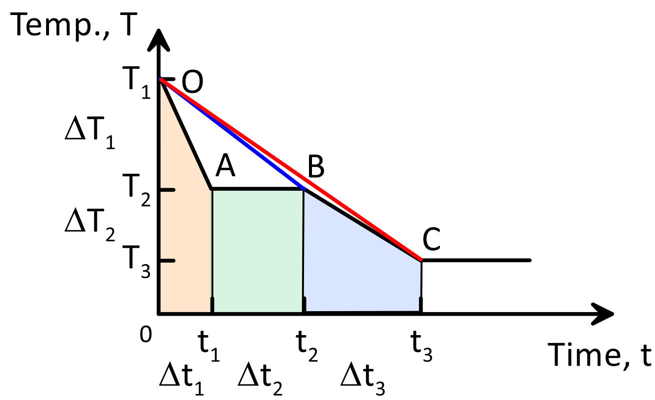


Figure 5.1. Time and temperature terminology

where

t_1 = time for the temperature change from one temperature to the next,

t = time of interest ($t \le t_1$),

$E_0 = E(T)$ = modulus at the temperature at the time of interest, t, and

$\varepsilon_0 = \alpha_T \Delta T$ = (coefficient of thermal expansion/contraction) × Temperature change

When $t = t_1$ Eqn. 5.1 reduces to:

$$\sigma(t_1) = E_0\varepsilon_0 \frac{t_1^{1-n}}{t_1(1-n)} = \sigma_0 \frac{t_1^{-n}}{(1-n)} \quad \text{or} \quad \frac{\sigma(t_1)}{\sigma_0} = \frac{t_1^{-n}}{(1-n)} \tag{5.2}$$

where $\sigma_0 = E(T)\alpha_T\Delta T = E(T)\varepsilon_0$, is the stress if the temperature change was applied *instantaneously*.

Figure 5.2 shows the stress at the end of the loading period $t = t_1$ normalized by the instantaneous stress, σ_0. The relationship in Figure 5.2 is very similar to the instantaneous loading stress relaxation but is slightly higher. Eqn. 5.1 represents a line through the peaks shown in Figure 4.5 for ramp loadings. The line of peaks, or the overshoot due to ramp loading, is about 9% higher than the instantaneous loading/relaxation curve. This ratio is given by

$$\frac{\sigma(t_1)\,\text{for ramp loading}}{\sigma(t_1)\,\text{for instantaneous loading}} = \frac{1}{1-n} = 1.093 \qquad (\text{for } n = 0.085) \tag{5.3}$$

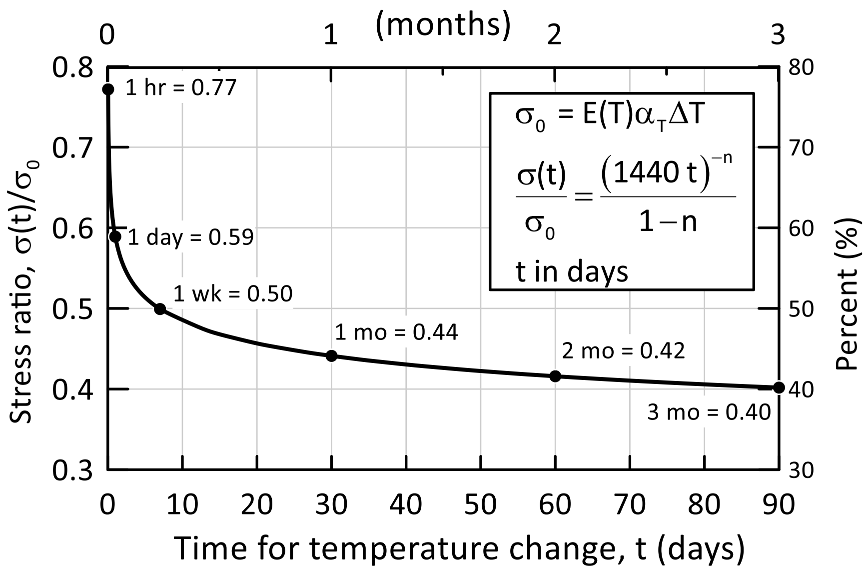


Figure 5.2. Normalized stress vs. time

Table 5.1. Temperatures and load durations for *typical* design in a *moderate* temperature zone

Temperature Phase	T_{start}	T_{finish}	Load duration
Installation	T_1 = 90 to 65°F (32 to 18°C)	T_2 = 65°F (18°C)	Δt_1 = 2 days
Relaxation	T_2 = 65°F (18°C)		Δt_2 = 0 to 30 days
Seasonal change	T_2 = 65°F (18°C)	T_3 = 40 °F (4°C)	Δt_3 = 90 days

Table 5.1 presents the design temperature ranges recommended in Section 3, that are expected to cover most *typical* design considerations for HDPE water pipelines in a *moderate* temperature zone (see Table 3.1 and Figure 3.4). Examples using the temperatures and times in Table 5.1 are given in the following sections. When the sign of ΔT is negative the stresses are tensile.

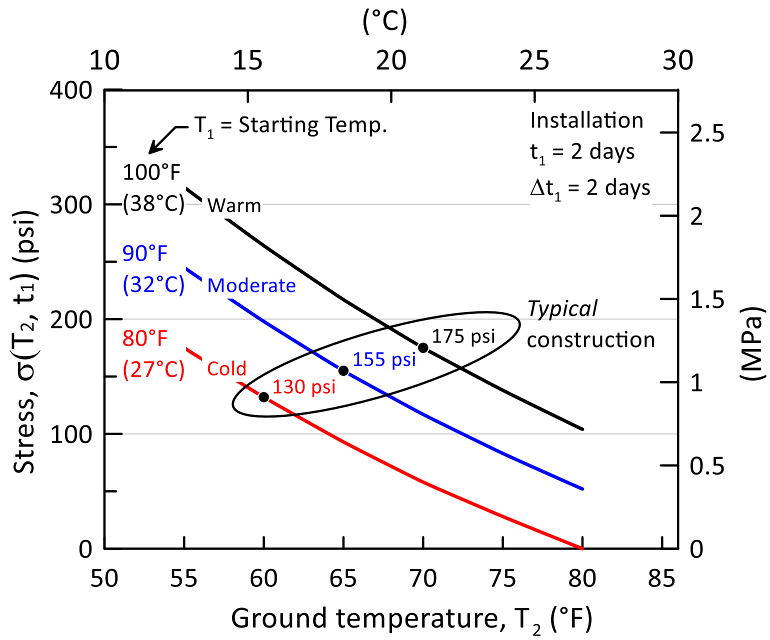


Figure 5.3. Stresses due to pipe installation for *typical* construction

5.2. Installation Stresses

These stresses represent moving from point O to point A on Fig. 5.1. The appropriate equation to use for this case is Eqn. 5.2 with the temperatures and times as in Table 5.1. Figure 5.3 shows installation stresses for pipe temperatures of 100 to 80ºF (38 to 27ºC) and cooling the ground temperature, T_2, in 2 days. For the case of cooling with *Typical* construction in a *Warm* temperature zone from 100 to 70ºF (39 to 21ºC) in 2 days the maximum stress is 175 psi (1.21 MPa). This installation stress is, at most, slightly less than 20% of a 1,000 psi (6.9 MPa) allowable stress or 5% of a yield stress of 3,500 psi (24 MPa).

The stresses shown in Figure 5.3 can be determined several ways. As an example, take line OA in Figure 5.1 with temperatures T_1 = 100ºF (38ºC), T_2 = 70ºF (21ºC), and $t_1 = \Delta t_1$ = 2 days. This is the maximum for *Typical* construction case in a *Warm* temperature zone and is the greatest range of installation temperature-times given in Table3.1. Four ways of determining the stress for this case are given below.

1. Using Figure 5.3:

Read the stress from Figure 5.3 with a Starting Temperature of T_1 = 100ºF (38ºC) and Ground Temperature of 70ºF (21ºC). $\sigma(T_2,t_1) \approx$ 175 psi (1.2 MPa).

2. Using Eqn. 5.1:

t = time of interest = t_1 = 2 day = 2,880 min ($t = t_1$),

$E_0 = E(T_2)$ = 131,672 psi (908 MPa)   (Eqn. 2.3), and

$\varepsilon_0 = \alpha_T \Delta T = (80\times10^{-6}/^{\circ}F)(\Delta T = 30^{\circ}F) = 2.40\times10^{-3}$

$= (144\times10^{-6}/^{\circ}C)(\Delta T = 16.6^{\circ}C) = 2.40\times10^{-3}$

n = 0.085

$$\sigma(T,t) = \frac{(E_0 = 131{,}672\text{ psi})(\varepsilon_0 = 2.40\times10^{-3})}{t_1 = 2{,}880\text{ min}} \frac{(t = 2{,}880\text{ min})^{(1-n=0.915)}}{1-n = 0.915} = 175\text{ psi}$$

$$\sigma(T,t) = \frac{(E_0 = 907.9\text{ MPa})(\varepsilon_0 = 2.40\times10^{-3})}{t_1 = 2{,}880\text{ min}} \frac{(t = 2{,}880\text{ min})^{(1-n=0.915)}}{1-n = 0.915} = 1.21\text{ MPa}$$

3. Using Eqn. 5.2 or Figure 5.2:

$\frac{\sigma(t_1)}{\sigma_0} = \frac{t_1^{-n}}{(1-n)} = 0.555$ from Eqn. 5.2 or from Fig. 5.2 with Δt = 2,880 minutes (hard to estimate from Fig 5.2 with such a small Δt).

$$\sigma(T,t) = \sigma_0 \frac{t_1^{-n}}{(1-n)}$$

$$\frac{t_1^{-n}}{(1-n)} = \frac{(2{,}880\text{ min})^{-0.085}}{0.915} = 0.555$$

$$\sigma_0 = E(T)\alpha_T \Delta T = (131{,}672\text{ psi})(80\times10^{-6}/^{\circ}F)(\Delta T = 30^{\circ}F) = 316\text{ psi}$$

$$\sigma(T,t) = 316\text{ psi}(0.555) = 175\text{ psi}$$

$$\sigma_0 = E(T)\alpha_T \Delta T = (907.9\text{ MPa})(144\times10^{-6}/^{\circ}C)(\Delta T = 16.7^{\circ}C) = 2.18\text{ MPa}$$

$$\sigma(T,t) = 2.18\text{ MPa}(0.555) = 1.21\text{ MPa}$$

4. Using Eqn. 5.3:

Instantaneous stress relaxed to t_1 = 2 days multiplied by 1.093 from Eqn. 5.3.

$\sigma(T,t) = 1.093 \times \sigma_0 t^{-n}$ = 1.093 × 316 psi (2,880 minutes$^{-0.085}$ = 0.508) = 175 psi

= 1.093 × 2.18 MPa (2,880 minutes$^{-0.085}$ = 0.508) = 1.21 MPa

All methods given above result in the same installation stress. The designer can select the temperature-time profile and choose the preferred method. Figure 5.3 considers the changing HDPE moduli and may be the easiest way to determine the stress if the design temperatures are within the range given on the figure.

The numerical examples given above are for a cooling time of 2 days. This is line segment O-A in Figure 5.1. For the same temperatures, if the time for cooling to ground temperature was reduced to 1 day, the maximum stress would increase to about 185 psi (1.28 MPa). The maximum stresses would be reduced to roughly 160 psi (1.10 MPa) for a cooling time of 7 days week. Figure 5.4 shows the effect of cooling times of 1 day to 7 days on the installation stresses. The solid symbol in Figure 5.4 is the stress for the four example calculation methods given above. The dashed lines show that a reduced cooling time increases the stresses by a very small amount. Increasing the ramp time to 7 days reduces the stresses slightly.

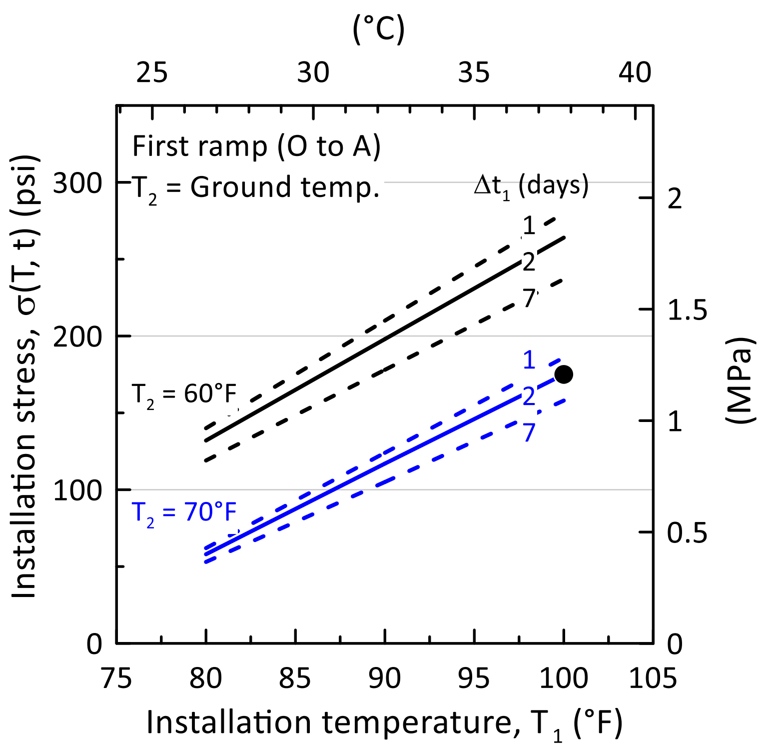


Figure 5.4. Installation stresses for varying temperatures and installation times

5.3. Relaxation Stresses

Following installation, the pipe stresses can relax between times t_1 and t_2. In Table 5.1 the recommended relaxation times are Δt_2 = 0 to 30 days. This means that the seasonal temperature change could start either immediately after installation or within 30 days. For constant temperature relaxation the stresses at any time during relaxation are always smaller than the installation stresses. Further reductions in stress following 30 days are not significant. Figure 5.5 shows the relaxation stresses for the three temperature zones and an installation time of 2 days followed by relaxation. The relaxation stress figures start at the installation stresses.

As an example, the stress at the end of a 2-day installation, starting at T_1 = 100ºF (38ºC) and ending at T_2 = 70ºF (21ºC) for a *Warm* temperature zone is 175 psi (1.21 MPa). This case is shown by the solid circle in Figure 5.5 and was used in the examples above. If the HDPE relaxes for an additional 30 days after installation, the total time is t_2 = 32 days = 46,080 minutes and the exact solution for the stress is $\sigma(T_2, t_2)$ = 127 psi (0.88 MPa), which is shown as another solid circle in Figure 5.5.

Using a more simplified temperature-time path from O to B (bypassing A; see Figure 5.1) for this same example, the normalized stress ratio in Figure 5.2 is:

$$\frac{\sigma\left(t_1 = 46{,}080\,\text{min}\right)}{\sigma_0} = \frac{t_1^{-n}}{(1-n)} = 0.439 \tag{5.5}$$

E_0 and ε_0 are the same as given in the examples above so σ_0 = 316 psi (2.18 MPa). Using this method the stress is 316 psi × 0.439 = 139 psi (2.18 MPa × 0.439 = 0.96 MPa) which is slightly higher, about 9%, than the exact solution of 127 psi (0.88 MPa) and quite acceptable.

5.4. Seasonal Cooling

Determining the stresses due to both installation and seasonal cooling requires two steps for the exact solution. This section gives examples of the methods used, and presents a simplification to quickly estimate the stresses, which again involves a small conservative error. The first step is to consider that during the seasonal cooling stage, Δt_3, the pipe continues to relax but now the temperature is not constant. The second step considers the second ramp temperature-time change of ΔT_2 starting at t_2. This is moving from point B to point C in Figure 5.1. The exact method requires keeping careful track of the *rate* at which the temperature changes so the temperature can

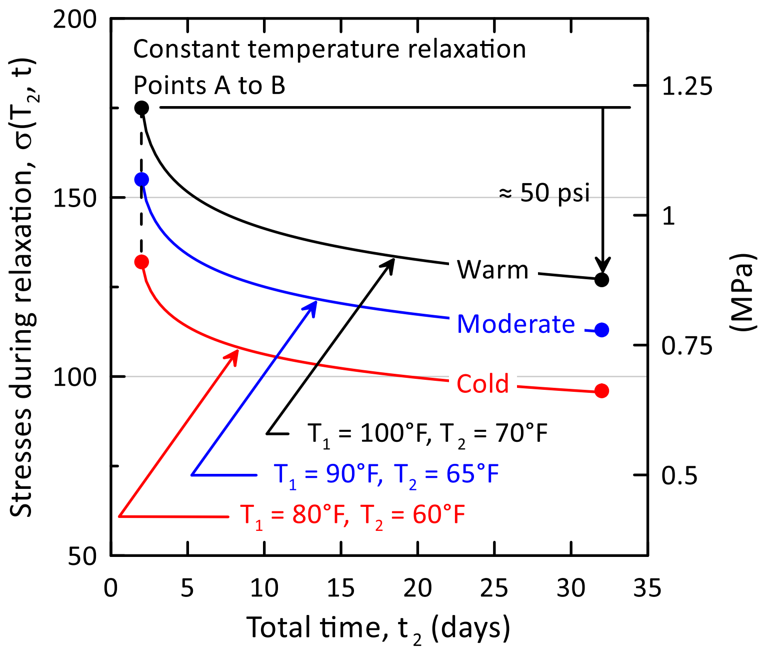


Figure 5.5. Stress relaxation at constant temperature, T_2

be determined at any time, thereby changing the modulus, E(T). The *times* at which the stresses from this step are determined must be the same as those used for the seasonal cooling ramp so that the stresses at the same times can be superimposed. If only the final stresses at the end of seasonal cooling are needed, the process is simpler, still requiring two steps in the process.

The exact solution for the temperature-time profile O-A-B-C in Figure 5.1 for the installation temperatures from 100 to 50ºF (38 to 10ºC) in 2 days, $\Delta t_2 = 0$ relaxation time, and a seasonal cooling of 70 to 33ºF (24 to 1ºC) in an additional 90 days gives a stress of $\sigma(T_3, t_3) = 255$ psi (1.76 MPa). A simpler and somewhat conservative method is to use the temperature-time path given by line O-C in Figure 5.1. This predicts stresses for the entire process in one single step. The smaller the relaxation phase then the more accurate the predicted stresses. The stress for path O-C would be a temperature change of 100 to 50 ºF (38 to 10ºC) in 92 days and the stress would be $\sigma(T_3, t_3)$ 269 psi (1.85 MPa), which is about 5% higher the exact solution of 255 psi (1.76 MPa). The calculation procedure is given below.

Using Figure 5.2 with a total time of 92 days (no relaxation) = 146,880 minutes ≈ 3 months would give a stress ratio of ≈ 0.401.

t_1 = 92 day = 132,480 minutes

$E_0 = E(T_3)$ = 167,388 psi (1,154 MPa)   (Eqn. 2.3)

$\varepsilon_0 = \alpha_T \Delta T = (80\times10^{-6}/^{o}F)(\Delta T = -50^{o}F) = -4.00\times10^{-3}$

$= (144\times10^{-6}/^{o}C)(\Delta T = -10.0^{o}C) = -4.00\times10^{-3}$

$\sigma_0 = E_0\varepsilon_0$ = 670 psi (4.62 MPa)

$\sigma(T,t)$ = 670 psi × 0.401 = 269 psi (1.86 MPa)

Allowing for 30 days of relaxation would give a total time of 122 days. Figure 5.2 has a maximum time scale of 90 days, so calculate the stress ratio using 122 days = 175,680 minutes ≈ 4 months for a stress ratio of 0.389. The resulting stress is $\sigma(T,t)$ = 670 psi × 0.389 = 261 psi (1.80 MPa), less than 4% higher than the exact solution of 252 psi (1.75 MPa) for this temperature-time profile O-A-B-C.

Table 5.2 presents the stresses in warm, moderate, and cold temperature zones with *typical* construction and for 0 and 30 days relaxation prior to seasonal cooling. The seasonal cooling time is 90 days. The stresses in the "0 days relaxation prior to seasonal cooling" are the same (unrounded) stresses given in Table 3.1 for *typical* construction conditions. It is interesting to note that the stresses at the end of seasonal cooling for 0 and 30 days are nearly the same, even though the stresses prior to the seasonal cooling due to different relaxation times are quite different. This is a result of the Boltzmann superposition, in which the interactions between prior relaxation rates and current temperatures have different time-temperature cooling relationships.

Table 5.2. Stresses for 0 and 30 days relaxation prior to seasonal cooling

		0 days relaxation prior to seasonal cooling			30 days relaxation prior to seasonal cooling		
Temp. zone	Seasonal cooling (ºF)	Total load duration (days)	Stress prior to seasonal cooling (psi)	Stress at the end of seasonal cooling (psi)[a]	Total load duration (days)	Stress prior to seasonal cooling (psi)	Stress at the end of seasonal cooling (psi)
Warm	70 to 50	92	175	255	122	127	252
Moderate	65 to 40	92	155	290	122	113	287
Cold	60 to 33	92	132	299	122	96	296

a – These are the (unrounded) stresses reported in Table 3.1 for *typical* construction

ºC = (ºF-32) × 5/9   MPa = psi × (6.89/1000)

5.5. Rapid Cold Water Influx

Estimating the additional stresses resulting from rapid influx of cold water can use the following Eqn. 5.2 or Figure 5.4 with t_1 = the time for the cold water to fill the pipeline and cool to the prevailing pipe temperature, say one hour. The prevailing pipe temperature is assumed to be the ground temperature. The designer calculates the HDPE modulus, $E_0 = E(T)$, at the cold water temperature using Eqn. 2.3 as usual, and the initial strain $\varepsilon_0 = \alpha_T \Delta T$. This is the standard method for determining pipe stresses.

As an example, let the ground temperature be 65ºF (18ºC) and the cold water temperature is 40°F (4ºC). These temperatures are conditions in a *Moderate* temperature zone. The cooling time is one hour = 60 minutes.

t_1 = 60 minutes,

E_0 = 188,729 psi (1,301 MPa)   (Eqn. 2.3), and

$\varepsilon_0 = \alpha_T \Delta T = (80\times10^{-6}/ºF)(\Delta T = 25F) = 2.0\times10^{-3}$

$\quad = (144\times10^{-6}/ºC)(\Delta T = 13.9ºC) = 2.00\times10^{-3}$

$\sigma_0 = E_0\varepsilon_0$ = 377 psi (2.60 MPa)

$$\sigma(t_1 = 60\ \text{min}) = (\sigma_0)\frac{(t_1 = 60)^{-0.085}}{(1-n)} = 0.772\ \sigma_0$$ or read from Figure 5.2.

$\sigma(T,t)$ = 377 psi × 0.772 = 291 psi (2.01 MPa)

The additional stresses due to cold water influx for all temperature zones are given in Table 5.3. These stresses likely would occur near the water intakes since the water temperatures would adjust to the pipe temperatures as the water moves through the pipeline. Note that in Table 5.3 the initial pipe temperature is the temperature at the start of seasonal cooling. If the pipe temperature is lower than this, the effect of a cold water influx would be smaller, depending on how close the pipe temperature is to the temperature of the cold water. Figure 5.6 shows the cold water influx stresses vs. pipe/ground temperature for the range of water temperatures give in Table 5.3. The symbols are for the maximum stresses due to the full cold water influx temperature ranges. If the pipe temperature, for example, was 50ºF (10ºC) (approximately mid-way in seasonal cooling) when the cold water influx started then the incremental stresses would be smaller. In Figure 5.6 these stresses would be about 120 psi (0.83 MPa) for *Warm* and *Moderate* temperature zones and 215 psi (1.48 MPa) for *Cold* temperature zones.

Table 5.3. Additional stresses for rapid cold water influx

Temp. zone	Initial pipe/ground temp.	Cold water temp.	Load duration	Stress (psi)
Warm	70ºF	40ºF	1 hr	350
Moderate	65ºF	40 ºF	1 hr	291
Cold	60ºF	33ºF	1 hr	342

ºC = (ºF-32) × 5/9
MPa = psi × (6.89/1000)

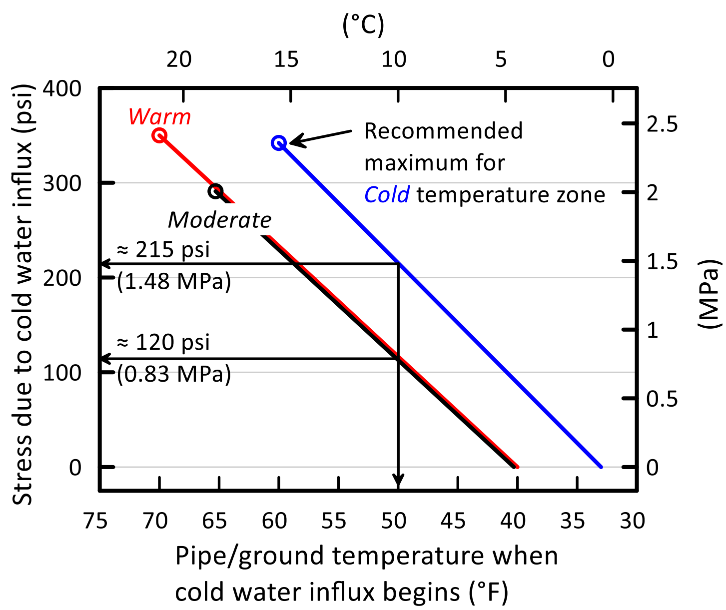


Figure 5.6. Stresses due to cold water influx vs. pipe/ground temperature

Table 5.4. Final stresses for *typical* and *best practices* construction

Temperature zone (See Fig. 3.4)	*Typical* construction: All temp. changes (92 days)	*Typical* construction: Final stress (psi)	*Best Practices* construction: All temp. changes (92 days)	*Best Practices* construction: Final stress (psi)
Warm	100/70/50°F	255	70/70/50°F	110
Moderate	90/65/40°F	290	65/65/40°F	150
Cold	80/60/33°F	300	60/60/33°F	180

°C = (°F-32)×5/9
MPa = psi × (6.89/1000)

5.6. Maximum Design Stress

The design stresses for *typical* construction conditions in all three temperature zones have been presented using several approaches. These methods were used to develop the stresses given in Table 3.1 and again summarized in Table 5.4 above. The main difference between *typical* and *best practices* is that for best practices the pipe has cooled to the soil temperature prior to hook-up. If the designer wanted to include a rapid cold water influx, these stresses in Table 5.3 would be added to any of the other stresses. The cold water influx complicates the loading because it can occur at any time, and the stresses could relax before an additional loading phase. Also, the starting temperature for the cold water stresses may not be the same as assumed in Table 5.3 because seasonal cooling has started. Keep in mind that the stresses shown in Table 5.4 are *examples* using the values recommended for routine design. The procedures outlined earlier in this section and Section 4 should be used for the particular design situation.

5.7. Summary

Stresses using the linear viscoelastic model for a) installation, b) stress relaxation following installation, and c) seasonal cooling were presented using straight-forward calculation procedures. Figure 5.2, normalized stress versus time, can be used for estimating stresses, and was shown to be accurate for many calculation approaches. For installation stresses, the predicted stresses are all identical, whether using the equations or Figure 5.2. Stresses estimated using more simplified methods such as shown in Figure 5.2 or using Eqn. 5.2 can be about 5 to 10% higher than the exact solutions, which generally is acceptable.

Determining the stresses for seasonal cooling require keeping careful track of temperature changes for *additional* stress relaxation at *different* temperatures, as well as the seasonal cooling ramp. For estimating these stresses, a loading path considering the full $\Delta T_1 + \Delta T_2$ and full time period, t_3, for the temperature-time profile can be used. This method of using the alternate load path of O to C (see Figure 5.1) results in reasonably accurate predictions of the HDPE stresses for the recommended full time-temperature profiles.

Section 6

Best Practices for the Control of Thermal Stresses

6.1. Introduction

This section gives recommendations to control/reduce thermal stresses in HDPE water pipelines. Most methods can be implemented without interfering with general pipeline construction and operation. The Plastics Pipe Institute has many publications that identify practical methods for mitigation of thermal stresses in pipelines. This section provides additional information that can be used as a guide to reducing thermal stresses and gives a few examples of the possible ramifications.

6.2. Reduction of Installation Stresses

During the installation phase the piping may be on the ground adjacent to the burial trench. PE temperatures can easily exceed 120 to 140ºF (50 to 60ºC) when exposed to direct sunlight. PPI's PE Piping Systems Field Manual (PPI, 2009) sums it up nicely in that "black piping can be hot." When the pipe is placed in the trench, but not connected to an existing system, a minimum of a 6 in. (150 mm) of soil should be placed on the of the pipe. The piping needs to be backfilled and pressure tested, and typically at least one overnight is required prior to any final connection. This allows the PE to cool to the prevailing ground temperature, which is likely to be in the range of 60 to 75ºF (16 to 24ºC).

Section 5 provided an example of the stresses caused by installation temperature changes of 90 to 65ºF (32 to 18ºC) in 2 days, no relaxation time, and a seasonal cooling of from 65 to 40ºF (32 to 4ºC) in an additional 90 days, *typical* conditions in a *moderate* temperature zone. This resulted in a stress of about 290 psi (2.00 MPa). Allowing the pipe to cool to the soil temperature of 65ºF (18ºC) prior to connection reduced the final stresses to about 150 (1.03 MPa), which is a substantial reduction, and only about 4 of the HDPE yield stress. These *best practices* conditions can reduce the overall stresses by 40 to 60%.

6.3. Geometric Accommodations

The pipeline can be installed so that a bit of geometry change may be possible for the backfilled pipeline. This could be accomplished by snaking the PE during installation. This may be practical for smaller diameter coiled pipe but not for straight sections of larger diameter piping. Also, highly compacted backfill could resist any potential pipe straightening. Small bends/deflections may allow some movements for larger diameters.

In general, any feature that allows some axial displacement of the HDPE pipeline will reduce the thermally induced stresses. If the PE will be connected to a bell and spigot system, then possible pipe pullout at the joints due to tensile forces must be considered. An anchor system may be required to limit pipe displacements at the joints to prevent pullout. However, a small amount of displacement can reduce these thermal stresses.

6.4. Summary

Thermal stresses in buried pipes are caused by temperature changes. Anything that can be done to reduce the temperature changes will reduce the stresses. Once the piping is buried in the ground, natural environmental events take control. Seasonal temperature changes naturally occur and cannot be controlled practically. Reducing the stresses during installation temperature change is the most effective way to reduce the thermal stresses.

Section 7

Summary and Conclusions

7.1. Introduction

This report contains several sections outlining the requirements necessary for estimating thermal stresses in HDPE water piping. To do this it is necessary to determine the relevant material properties that will be used. Then it is necessary to decide the thermal loading scenarios for the piping. These include pipe installation, seasonal cooling, and the possibility of a rapid influx of cold water. The next step is the development of a mathematical model to evaluate thermal stresses and to have simplified approach so that accurate estimates of pipe stresses can be determined without requiring the use of detailed equations and procedures. That is the primary purpose of this report.

7.2. Summary

This report addresses methods to determine the stresses in HDPE piping caused by thermal stresses. The general HDPE properties required for a linearly viscoelastic material model were identified in Section 2. Key parameters are the coefficient of thermal expansion/contraction, α_T = 80×10^{-6}/ºF (144×10^{-6}/ºC), and the temperature-dependent Young's modulus, E(T). The moduli used in this report are in excellent agreement with those given in the PPI (2008) Handbook of Polyethylene Pipe. Stresses in HDPE relax with time. The relaxation rate of the HDPE used in this report is n = 0.085, which is a conservative value. Relaxation rates reported in the literature can be as high as n = 0.1 for polyethylene. The value of n used in this report is based on physical testing of HDPE pipe under both stress- and strain-controlled testing at several temperatures.

Section 3 presents an investigation into the ground temperatures in the North American U.S. and Canada. As expected, there is a large range of temperatures across this huge expanse of land. Three temperature zones are identified as cold, moderate, and warm. For the most part, water pipelines are buried beneath the frost depth. The minimum temperatures during the warmer seasons at this depth is about 55ºF (13ºC). During the cold seasons, the minimum temperatures in the ground are about 50, 40, and 33 ºF (10, 4, and 1 ºC) for these three zones. Section 3 recommends temperature changes and load durations for a) pipe installation, b) stress relaxation following installation, and c) seasonal temperature changes.

Having defined the material properties and anticipated temperature ranges, the linear viscoelastic model used to estimate pipeline stresses is presented in Section 4. Stresses in HDPE can be developed due to "instantaneous" loading, in which the loading function is applied very quickly so that relaxation does not occur along with the loading. Another type of loading is referred to as ramp loading, in which the loading function changes with time. This report assumes a linearly changing temperature-time profile, and presents methods used to determine the stresses for these temperature-time changes.

Section 5 presents alternate methods to determine HDPE pipe thermal stresses and the stresses typical for several temperature scenarios. Reasonable bounds on the complete temperature-time profiles for warm, moderate, and cold temperature zones are recommended. The resulting stress for *typical* construction are roughly 250 to 300 psi (1.7 to 2.1 MPa) for the three temperature zones.

For most cases, the simplest method is to estimate stresses for approximate loading conditions, considering *all* temperature-time phases as a single step. This single step approach is repeated here. Figure 7.1 shows the temperature-time profile for a complete loading schedule. The detailed load path would follow points O-A-B-C, using times 0, t_1, t_2, and t_3. The single-step load path would be from line O-C with the *full* $\Delta T = \Delta T_1 + \Delta T_2$ and using the *single* time step from 0 to t_3. Figure 7.2 is another repeat of the simplified design curve. Enter the figure using the single time, t_3, and read the stress ratio, $\sigma(t)/\sigma_0$. The stress, $\sigma(t)$, is this stress ratio × [$\sigma_0 = E(T_3)\alpha_T\Delta T$].

Section 5 presents minimum water temperatures for a rapid influx of near-freezing cold water. The stresses produced are described, and example calculations are provided.

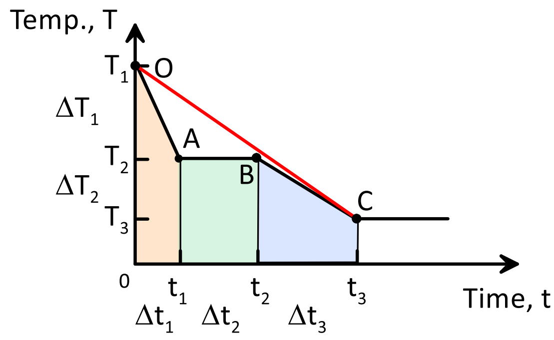


Figure 7.1. One-step temperature-time load path (Line O-C)

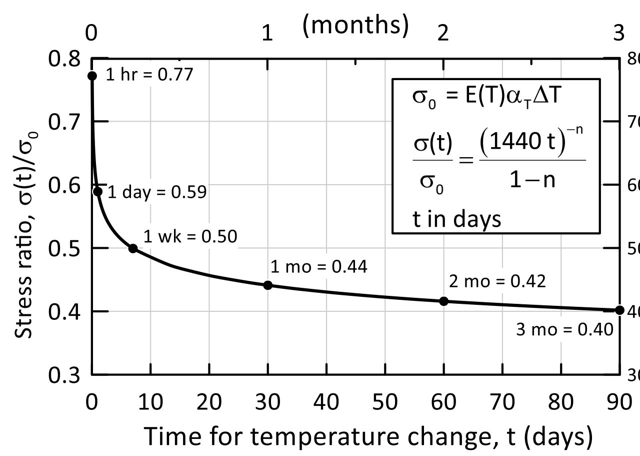


Figure 7.2. Normalized stress vs. time

Section 6 presents a few methods and considerations for reducing the stresses due to thermal changes in HDPE piping. Most of the methods are based on construction and operational considerations. The main thing that can be done is to reduce the temperature differential during the installation phase. Most often, the pipe trench is backfilled to some extent prior to the hydrostatic pressure test. And, the pipe further equilibrates overnight before final connection to the existing system. This cooling can decrease the overall pipeline stresses substantially since most of the temperature change now will be due to seasonal cooling. Allowing the pipe to cool to the soil temperatures of 60 to 70ºF (16 to 21ºC) prior to connection reduces the stresses for the full temperature profile, including seasonal cooling to 110, 150, and 180 psi (0.76, 1.03 and 1.24 MPa) for *warm*, *moderate* and *cold* temperature minimums, respectively. These stresses are about 3 to 5% of the HDPE yield stress.

7.3. Conclusions and Closing Considerations

The methods used in this report present guidelines for estimating thermal stresses in HDPE water piping. The equations are presented for predicting stresses for a known set of temperatures and load durations and the sequence in which they are applied. The report presents rational estimates of the temperatures anticipated in broad geographical zones. The typical ground temperatures and frost depths are estimated, and recommended values are given as a guide to the design engineer. Depth of frost penetration and minimum seasonal temperatures are provided, but it remains the task of the design professional to select the appropriate conditions.

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Appendix A

Stress Calculation Examples

A.1. Example #1: Project in Cold Climate Region

Possible project location: Crookston, MN

Temperatures (per USDA, NRCS data over five year period):

- Summer ground temperature, T_2, at 40 in (1.02 m) depth : 62°F (16.7°C)
- Winter ground temperature, T_3, at 40 in (1.02 m) depth : 32°F (0°C)
- Summer maximum air temperature : 98°F (36.7°C)

Timeline:

- Pipe installation during summer
- **Pipe temperature at the time of hook-up, T_1, is equal to the air temperature**
- Pipe temperature change from installation to ground temperature (from T_1 to T_2) occurs in 1 hour
- Seasonal ground/pipe temperature drop starts 30 days after installation
- Seasonal ground/pipe temperature change (from T_2 to T_3) occurs over 100 days

<u>Known parameters/values:</u>

- Fixed material properties:
  - Thermal expansion/contraction coefficient, $\alpha_T = 80 \times 10^{-6}$ /°F (144×10^{-6} /°C)
  - Power law relaxation exponent, $n = 0.085$

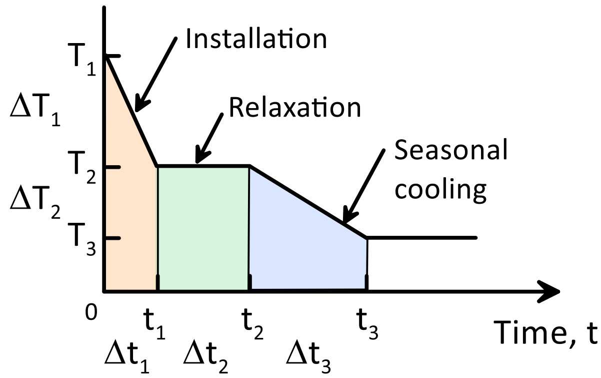
- Case specific temperature values:
  - Pipe hook-up temperature, T_1 = 98°F (36.7°C)
  - Summer ground/pipe temperature, T_2 = 62°F (16.7°C)
  - Winter ground/pipe temperature, T_3 = 32°F (0°C)
  - Installation temperature change, $\Delta T_1 = T_2 - T_1 = 62 - 98 = -36$°F (–20°C)
  - Seasonal temperature change, $\Delta T_2 = T_3 - T_2 = 32 - 62 = -30$°F (–16.7°C)

- Case specific time values:
  - Duration of installation related pipe temperature change, Δt_1 = 1 hour = 0.0417 days
  - Stress relaxation at constant summer temperature, Δt_2 = 30 days
  - Duration of seasonal ground/pipe temperature change, Δt_3 = 100 days

Solution:

- There are two temperature changes in this case, so there will be two temperature ramp loadings as shown below.

- The maximum thermal stress in the pipe will be at the end of one of these two temperature changes (i.e., either at $t = t_1$ or at $t = t_3$).



- Thermal stress due to first temperature change, from T_1 to T_2, at the end of loading ($t = t_1$):

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad \text{(Eqn 4.9a)}$$

– Where, $t_1 = \Delta t_1$ and $t = \Delta t_1 = t_1$ for this temperature loading

– Modulus, E_0, at 62°F (16.7°C): (Eqn 2.3)

$E_{@62°F} = 305{,}000 \times (e^{-0.012 \times T\,(°F)})$ psi $= 305{,}000 \times (e^{-0.012 \times 62°F}) = 144{,}939$ psi
$E_{@16.7°C} = 1{,}432{,}000 \times (e^{-0.0216 \times T\,(°C)})$ kPa $= 1{,}432{,}000 \times (e^{-0.0216 \times 16.7°C}) = 998{,}353$ kPa

– Strain, $\varepsilon_0 = \alpha_T\, \Delta T_1$

$\varepsilon_0 = \alpha_T\, \Delta T_1 = 80 \times 10^{-6}$ /°F $\times |-36°F| = 144 \times 10^{-6}$ /°C $\times |-20°C| = 2.88 \times 10^{-3}$

– Temperature loading period, $t_1 = \Delta t_1 = 1$ hour $= 60$ min

Then, the thermal stress at t_1 is:

$$\begin{aligned}
\sigma(t) &= \frac{E_0 \varepsilon_0}{\Delta t_1} \frac{\Delta t_1^{1-n}}{1-n} \\
&= \frac{(144{,}939\,\text{psi})\left[(80\times10^{-6}\,/\,°\text{F})(|-36°\text{F}|)\right]}{60\text{ min}} \frac{60\text{ min}^{(1-0.085)}}{1-0.085} = 322\text{ psi} \\
&= \frac{(998{,}353\,\text{kPa})\left[(144\times10^{-6}\,/\,°\text{C})(|-20°\text{C}|)\right]}{60\text{ min}} \frac{60\text{ min}^{(1-0.085)}}{1-0.085} = 2{,}219\text{ kPa}
\end{aligned}$$

- Thermal stress at the end of second temperature change, from T_2 to T_3 is (i.e., at $t = t_3$):

At this time, t_3, there are thermal stresses in the pipe due to the two temperature changes. While the second temperature ramp loading just ended and introduced new thermal stresses, there were already thermal stresses in the pipe due to the first temperature change, ΔT_1, going through stress relaxation.

Part (a):

Thermal stress due to second temperature change, from T_2 to T_3, at the end of loading (@ $t = t_3$):

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad \text{(Eqn 4.9a)}$$

– Where, $t_1 = \Delta t_3$ and $t = \Delta t_3$ for this temperature loading

– Modulus, E_0, at 32°F (0°C): (Eqn 2.3)

$E_{@32°F} = 305{,}000 \times (e^{-0.012 \times T\,(°F)})$ psi $= 305{,}000 \times (e^{-0.012 \times 32°F}) = 207{,}745$ psi
$E_{@0°C} = 1{,}432{,}000 \times (e^{-0.0216 \times T\,(°C)})$ kPa $= 1{,}432{,}000 \times (e^{-0.0216 \times 0°C}) = 1{,}432{,}000$ kPa

– Strain, $\varepsilon_0 = \alpha_T \, \Delta T_2$

$\varepsilon_0 = \alpha_T \, \Delta T_2 = 80 \times 10^{-6}$ /°F × |–30°F| = 144×10^{-6} /°C × |–16.7°C| = 2.4×10^{-3}

– Temperature loading period, $t_1 = \Delta t_3 = 100$ days = 144,000 min

The thermal stress at t_3 due to the second temperature change, Part (a):

$$\begin{aligned}
\sigma_a &= \frac{E_0 \varepsilon_0}{\Delta t_3} \frac{\Delta t_3^{1-n}}{1-n} \\
&= \frac{(207{,}745\,\text{psi})\left[(80\times10^{-6}\,/\,°\text{F})(|-30°\text{F}|)\right]}{144{,}000\ \text{min}} \frac{144{,}000\ \text{min}^{(1-0.085)}}{1-0.085} = 199\ \text{psi} \\
&= \frac{(1{,}432{,}000\,\text{kPa})\left[(144\times10^{-6}\,/\,°\text{C})(|-16.7°\text{C}|)\right]}{144{,}000\ \text{min}} \frac{144{,}000\ \text{min}^{(1-0.085)}}{1-0.085} = 1{,}371\,\text{kPa}
\end{aligned}$$

Part (b):

Thermal stress at $t = t_3$ due to the ongoing stress relaxation from the first temperature change:

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1}\left[\frac{t^{1-n} - (t - t_1)^{1-n}}{1-n}\right] \quad \text{(Eqn 4.9b)}$$

– Where, $t_1 = \Delta t_1$ and $t = t_3$ for this temperature loading

– Modulus of the pipe, E_0, at 32°F (0°C): E = 207,745 psi (1,432,000 kPa)   (see above)

– Strain, $\varepsilon_0 = \alpha_T \, \Delta T_1 = 2.88 \times 10^{-3}$ (see above)

– Temperature loading period, $t_1 = \Delta t_1$ = 1 hour = 60 min

– Time, t, past since the start of first temperature loading:

$t = t_3 = \Delta t_1 + \Delta t_2 + \Delta t_3$ = 0.0417 days + 30 days + 100 days = 130.0417 days = 187,260 min

The thermal stress at t_3 due to the first temperature change, Part (b):

$$\begin{aligned}\sigma_b &= \frac{E_0 \varepsilon_0}{\Delta t_1}\left[\frac{t_3^{1-n} - (t_3 - \Delta t_1)^{1-n}}{1-n}\right] \\ &= \frac{(207{,}745\,\text{psi})\left[(80\times10^{-6}\,/\,{}^\circ\text{F})(|-36^\circ\text{F}|)\right]}{60}\left[\frac{187{,}260^{(1-0.085)} - (187{,}260-60)^{(1-0.085)}}{1-0.085}\right] \\ &= 213\,\text{psi}\end{aligned}$$

$$\begin{aligned} &= \frac{(1{,}432{,}000\,\text{kPa})\left[(144\times10^{-6}\,/\,{}^\circ\text{C})(|-20^\circ\text{C}|)\right]}{60}\left[\frac{187{,}260^{(1-0.085)} - (187{,}260-60)^{(1-0.085)}}{1-0.085}\right] \\ &= 1{,}469\,\text{kPa}\end{aligned}$$

Then, the total thermal stress at t_3 due to both temperature changes is:

$\sigma = \sigma_a + \sigma_b$ = 199 + 213 = 412 psi (= 1,371 + 1,470 = 2,840 kPa)

Summary:

- The stress history is shown in Figure A.1.
- Thermal stress in the pipe at the end of seasonal temperature change, ΔT_2, is greater than the thermal stress at the end of installation temperature change ΔT_1.
- Maximum predicted thermal stress in the pipe is 412 psi (2,840 kPa) and it occurs at the end of seasonal ground temperature drop.

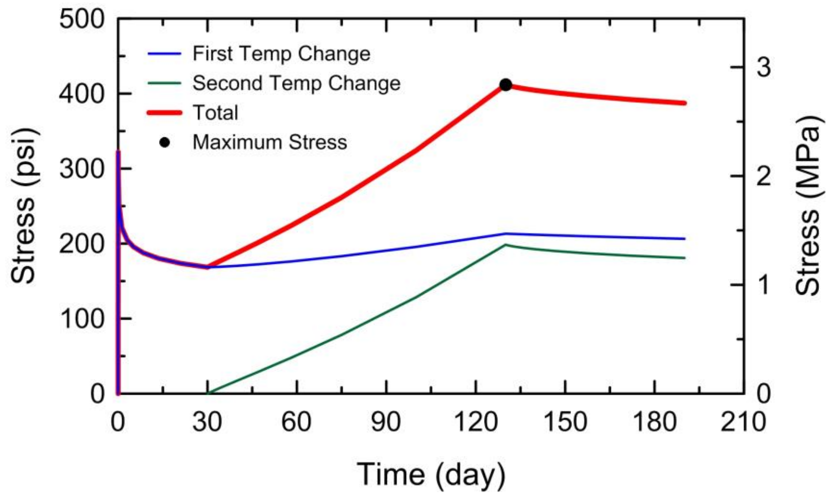


Figure A.1. Example #1: Thermal stress history of the pipe

A.2. Example #2: Effect of Installation Temperature

Possible project location: Crookston, MN

Temperatures (per USDA, NRCS data over five year period):

- Summer ground temperature, T_2, at 40 in (1.02 m) depth : 62°F (16.7°C)
- Winter ground temperature, T_3, at 40 in (1.02 m) depth : 32°F (0°C)
- Summer maximum air temperature : 98°F (36.7°C)

Timeline:

- Pipe installation during summer
- **Waiting period before the connections, and the pipe temperature at the time of hook-up, T_1, is equal to the summer ground temperature**
- Therefore, no installation related temperature changes
- Seasonal ground/pipe temperature drop starts 30 days after installation
- Seasonal ground/pipe temperature change (from T_2 to T_3) occurs over 100 days

<u>Known parameters/values:</u>

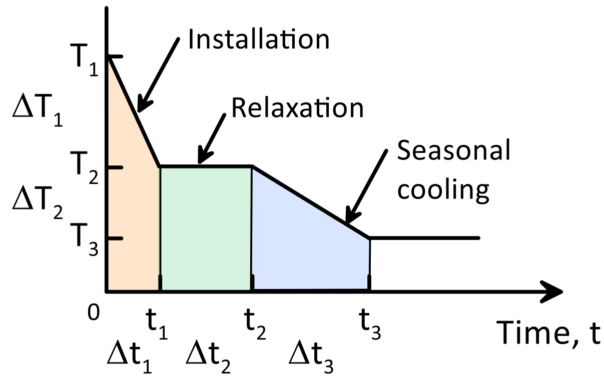
- Fixed material properties:
  - Thermal expansion/contraction coefficient, $\alpha_T = 80 \times 10^{-6}$ /°F (144×10^{-6} /°C)
  - Power law relaxation exponent, $n = 0.085$

- Case specific temperature values:
  - Pipe hook-up temperature, T_1 = 62°F (16.7°C)
  - Summer ground/pipe temperature, T_2 = 62°F (16.7°C)
  - Winter ground/pipe temperature, T_3 = 32°F (0°C)
  - Installation temperature change, $\Delta T_1 = T_2 - T_1 = 62 - 62 = 0$°F (0°C)
  - Seasonal temperature change, $\Delta T_2 = T_3 - T_2 = 32 - 62 = -30$°F (–16.7°C)

- Case specific time values:
  - Duration of seasonal ground/pipe temperature change, Δt_3 = 100 days

Solution:

- There is only seasonal temperature changes in this case, so there will be one temperature ramp loading [$T_1 = T_2$, $\Delta T_1 = 0°F$ (0°C), i.e., no installation related temperature loading].



- The maximum thermal stress in the pipe will be at the end of the seasonal temperature change.

- Thermal stress at the end of seasonal temperature change, from T_2 to T_3 is (i.e., at $t = t_3$):

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad \text{(Eqn 4.9a)}$$

– Where, $t_1 = \Delta t_3$ and $t = \Delta t_3$ for this temperature loading

– Modulus, E_0, at 32°F (0°C): (Eqn 2.3)

$E_{@32°F} = 305{,}000 \times (e^{-0.012 \times T\,(°F)})$ psi $= 305{,}000 \times (e^{-0.012 \times 32°F}) = 207{,}745$ psi
$E_{@0°C} = 1{,}432{,}000 \times (e^{-0.0216 \times T\,(°C)})$ kPa $= 1{,}432{,}000 \times (e^{-0.0216 \times 0°C}) = 1{,}432{,}000$ kPa

– Strain, $\varepsilon_0 = \alpha_T \, \Delta T_2$

$\varepsilon_0 = \alpha_T \, \Delta T_2 = 80 \times 10^{-6}$ /°F $\times |-30°F| = 144 \times 10^{-6}$ /°C $\times |-16.7°C| = 2.4 \times 10^{-3}$

– Temperature loading period, $t_1 = \Delta t_3 = 100$ days $= 144{,}000$ min

Thermal stress due to second temperature change, from T_2 to T_3, at the end of loading (@ $t = t_3$):

$$\begin{aligned}\sigma(t) &= \frac{E_0 \varepsilon_0}{\Delta t_3} \frac{\Delta t_3^{1-n}}{1-n} \\ &= \frac{(207{,}745\,\text{psi})\left[(80 \times 10^{-6} / °F)(|-30°F|)\right]}{144{,}000 \text{ min}} \frac{144{,}000 \text{ min}^{(1-0.085)}}{1-0.085} = 199 \text{ psi} \\ &= \frac{(1{,}432{,}000\,\text{kPa})\left[(144 \times 10^{-6} / °F)(|-16.7°C|)\right]}{144{,}000 \text{ min}} \frac{144{,}000 \text{ min}^{(1-0.085)}}{1-0.085} = 1{,}371\,\text{kPa}\end{aligned}$$

Summary:

- The stress history is shown in Figure A.2.
- There is only one temperature loading which is from the seasonal ground/pipe temperature changes. There are no installation related thermal stresses since the pipe temperature is the same as the ground temperature at the time of pipe hook-up.
- Maximum predicted thermal stress in the pipe is 199 psi (1,371 kPa) and it occurs at the end of seasonal ground temperature drop.

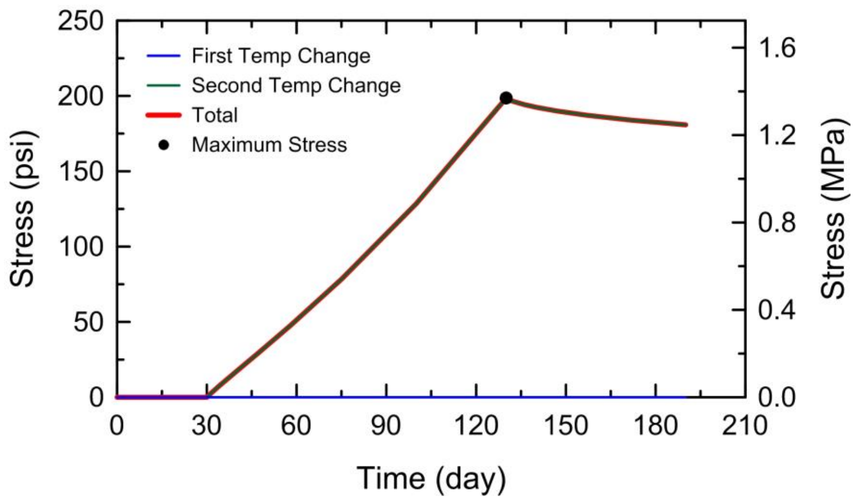


Figure A.2. Example #2: Thermal stress history of the pipe

A.3. Example #3: Project in Warm Climate Region

Possible project location: Weslaco, TX

Temperatures (per USDA, NRCS data over five year period):

- Summer ground temperature, T_2, at 40 in (1.02 m) depth : 89°F (31.7°C)
- Winter ground temperature, T_3, at 40 in (1.02 m) depth : 62°F (16.7°C)
- Summer maximum air temperature : 105°F (40.6°C)

Timeline:

- Pipe installation during summer
- **Pipe temperature at the time of hook-up, T_1, is equal to the air temperature**
- Pipe temperature change from installation to ground temperature (from T_1 to T_2) occurs in 1 hour
- Seasonal ground/pipe temperature drop starts 30 days after installation
- Seasonal ground/pipe temperature change (from T_2 to T_3) occurs over 100 days

<u>Known parameters/values:</u>

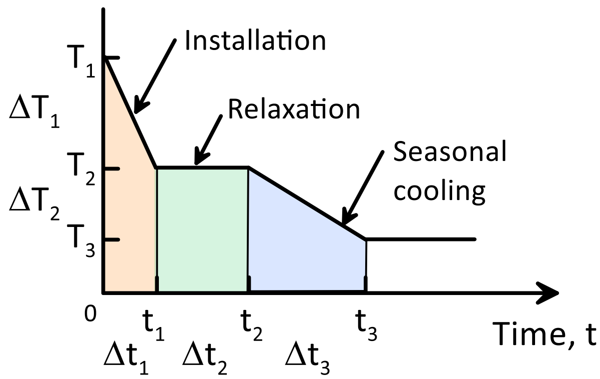
- Fixed material properties:
  - Thermal expansion/contraction coefficient, $\alpha_T = 80\times10^{-6}$ /°F (144×10^{-6} /°C)
  - Power law relaxation exponent, $n = 0.085$

- Case specific temperature values:
  - Pipe hook-up temperature, T_1 = 105°F (40.6°C)
  - Summer ground/pipe temperature, T_2 = 89°F (31.7°C)
  - Winter ground/pipe temperature, T_3 = 62°F (16.7°C)
  - Installation temperature change, $\Delta T_1 = T_2 - T_1 = 89 - 105 = -16$°F (–8.9°C)
  - Seasonal temperature change, $\Delta T_2 = T_3 - T_2 = 62 - 89 = -27$°F (–15.0°C)

- Case specific time values:
  - Duration of installation related pipe temperature change, Δt_1 = 1 hour = 0.0417 days
  - Stress relaxation at constant summer temperature, Δt_2 = 30 days
  - Duration of seasonal ground/pipe temperature change, Δt_3 = 100 days

Solution:

- There are two temperature changes in this case, so there will be two temperature ramp loadings as shown below.



- The maximum thermal stress in the pipe will be at the end of one of these two temperature changes (i.e., either at $t = t_1$ or at $t = t_3$).

- Thermal stress due to first temperature change, from T_1 to T_2, at the end of loading (@ $t = t_1$):

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad \text{(Eqn 4.9a)}$$

– Where, $t_1 = \Delta t_1$ and $t = \Delta t_1 = t_1$ for this temperature loading

– Modulus, E_0, at 89°F (31.7°C): (Eqn 2.3)

$E_{@89°F} = 305{,}000 \times (e^{-0.012 \times T\,(°F)})$ psi $= 305{,}000 \times (e^{-0.012 \times 89°F}) = 104{,}827$ psi
$E_{@31.7°C} = 1{,}432{,}000 \times (e^{-0.0216 \times T\,(°C)})$ kPa $= 1{,}432{,}000 \times (e^{-0.0216 \times 31.7°C}) = 722{,}059$ kPa

– Strain, $\varepsilon_0 = \alpha_T \Delta T_1$

$\varepsilon_0 = \alpha_T \Delta T_1 = 80\times10^{-6}$ /°F $\times |-16°F| = 144\times10^{-6}$ /°C $\times |-8.9°C| = 1.28 \times 10^{-3}$

– Temperature loading period, $t_1 = \Delta t_1 = 1$ hour $= 60$ min

Then, the thermal stress at t_1 is:

$$\sigma(t) = \frac{E_0 \varepsilon_0}{\Delta t_1} \frac{\Delta t_1^{1-n}}{1-n}$$
$$= \frac{(104{,}827\,\text{psi})\left[(80\times10^{-6}\,/\,°F)(|-16°F|)\right]}{60\text{ min}} \frac{60\text{ min}^{(1-0.085)}}{1-0.085} = 104\text{ psi}$$
$$= \frac{(722{,}059\,\text{kPa})\left[(144\times10^{-6}\,/\,°C)(|-8.9°C|)\right]}{60\text{ min}} \frac{60\text{ min}^{(1-0.085)}}{1-0.085} = 714\text{ kPa}$$

- Thermal stress at the end of second temperature change, from T_2 to T_3 is (i.e., at $t = t_3$):

At this time, t_3, there are thermal stresses in the pipe due to the two temperature changes. While the second temperature ramp loading just ended and introduced new thermal stresses, there were already thermal stresses in the pipe due to the first temperature change, ΔT_1, going through stress relaxation.

Part (a):

Thermal stress due to second temperature change, from T_2 to T_3, at the end of loading (@ $t = t_3$):

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1} \frac{t^{1-n}}{1-n} \qquad \text{(Eqn 4.9a)}$$

– Where, $t_1 = \Delta t_3$ and $t = \Delta t_3$ for this temperature loading

– Modulus, E_0, at 62°F (16.7°C): (Eqn 2.3)

$E_{@62°F} = 305{,}000 \times (e^{-0.012 \times T\,(°F)})$ psi $= 305{,}000 \times (e^{-0.012 \times 62°F}) = 144{,}939$ psi
$E_{@16.7°C} = 1{,}432{,}000 \times (e^{-0.0216 \times T\,(°C)})$ kPa $= 1{,}432{,}000 \times (e^{-0.0216 \times 16.7°C}) = 998{,}353$ kPa

– Strain, $\varepsilon_0 = \alpha_T\, \Delta T_2$

$\varepsilon_0 = \alpha_T\, \Delta T_2 = 80\times10^{-6}$ /°F $\times$ |–27°F| $= 144 \times 10^{-6}$ /°C $\times$ |–15°C| $= 2.16 \times 10^{-3}$

– Temperature loading period, $t_1 = \Delta t_3 = 100$ days $= 144{,}000$ min

The thermal stress at t_3 due to the second temperature change, Part (a):

$$\sigma_a = \frac{E_0 \varepsilon_0}{\Delta t_3} \frac{\Delta t_3^{1-n}}{1-n}$$
$$= \frac{(144{,}939\,\text{psi})\left[(80\times10^{-6})(|-27°\text{F}|)\right]}{144{,}000\ \text{min}} \frac{144{,}000\ \text{min}^{(1-0.085)}}{1-0.085} = 125\ \text{psi}$$
$$= \frac{(998{,}353\,\text{kPa})\left[(144\times10^{-6})(|-15°\text{C}|)\right]}{144{,}000\ \text{min}} \frac{144{,}000\ \text{min}^{(1-0.085)}}{1-0.085} = 859\ \text{kPa}$$

Part (b):

Thermal stress at t = t_3 due to the ongoing stress relaxation from the first temperature change:

$$\sigma(t) = \frac{E_0 \varepsilon_0}{t_1}\left[\frac{t^{1-n} - (t - t_1)^{1-n}}{1-n}\right] \qquad \text{(Eqn. 4.9b)}$$

- Where, $t_1 = \Delta t_1$ and $t = t_3$ for this temperature loading
- Modulus of the pipe, E_0, at 62°F (16.7°C): E = 144,939 psi (998,353 kPa)   (see above)
- Strain, $\varepsilon_0 = \alpha_T \, \Delta T_1 = 2.16 \times 10^{-3}$ (see above)
- Temperature loading period, $t_1 = \Delta t_1$ = 1 hour = 60 min
- Time, t, past since the start of first temperature loading:

  $t = t_3 = \Delta t_1 + \Delta t_2 + \Delta t_3$ = 0.0417 days + 30 days + 100 days = 130.0417 days = 187,260 min

The thermal stress at t_3 due to the first temperature change, Part (b):

$$\sigma_b = \frac{E_0 \varepsilon_0}{\Delta t_1}\left[\frac{t_3^{1-n} - (t_3 - \Delta t_1)^{1-n}}{1-n}\right]$$

$$= \frac{(144{,}939\,\text{psi})\left[(80\times10^{-6}\,/\,°\text{F})(|-16°\text{F}|)\right]}{60}\left[\frac{187{,}260^{(1-0.085)} - (187{,}260 - 60)^{(1-0.085)}}{1-0.085}\right]$$

$$= 66\ \text{psi}$$

$$= \frac{(998{,}353\,\text{kPa})\left[(144\times10^{-6}\,/\,°\text{C})(|-8.9°\text{C}|)\right]}{60}\left[\frac{187{,}260^{(1-0.085)} - (187{,}260 - 60)^{(1-0.085)}}{1-0.085}\right]$$

$$= 456\ \text{kPa}$$

Then, the total thermal stress at t_3 due to both temperature changes is:

$\sigma = \sigma_a + \sigma_b$ = 125 + 66 = 191 psi (= 859 + 456 = 1,315 kPa)

Summary:

- The stress history is shown in Figure A.3.
- Thermal stress in the pipe at the end of seasonal temperature change, ΔT_2, is greater than the thermal stress at the end of installation temperature change ΔT_1.
- Maximum predicted thermal stress in the pipe is 191 psi (1,315 kPa) and it occurs at the end of seasonal ground temperature drop.

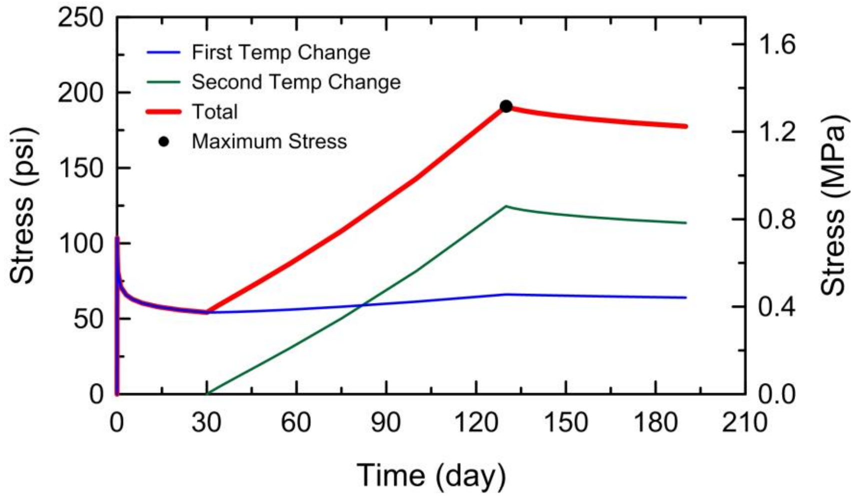


Figure A.3. Example #3: Thermal stress history of the pipe