EVALUATING THE COMPATIBILITY OF CHEMICAL DISINFECTANTS WITH PLASTIC PIPE MATERIALS USED FOR POTABLE WATER DISTRIBUTION

TECHNICAL MEMORANDUM

FINAL
August 2008

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Typically, pipeline designers have focused a majority of their analysis on the physical aspects of pipeline design (such as, soil load, hydraulics, and construction detail). To a large extent, industry standards, such as American Water Works Association (AWWA) and the American Society of Testing and Materials (ASTM) have successfully defined minimum requirements for users in areas such as dimensions, pressure ratings, and other product performance attributes. Recently, an increasing amount of research on accelerated pipe aging has been able to shed new light on the performance of plastic pipeline materials in various environments. Specifically, research in the past six years (some initiated after premature and unexplained field failures were observed) have begun to elucidate the mechanism for oxidative attack on polyethylene (PE) pipes in the presence of primary and secondary disinfectants commonly used to treat potable water. A desktop study was conducted to evaluate the available research and pipe industry standards and guidelines relevant to the effects of drinking water disinfectants on PE and polyvinyl chloride (PVC) pipe. The following is a summary of findings from this study:

1. The majority of chemical compatibility information available to pipe designers is based on un-stressed sample testing and does not factor in the dynamic aspect of material degradation in the presence of mechanical stress, as would be present in pressurized or otherwise externally stressed pipelines.
2. Premature Stage 3 “end of life failure” (chain scission) is possible in PE pipelines in the presence of chlorine, chlorine dioxide, and chloramine disinfectants. Research indicates that chlorine dioxide is the most aggressive disinfectant followed by chlorine and then chloramines:
    a. A commonly observed mechanism of initial attack on the immediate inner wall surface with additional penetration due to oxidant diffusion and free radical attack results in additional cracking into pipe structure while under pressure.
    b. No refereed publications were identified investigating the influence of potable water disinfectants on PVC as there have been no observed premature oxidation induced failures (Burn *et al* 2005; Seargeant 2007). This may be due to material differences impacting oxidant diffusion and chemical cross-linking while under oxidative attack.
3. Recent developments in HDPE materials (PE-100) have allowed for a higher design factor to reflect a superior resistance to slow crack growth failure (SCG – Stage 1 and 2 failures), but the design factor may not take into account the potential for loss of wall strength due to oxidative attack and potential Stage 3 failure with respect to design life.

4. Commonly used North American pipe standards (AWWA, ASTM) do not take into account disinfection protocol when establishing hydrostatic design basis (HDB) or life expectancy and there is no established design factor to account for oxidation induced pipe degradation.

SUMMARY OF FINDINGS

Pipe Interactions with Chemical Disinfectants

- A summary of the aging conditions used to estimate the effects of disinfectants on PE pipe materials from the studies discussed above is shown in Table 3.1. All except for two studies (Dear and Mason 2006, Colin et al., 2006) investigated chlorine concentrations relevant for distribution systems.

- Stage 3 failure in PE can be caused by oxidation due to the presence of disinfectants. Chlorine dioxide is more aggressive than chlorine, and chlorine is more aggressive than chloramines.

- Chlorine dioxide was observed to deplete the antioxidant in PE pipe material much more rapidly than chlorine or chloramines. The attack was restricted to a layer of about 1 mm in thickness along the inner pipe wall with subsequent free radical attack on the PE chain structure creating chain scission and reduced mechanical properties.

- Lower penetration of disinfectants (chlorine, chlorine dioxide, and chloramines) and loss of stabilizer is expected in PVC pipe material due to lower diffusion rates than PE pipe material as based on their respective glass transition temperatures. However, no refereed publications were identified which investigated the influence of potable water disinfectants on PVC.

- The presence of disinfectants may increase the strength (molecular weight) of PVC.

- There are three commonly accepted failure modes for plastic pipe: Stage 1, 2, and 3. However, Chung *et al* (2007) has proposed two additional stages of failure for PE pipe, which include Mode 2 failure (Mechanical Initiation-Oxidative Propagation) and Mode 3 failure (Oxidative Initiation-Mechanical Propagation). These new modes of failure were observed in PE pipes used for potable water distribution.

Disinfection and Disinfection Trends

- Chlorine and chloramines are the most common secondary disinfectants employed in North America; chlorine dioxide is predominately used in the U.S. as a pre-oxidant or for primary disinfection credit. In Europe, however, chlorine dioxide use is more common in distribution systems due to a more selective use at lower doses.

- Disinfectant use since 1978 indicates a general trend towards the use of alternative disinfectants (that is, chloramines, chlorine dioxide, ozone) to chlorine.

Lifetime Evaluations of Plastic Pipes

- Historically, PE and PVC water mains have failed infrequently and are expected to have at least a 50-year design life.

- Recently, PE water mains are failing prematurely in France, possibly due to chemical ageing (Stage 3 failure mode) caused by oxidation. Jana Labs also has exhumed PE water mains that have failed prematurely under Stage 3 failure mode.

Plastic Pipe Standards

- There are three commonly accepted failure modes for plastic pipe: Stage 1, 2, and 3. However, Chung *et al* (2007) has proposed two additional stages of failure, which include Mode 2 failure (Mechanical Initiation-Oxidative Propagation) and Mode 3 failure (Oxidative Initiation-Mechanical Propagation). Pipe standards only address Stage 1, 2, and 3 failures. None of the pipe standards addresses Mode 2 or Mode 3 failures.

- PE tends to fail by the SCG mechanism (Stage 2 failure mode). Recently, HDPE materials with higher resistance to SCG have been developed allowing for a higher design factor. The higher design factor allows for thinner sidewall design. The higher design factor may be appropriate for avoiding Stage 1 and 2 failures beyond 50 years but may not be appropriate for avoiding Stage 3 failures prior to 50 years. It could be a cause for concern that thinner walled pipes are now allowed for use in potable water distribution system with the presence of oxidants.

- ASTM and AWWA pipe design standards do not take disinfection into account when establishing the HDB. The pipes are tested with pure water.

- Establishment of the “50-year design life” as a mathematical extrapolation assumes that no chemical aging will occur in PE and PVC. The 50-year design life assumes the PE failure mode will not change from Stage 1 (for substantiated materials according to PPI-TR-3), and Stage 2 for other PE materials in PPI-TR-4. If the failure mode does change, the design life could be less than 50 years.

- ASTM D 2837 requires the design engineer to choose “appropriate” design factors to account for more aggressive environments. PPI-TR-9 provides design factors for PE and PVC pressure applications but not for disinfectants or oxidative environments

- Chemical dip tests are not helpful for testing a material’s resistance to oxidation when used in pressure applications as noted by several disclaimers in PPI-TR-19.

- Short-term tests involving the exposure of PE pipes to high concentrations of disinfectants, as referenced by PPI TN-34, are not helpful in examining long-term effects.

- ASTM F 2023 provides guidance for predicting PEX failure due to Stage 3 failure mode. PEX materials that pass or do not pass the lifetime predictor tests prescribed by ASTM F 876 are listed in PPI-TR-4.

- ASTM F 2263 provides guidance for predicting MDPE and HDPE failure due to Stage 3 failure mode. PPI-TR-4 does not reference ASTM F 2263, nor does it discuss how long the pipes will last with reference to Stage 3 failure modes. PPI-TR-4 only references a 50-year design life based on Stage 1 and Stage 2 failures.

- Design engineers need guidance in choosing a design factor for plastic pipe. According to ASTM D 2837 it is up to the design engineer to choose an appropriate design factor. Guidance is offered (for PE and PVC) by PPI-TR-9 for a chemical design factor for liquid hydrocarbon exposure but not for PE exposed to chemical disinfectants in a pressurized pipe.

- A summary of the testing and design standards for plastic pipe is presented in Table 3.1. Based on this summary, the following were observed:
  - No pipe standards presented information on the use of chlorine dioxide, and only one standard presented information on the use of chloramines.
  - Three standards (ASTM F 2023, PPI-TR-3, and PPI TR-4) present the resistance of PEX to pressurized chlorinated water.

- ASTM F 2263 is the only standard that presents a test method for MDPE or HDPE with regard to Stage 3 failure. Nevertheless, this method is not used in any of the standards that establish HDB or design life for MDPE or HDPE pipes (ASTM D 2837, PPI-TR-3, PPI-TR-4).

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1.0 INTRODUCTION

1.1 Background

Typically, pipeline designers have focused a majority of their analysis on the physical aspects of pipeline design (that is, soil load, hydraulics and construction detail). To a large extent, industry standards, such as American Water Works Association (AWWA) and the American Society of Testing and Materials (ASTM) have successfully defined minimum requirements for users in areas such as dimensions, pressure ratings, and other product performance attributes. Recently, an increasing amount of research on accelerated pipe aging has been able to shed new light on the performance of plastic pipeline materials in various environments.

While the vast majority of new water and sewer lines installed in North America are thermoplastic material, such as polyvinyl chloride (PVC) and polyethylene (PE) , the two materials have very different characteristics that lend themselves to different aspects of pipeline applications. PE achieved enormous success in the gas distribution business, while PVC achieved similar success in water, sewer, and drain markets. PE’s greater ductility and inherent flexibility have made it a material of choice in demanding trenchless installation techniques with PVC continuing to dominate the traditional direct bury installation method.

Material and chemical differences between the two thermoplastics dictate the degree of performance in various environments. As thermoplastic polymers, both PVC and PE exhibit strong resistance to traditional corrosion and galvanic attack, but can be compromised by environmental attack from solvents (such as, salvation and plasticization), chemicals (such as, oxidation and environmental stress cracking) and sunlight (Ultraviolet (UV) weathering). A recent AWWA Research Foundation multi-year study (Ong et al., 2007) compared PVC and PE in the presence of various gasoline-related contaminants and UV has been extensively studied as an agent in PVC aging (UniBell UNI-TR-5-03). Other recent studies, jointly funded by the AWWA Research Foundation and the Commonwealth Scientific & Industrial Research Organization (CSIRO) have also investigated the long-term performance prediction of PVC (Burn et al., 2005) and PE (Davis et al., 2007) pipes. Disinfectants, such as chlorine, chlorine dioxide, and chloramines, are used in drinking water distribution systems to provide the regulatory required disinfectant residual. Since 2001, research into the mechanisms of oxidative attack on HDPE pipe has increased because premature field failures were observed in Europe. European researchers (Colin et al. 2006) have reported a reduction in mechanical strength and service life of some plastic piping in drinking water applications, possibly due to the use of disinfectants. In some cases, premature failure occurred in PE pipes only after two to ten years of service (Audouin et al. 2007).

This desktop study presents a summary of findings of the recent research on PE and PVC pipe in the presence of secondary disinfectants (oxidants), trends in disinfectant use in the drinking water industry, and review the relevant pipe design standards for both PVC and HDPE. Based on these findings, recommendations for future research into the effects of disinfectants on PE and PVC are also presented.

1.2 Purpose and Scope of Work

The purpose of this desktop study is to evaluate and summarize previously reported and ongoing research into the potential effects that secondary disinfectants (that is, those used to maintain a disinfectant residual in the distribution system) may have on plastic pipe materials used for drinking water supply. This evaluation provides a review of:

- Current and future trends of chemical disinfection practices for drinking water
- The effects of secondary disinfectants on plastic pipe materials, including potential chemical reactions, mechanical strength, and expected life of the pipe

1.3 Definitions

The following definitions for plastic pipe failure modes and design parameters are commonly used throughout this desktop study and are provided as a quick reference.

- μm — micrometer
- ASTM — American Society for Testing and Materials
- AWWA — American Water Works Association
- AwwaRF — American Water Works Association Research Foundation
- $-CHCl-CH_2-CO_2H$ — Chlorocarboxylic Acid
- CPVC — Chlorinated Polyvinyl Chloride
- DBP — Disinfection By-Products
- D/DBPR — Disinfectants and Disinfection By-Products Rule
- DF — Design Factor
- DF_C — Chemical Design Factor

- DF_S — Service Design Factor
- DF_T — Temperature Design Factor
- DR — Dimension Ratio
- DSC — Differential Scanning Colorimeter
- EDAX — Energy Dispersive X-Ray Analysis
- EPA — United States Environmental Protection Agency
- F — Safety Factor
- HCl — Hydrochloric Acid
- HDB — Hydrostatic Design Basis
- HDPE — High Density Polyethylene
- HDS — Hydrostatic Design Stress
- HSB — Hydrostatic Stress Board
- LCL — Lower Confidence Limit
- LTHS — Long-Term Hydrostatic Strength
- MCL — Maximum Contaminant Level
- MDPE — Medium Density Polyethylene
- mg/L — milligrams per liter
- mm — millimeter
- MRDL — Maximum Residual Disinfectant Level
- MRDLG — Maximum Residual Disinfectant Level Goal
- NR — Not Reported
- OIT — Oxidation Induction Time
- PB — Polybutylene
- PB-1 — Isotactic Polybutene-1
- PC — Pressure Classes

- PE — Polyethylene
- PE80 — Black Pigmented MDPE/HDPE
- PE-100— Black Pigmented HDPE
- PEX — Cross-Linked Polyethylene
- phr — parts per hundred of resin
- PPI — Plastics Pipe Institute, Inc.
- PR — Pressure Rating
- PR_{HDB} — HDB Pressure Rating
- psi — pounds per square inch
- psig — pounds per square inch gauge
- PVC — Polyvinyl Chloride
- R^{o} — Free radicals, alkyl radicals
- ROO^{o} — Peroxyradical
- ROOH — Hydroperoxides
- RPM — Rate Process Method
- SCG — Slow Crack Growth
- T_g — Glass Transition Temperature
- U.S. — United States
- UV — Ultraviolet
- VOC — Volatile Organic Compounds

1.3.1 Failure Modes of Plastic Pipes

Plastic pipes fail differently depending on the magnitude of stress and the duration of time under stress. Historically, plastic pipe failure has been categorized into three different failure modes:

- **Stage 1** failure is often referred to as ductile failure or ballooning. Stage 1 failure occurs when the pipe is subjected to mechanical overload and the material fails due to ductile yielding. Substantial material deformation occurs during Stage 1 failure.

- **Stage 2** failure is usually referred to as brittle-mechanical failure. This type of failure is caused by slow crack growth. It occurs when a stress crack propagates through the pipe wall in a brittle manner with no evidence of chemical degradation and little or no material deformation. Stage 2 failure is often indicated by long slit failures and pinhole leaks. It is typically characterized as a "mechanical knee" in the log hoop stress-log time plot.

- **Stage 3** failure is usually referred to as brittle-chemical or brittle-oxidative failure. This failure occurs when the pipe materials are physically degraded due to oxidation. Stage 3 failure is a chemical process and is dependant on the chemical environment that the pipe will experience in service. Stage 3 failure is characterized by a steep slope on the log hoop stress-log time curve and demonstrates very little dependence of failure time on pressure. The change in slope from Stage 2 to Stage 3 is often referred to as the "chemical knee."

Stage 1, 2, and 3 failure modes are further defined within American Society for Testing and Materials (ASTM) F 2263 and ASTM F 2023, and the three failure modes are depicted graphically in Figure 1.1.

Figure 1.1 illustrates a region defined by three lines on a log hoop stress-log time plot. This region is often referred to as the lifetime area. When a combination of stress and time causes a pipe to operate outside of this lifetime area, it will fail.

In addition, Chung *et al*. (2007) defined four modes of failure within the Stage 2 and 3 failure modes that occurred during pressurized flow-through tests of PE with cold, chlorinated water according to ASTM F 2263:

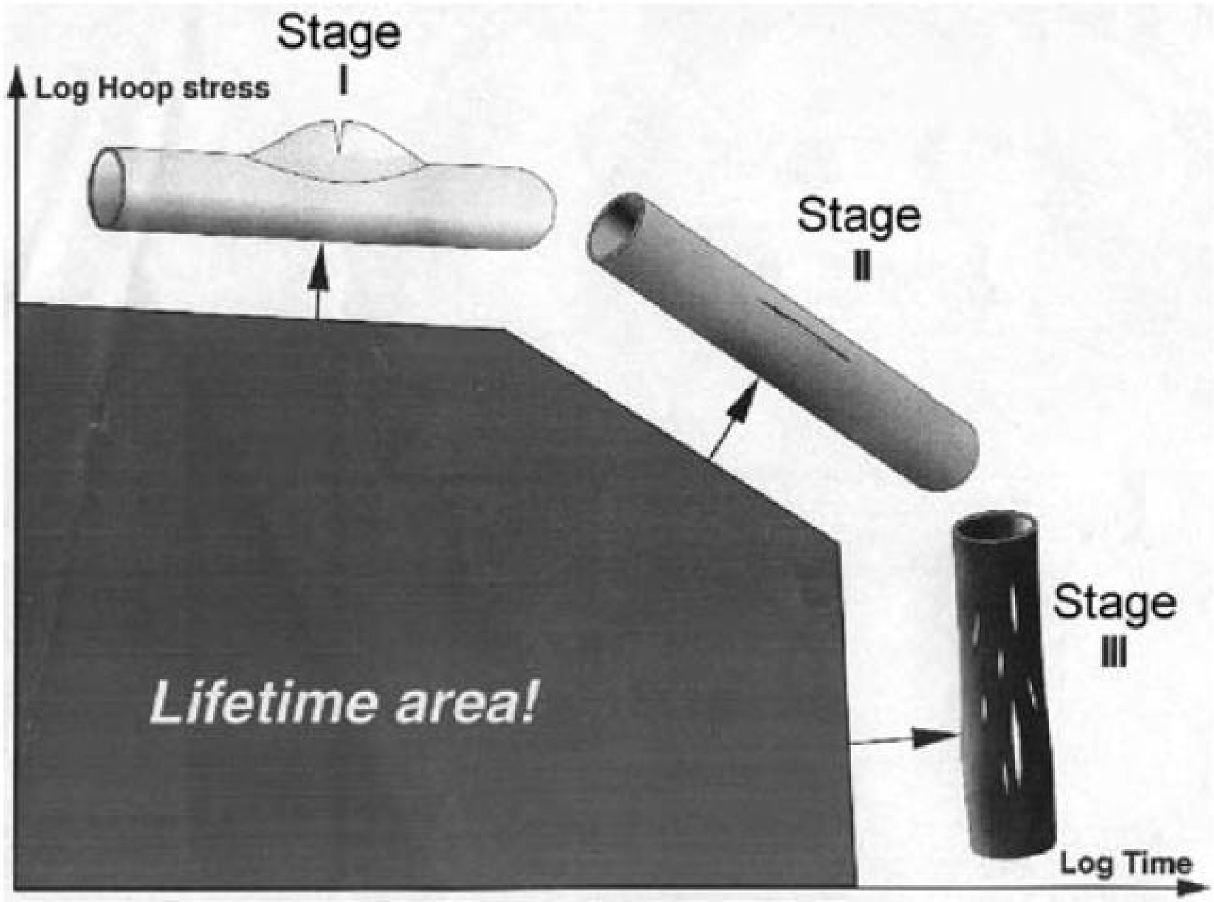
- Mode 1 Failure. Mechanical Initiation-Mechanical Propagation (true Stage 2 failure)

- Mode 2 Failure. Mechanical Initiation-Oxidative Propagation

- Mode 3 Failure. Oxidative Initiation-Mechanical Propagation

- Mode 4 Failure. Oxidative Initiation-Oxidative Propagation (true Stage 3 failure)

Mode 1 corresponds to Stage 2 failure and Mode 4 corresponds to Stage 3 failure as defined above. Mode 2 and 3 failures differ from the standard failure stages in the mode of crack initiation and crack propagation. Mode 2 failures are dependant upon the oxidative resistance of the pipe material similar to Stage 3 failures but initiate in a similar manner as Stage 2 failures. Mode 3 failures initiate similar to a Stage 3 failure but the crack propagation is dependant upon the slow crack growth resistance of the material. These two additional failure modes (Mode 2 and Mode 3) demonstrate that the HDPE fails differently than PEX.



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THREE MODES OF FAILURE FOR PLASTIC PIPE

FIGURE 1.1

1.3.2 Substantiation and Rate Process Method

Substantiation is a requirement for PE materials to show that extrapolation of the 73 degrees Fahrenheit stress regression curve is linear to the 438,000-hour (50-year) intercept (PPI-TR4, 2007). In other words, substantiation uses test data from pipe materials at higher temperatures to predict how pipe materials at lower temperatures will behave in the long term. This extrapolation process is known as the rate process method and uses elevated temperatures as a substitute for longer time periods as shown in Figure 1.2.

1.3.3 Terminology for Plastic Pipe Design

The following definitions are presented in PPI-TR-9 (discussed below) and recognized by ASTM standards:

1.3.3.1 Long-Term Hydrostatic Strength

Long-Term Hydrostatic Strength (LTHS) is the hoop stress that, when applied continuously, will cause failure of the pipe at 100,000 hours (11.43 years). This is the intercept of the stress regression line with the 100,000-hour coordinate as defined in ASTM D 2837. The typical condition uses water as the pressurizing fluid at 73 degrees Fahrenheit (23 degrees Celsius).

1.3.3.2 Hydrostatic Design Basis

Hydrostatic Design Basis (HDB) is one of a series of established stress values specified in ASTM D 2837 for a plastic compound obtained by categorizing the LTHS determined in accordance with ASTM D 2837. HDB refers to the categorized LTHS in the circumferential, or hoop direction, for a given set of end use conditions. Established HDBs are listed in PPI-TR-4.

1.3.3.3 Design Factor

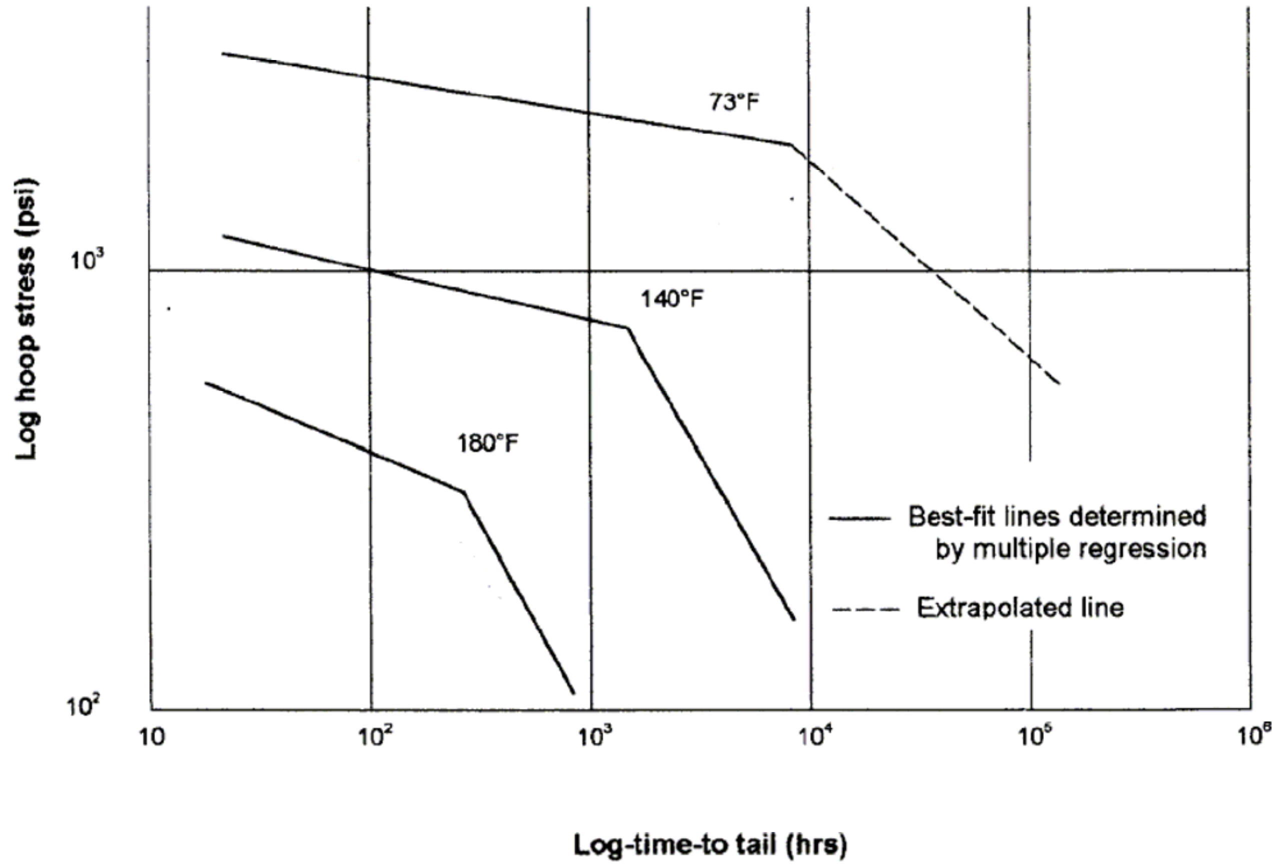
The design factor (DF) is a number less than 1.00 that takes into consideration the variables and degree of safety involved in a properly installed thermoplastic pressure piping installation. For the purposes of PPI-TR-9, a service design factor recommended for use with an HDB category is designated DF_S, a temperature design factor is designated DF_T, and a chemical design factor is designated as DF_C.

$$DF = DF_S \cdot DF_T \cdot DF_C$$

1.3.3.4 Hydrostatic Design Stress

Hydrostatic Design Stress (HDS) is the estimated maximum tensile stress (pounds per square inch (psi)) in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure that can be continuously applied with a high degree of certainty that failure of the pipe will not occur.

$$HDS = HDB \cdot DF$$



RUPTURE DATA FROM PE PIPES TESTED AT HIGHER TEMPERATURES IS USED TO PREDICT RUPTURES AT LOWER TEMPERATURES

FIGURE 1.2

1.3.3.5 HDB Pressure Rating

HDB Pressure Rating (PR_{HDB}) is the estimated maximum pressure (pounds per square inch gauge (psig)) that the medium in the pipe can exert continuously with a high degree of certainty that failure of the pipe will not occur.

$$PR_{HDB} = 2\frac{HDB \cdot DF}{DR - 1} = 2\frac{HDS}{DR - 1}$$

2.0 FINDINGS

The results of a desktop study of four areas related to plastic pipes and secondary disinfection are presented below. These topics include the following:

- Pipe interactions with chemical disinfectants
- Disinfectant trends
- Lifetime prediction for plastic pipes
- Plastic pipe standards related to mechanical strength, design life, and secondary disinfectants.

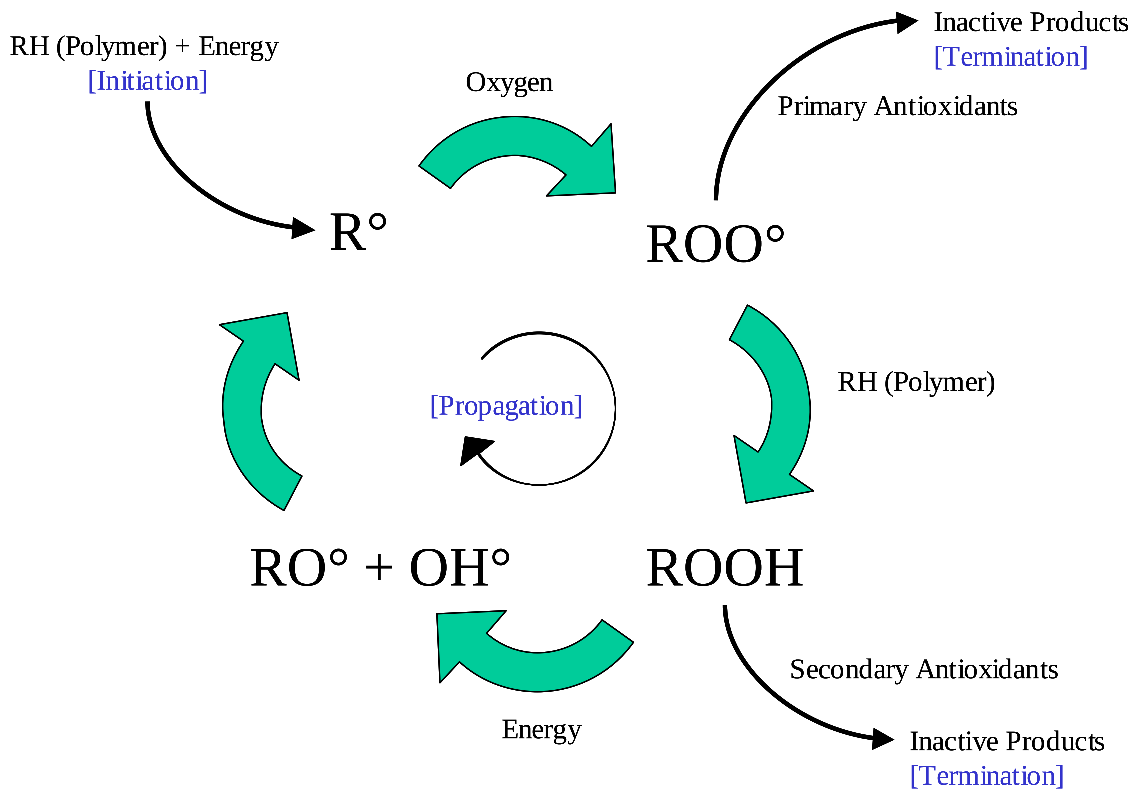
A summary of the findings and recommendations for future research are presented in Section 3.

2.1 Pipe Interactions with Chemical Disinfectants

Plastic pipes are comprised of polymers that may be susceptible to degradation as a result of exposure to oxygen, UV light, and high temperatures (Rosen 1993). Autoxidation is a free radical chain process that may be initiated by chemical (chlorine, ozone, etc.) or physical (UV light, heat, etc.) agents. Such reactions can be divided into three stages:

1. Chain initiation
2. Propagation
3. Termination

This process, as described by Lundback (2005), is illustrated in Figure 2.1. In the initiation process, the addition of energy causes free radicals (R^o) to be formed. Then, during propagation, a free radical can react with oxygen to form a peroxyradical (ROO^o), which can react with another polymer (RH) to form hydroperoxides (ROOH). The hydroperoxides are normally unstable and decompose to form additional radical species. Propagation of this oxidation scheme can lead to chain scission in PE. Termination occurs when radicals react with each other to form non-reactive products. Antioxidants and stabilizers are commonly added to scavenge the peroxyradicals and interrupt the degradation process.



Note: Adapted from Lundback 2005
R° = alkyl radicals
RO° = alkoxy radicals
ROO° = peroxyradicals
ROOH° = hydroperoxide

AUTOXIDATION SCHEME

FIGURE 2.1

2.1.1 Use of Antioxidants in PE pipe

Polyolefins, the family of polymers of which PE is a member, are subject to oxidation, and therefore are typically manufactured with antioxidant packages to prevent excessive damage to the pipe material. The literature surveyed presents an extensive history of research into antioxidant consumption in polyolefin materials. Of the antioxidant packages used, phenolic antioxidants are the most common (Pospisal *et al*., 1993). These antioxidants contain an easily removed hydrogen atom that reacts with the free radical to yield inactive products (Lundback 2005). Antioxidants are consumed by migration or diffusion toward both the inner wall in contact with water and the outer wall in contact with the ambient pipe environment, producing a gradient through the pipe cross section (Dear and Mason 2006). Viebke *et al*. (1994) emphasized the importance of an efficient antioxidant system in PE pipes by pressure testing medium density polyethylene (MDPE) without antioxidants at temperatures ranging from 70 to 105 degrees Celsius. They determined that the time to Stage 3 failure (defined by Veibke as the fracture induced by thermal oxidation) of unstabilized PE pipe was less than 12 percent of the corresponding life of PE pipe stabilized with antioxidants.

2.1.2 Use of Heat Stabilizers for PVC Pipe

PVC pipe has not been observed to experience oxidative attack in long-term performance studies (Burn et al., 2005; Seargeant, 2007). However, PVC manufacturers must add heat stabilizers to prevent thermal degradation of the material, which is a yellowing of the polymer and precedes the loss of mechanical properties (PVC Handbook, 2005). Thermal degradation of PVC may produce hydrochloric acid (HCl), which then catalyzes further degradation of the pipe material. Heat stabilizers are used in PVC pipe to inhibit this degradation. Compounds such as metal oxides, which react with HCl to form stable products, are used as heat stabilizers (Rosen et al., 1993). In the United States (U.S.) and Canada, tin-based heat stabilizers (Organotin stabilizers) have been used in PVC for many years (Johnson and Clark 2006, Burn et al., 2005). However, in Europe and Australia, calcium/zinc heat stabilizers have been adopted (Burn et al., 2005).

2.1.3 Antioxidant/Stabilizer Loss Mechanisms

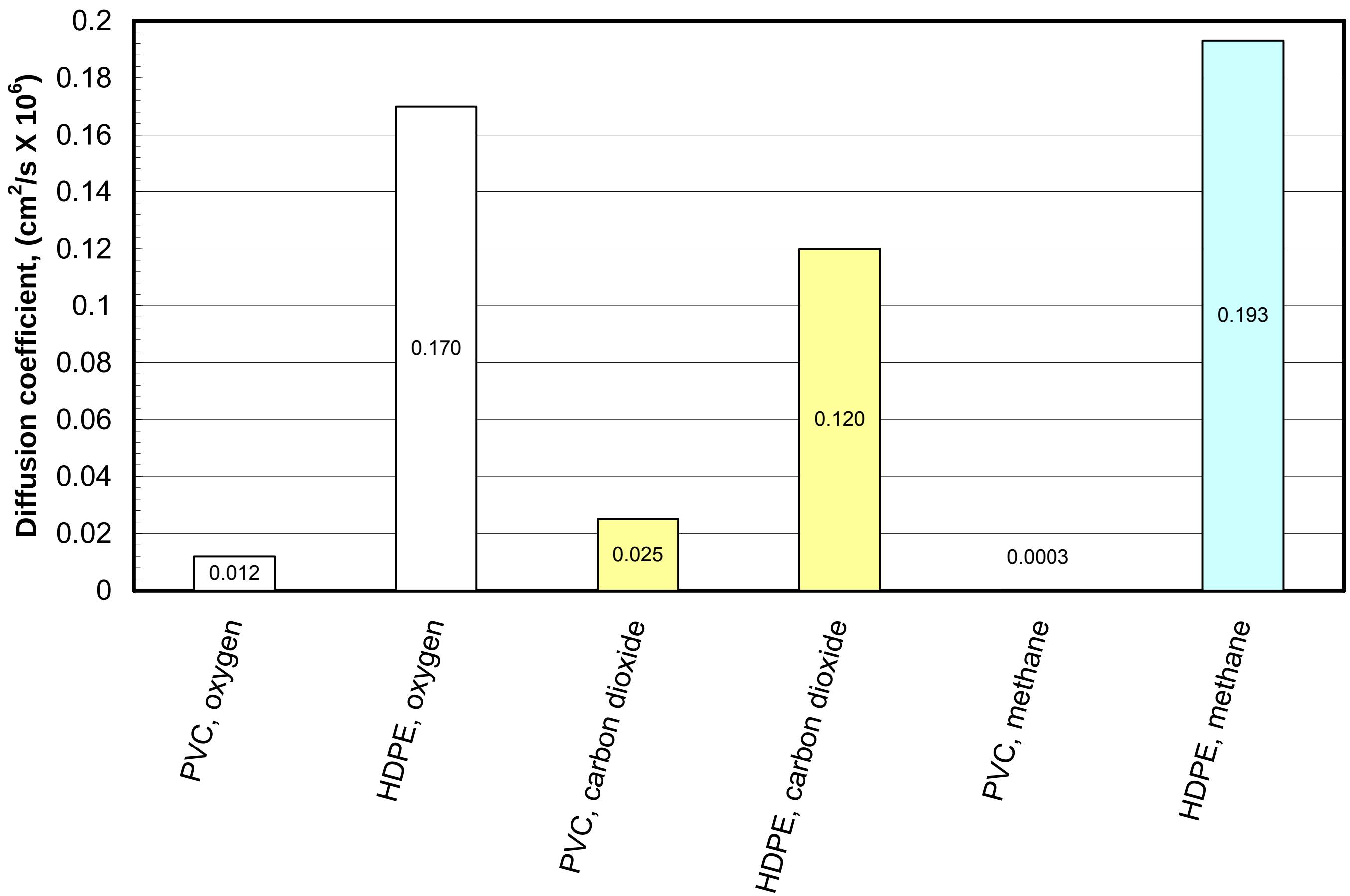
Antioxidant loss is controlled by the rate of diffusion of the antioxidant within the pipe wall and by its rate of migration from the pipe wall boundary. The rate of diffusion within the pipe wall is a function of the material of the pipe wall and chemical diffusing through the pipe wall. The glass transition temperature (T_g) provides guidance for the ability of chemicals to diffuse through a pipe wall. T_g is the temperature, or narrow range of temperatures, below which an amorphous polymer is in a glassy state, and above which it is rubbery (Rosen 1993). The T_g is greater in PVC than PE (approximately 82 degrees Celsuis versus minus 55 degrees Celsius, respectively), indicating that HDPE would have higher diffusion rates because it is softer at room temperature than PVC (Summers, 2008). Moreover, at room temperature, PVC is an amorphous glassy polymer with very limited flexibility of the polymer chains while PE is a partially crystalline rubbery polymer having amorphous areas with high polymer chain mobility (Ong et al., 2007). A comparison of the diffusion coefficients for oxygen, carbon dioxide, and methane through PVC and HDPE pipe are shown in Figure 2.2. Additionally, Ong et al., (2007) determined that gasoline rapidly permeates PE pipe, whereas PVC pipe is relatively impervious to gasoline. Therefore, if antioxidants and chemical disinfectants behave similarly, then antioxidant diffusion may be faster in HDPE than PVC and chemical disinfectants may more readily penetrate HDPE than PVC (Summers, 2008). The very slow diffusion in rigid PVC is also demonstrated by the extraction data of tin stabilizers (Summers, 2008).

Antioxidant migration from PE pipe has also been studied by measuring the oxidation induction time (OIT). It has been shown that the OIT exhibits an Arrhenius temperature dependence and that there is a linear relationship between it and the amount of active antioxidant that remains in the pipe wall (Lundback, 2005). Viebke and co-workers (1996) investigated antioxidant loss in hot water PE pipes. Loss of the antioxidant Santonox R was investigated by hydrostatic pressure testing of MDPE pipes at 95 and 105 degrees Celsius. OIT measurements of the relative antioxidant content in the pipe wall revealed a loss of more than 80 percent of the initial antioxidant content during the first 1,000 hours of pressure testing at both temperatures. Viebke and Gedde (1997) also determined that in PE pipe used for hot water, the chemical consumption by the antioxidant was negligible compared to the physical loss due to diffusion at temperatures of 70 to 110 degrees Celsius.

Lundback et al., (2006a) studied the loss of Santonox R in branched PE in aerobic (air) and anaerobic (pure nitrogen) conditions to simulate oxidative and inert environments, respectively. They observed similar antioxidant concentration profiles after ageing under both conditions, suggesting that the fraction of the antioxidant consumed is negligible in comparison with the loss of antioxidant by migration to the surrounding media. They also determined that the rate of migration of antioxidant at the plaque boundary was higher, particularly at 90 and 95 degrees Celsius, in water saturated with air than in oxygen-free water. They attributed this difference to faster degradation of the antioxidant in the oxygen containing water.

Skjevrak et al. (2003) showed that the quality of water in static contact with plastic pipes could be affected by migration of organic components to a varying extent. The investigators tested virgin PVC and HDPE pipes prior to potential impacts of use and ageing. Volatile organic components (VOC) migrating from HDPE pipes were found to be comprised of compounds related to antioxidants (2,4-di-tertbutyl phenol was a major individual component) in addition to esters, aldehydes, ketones, aromatic hydrocarbons, and terpenoids. The test water from PVC pipes contained few VOCs (hexanal, octanal, nonanal and decanal) in low concentrations after the initial rinse and wash procedure.

Few studies were identified relating to the migration of stabilizer from PVC pipe wall. In the study performed by Johnson and Clark (2006), extraction tests were performed on virgin PVC pipe. They determined that the amount of tin stabilizer migrating from PVC pipe decreases with time. Since the concentration of stabilizer that leaches into the water



Source: Summers, 2008

Note: Diffusion Coefficients from Pauly (1999)

DIFFUSION COEFFICIENTS OF SEVERAL GASSES IN RIGID PVC AND HDPE

FIGURE 2.2

EVALUATING THE COMPATIBILITY OF CHEMICAL DISINFECTANTS WITH PLASTIC PIPE MATERIALS USED FOR POTABLE WATER DISTRIBUTION

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decreases with time, the migration may be attributed to excess and degraded stabilizer located close to the surface of the pipe (Burn et al., 2005).

2.1.4 Effects of Potable Water Disinfectants on Plastic Pipe Materials

Summaries of studies specifically related to effects of secondary disinfectants on pipe materials, antioxidants, and stabilizers are presented in this section.

2.1.4.1 Polyolefin - Polybutylene

An evaluation of polybutylene is beyond the scope of this project, but is briefly presented to further illustrate the effect of chlorinated water on antioxidants and plastic pipe materials. Polybutylene was once promoted for hot and cold water systems within homes; however, this product failed after 8 to 15 years in service (Summers, 2008). Recent studies (Lundback et al., 2006b) have indicated that chlorinated water caused early depletion of the antioxidant system, polymer degradation near the pipe inner wall, and early pipe failure in isotactic polybutene-1 (PB-1) pipe material. The PB-1 pipes exposed to free chlorine failed approximately 10 times faster than those exposed to pure water, even at low chlorine concentrations.

2.1.4.2 Polyolefin - Cross-Linked Polyethylene

Cross-linked polyethylene (PEX) is a flexible, thermoset polymer formed by permanently linking, or cross-linking, individual HDPE molecules. PEX may be used for domestic hot and cold-water plumbing systems. PEX is not used for distribution system transmission mains, but investigations regarding the impact of chlorinated water on PEX pipe materials have been conducted which may provide some insight into similar interactions with HDPE.

Vibien et al. tested PEX at multiple temperatures and pressures and used the rate process method to model the experimental data and, ultimately, to predict the long-term material performance. For domestic plumbing applications, the commonly accepted worst-case conditions are 80 psi and 60 degrees Celsius (Vibien *et al*.). Therefore, Vibien and coworkers concluded that even though the presence of chlorine in potable water reduces the performance lifetime of PEX, the material still appeared to have very good chlorine resistance with greater than 50 years of expected lifetime. Based on their results, the investigators postulated the basic mechanism of chlorine attack on PEX materials to be:

1. Rapid chlorine oxidation of the inner pipe wall.
2. After sufficient oxidation and degradation of the inner wall occurs, a combination of degradation and applied stresses on the inner pipe surface causes micro-cracks to form in the degraded inner layer.
3. Crack density and crack length increase with exposure time. Cracks propagate through the wall of the pipe material.
4. The cracks begin to coalesce to form larger cracks.

5. A brittle slit or pinhole failure may be observed when a crack propagates through the entire wall surface.

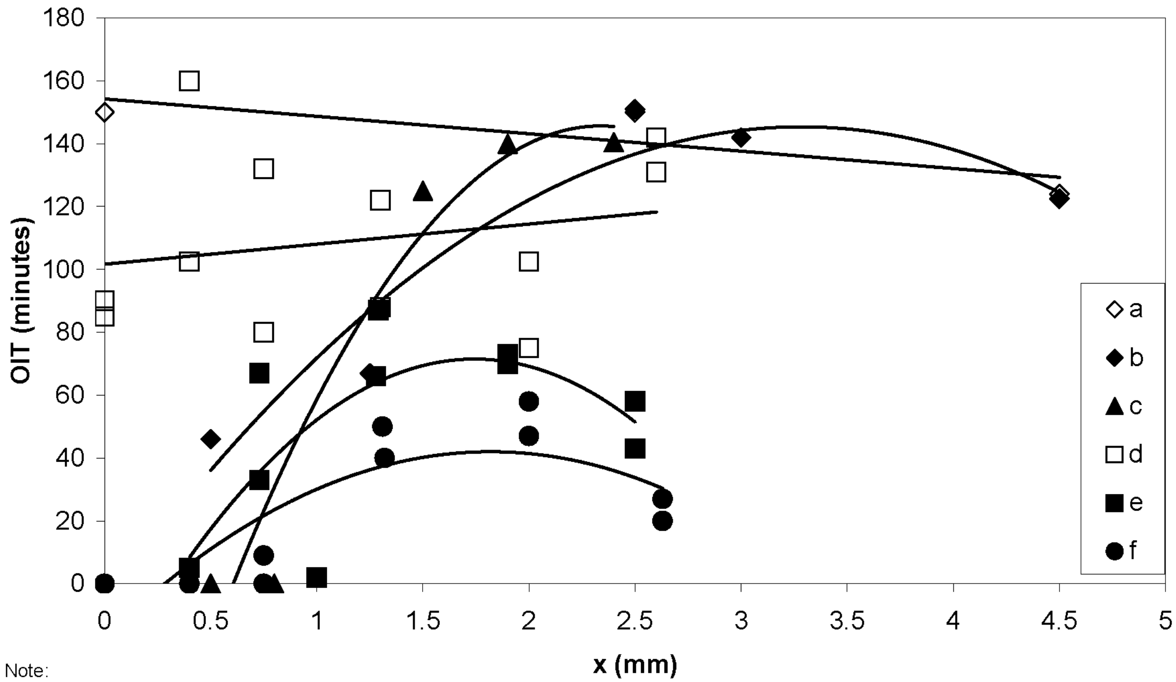
The effect of other common potable water disinfectants (that is, chloramines and chlorine dioxide) on PEX has also been investigated. Chung et al. (2007) conducted disinfection resistance testing in accordance with ASTM F2023 on PEX with 4.3 milligrams per liter (mg/L) of chlorine, chloramines, and chlorine dioxide. Failures resulting from each of the disinfectants appeared to have similar characteristics. However, chlorine dioxide was observed to deplete the stabilizer much more rapidly than chlorine or chloramines, potentially due to inherent differences in their physical properties (Chung et al. 2007). Chlorine dioxide is a dissolved gas in solution and may diffuse into and react with the bulk polymer, where as, chlorine and chloramines are liquids, and may be confined to the pipe wall that is in direct contact with the liquid phase (Chung et al. 2007).

2.1.4.3 Polyolefin - MDPE/HDPE

The effect of chlorine on MDPE pipes in distribution networks was investigated by Dear and Mason (2006). They studied the impact of high concentrations of chlorine (that is, 100, 1,000, and 10,000 mg/L) on MDPE pipe materials by measuring the chlorine penetration depth into the inner pipe wall using energy dispersive X-ray analysis (EDAX), antioxidant depletion by OIT, and weight average molecular mass. They observed that chlorine diffused through the pipe wall, consumed the available antioxidant, and oxidized the polymer chains (chain scission) leading to a reduction in molecular mass of the pipe. Therefore, the presence of chlorine accelerated the embrittlement process, shortening the lifetime of the pipe. Based on their results, Dear and Mason (2006) concluded that the life of PE pipes used in water treatment plants may be less than 10 years if chlorine concentrations as high as 3,000 mg/L are used.

Hassinen et al. (2004) investigated the effect of lower chlorine concentrations (3 mg/L), similar to those found in distribution systems, on HDPE pipe stabilized with hindered phenols and phosphites. Pressure testing of HDPE pipe at elevated temperatures (95 and 105 degrees Celsius) and low chlorine concentrations revealed that the antioxidants were rapidly consumed, as illustrated by the OIT profile in Figure 2.3. Polymer degradation appeared to be confined to the inner surface and started when the antioxidant system was depleted at the inner pipe wall.

Colin et al. (2006) investigated antioxidant loss in black pigmented MDPE (PE80), rapidly aged in testing loops at temperatures of 20 and 40 degrees Celsius with chlorine dioxide and chlorine concentrations of 100 mg/L. The researchers determined that chlorine dioxide attacked PE pipes faster than chlorine and that the attack was restricted to a layer of about 1 millimeter (mm) deep (Figure 2.3).



Note:
1. OIT determined at 190 °C
2. MDPE pipe aged for 19 weeks at 40 °C (Data from Colin et al. 2006):
(a) demineralized water, (b) water with 100 mg/L free chlorine, (c) water with 100 mg/L ClO_2
3. HDPE pipe aged at 95 °C with 3 mg/L free chlorine (Data from Hassinen et al. 2004):
(d) 0 weeks, (e) 1.5 weeks, (f) 3.7 weeks
4. Lines are eye guides

ANTIOXIDANT CONSUMPTION ILLUSTRATED BY OIT PROFILE DATA

FIGURE 2.3

EVALUATING THE COMPATIBILITY OF CHEMICAL DISINFECTANTS WITH PLASTIC PIPE MATERIALS USED FOR POTABLE WATER DISTRIBUTION

carollo

Chung et al. (2008) observed a similar mechanism of attack for polyethylene pipe as previously observed by Vibien et al. during chlorine testing with PEX materials:

- Antioxidant is consumed on the inner surface.
- Once the antioxidant is depleted below a critical level, oxidation and degradation of the inner surface occur.
- As oxidation and degradation continues, the inner surface becomes embrittled and cracks begin to form.
- Further exposure leads to high crack density and deeper cracks.

Chung et al. (2008) also observed that the temperature dependence of failure times due to chlorine and chlorine dioxide exposure appears to be similar, but that additional testing is necessary to confirm that the relationship between temperature and failure is valid for overall performance prediction.

Field failures of plastic piping components used in potable water applications have also been investigated by Colin et al. (2006) and Chung et al. (2007a). Colin et al. (2006) reported that premature failures of PE (the authors did not specify the type of PE pipes) distributing drinking water using a chlorine dioxide residual have been observed at various sites in France since 2003. They measured the antioxidant concentration in naturally aged samples collected from water distribution networks at these sites that had been exposed to chlorine dioxide residuals and had been in service from 5 to 15 years. They determined that the depth in which the antioxidant had been completely consumed was approximately 1 mm, similar to the results observed from accelerated ageing. Colin et al. (2006) has also explored models of chlorine dioxide and phenolic antioxidant diffusion, which accounted for reactions of chlorine dioxide with both phenolic antioxidants and polyethylene. The model correlated well with results from accelerated ageing experiments at high chlorine dioxide concentrations. However, in naturally aged pipes, the model did not accurately predict the antioxidant concentration profile at the boundary between the chemically attacked layer and the core. Colin et al. (2006) postulated that this may be due to a decrease in antioxidant diffusivity within the chemically attacked zone due to cross-linking of the polyethylene.

Chung et al. (2007a) investigated polyolefin pipe (the authors provided no additional information on pipe material) field failures and determined that exposure to potable water can result in Mode 3 failures (Oxidative Initiation-Mechanical Propagation). The researchers noted that the field failures were observed to have the following features:

- Degradation of the inner surface
- Varying levels of degradation of the fracture face
- No degradation at the crack front

- Fracture face characteristics, which are generally similar to slow crack growth characteristics

Chung et al. (2007) also noted that the field failures were consistent with accelerated laboratory failures, indicating that ASTM F 2263 may be a valid method of studying the effect of disinfectants on potable water PE piping materials.

2.1.4.4 PVC

As previously described, PVC pipe is expected to have lower diffusion rates of stabilizer and disinfectant than polyolefin pipes, such as HDPE, because it has a higher glass transition temperature than HDPE. No refereed publications were identified which investigated the influence of potable water disinfectants on PVC. However, Garcia and Black estimated the depth of oxidation in weatherable grade PVC (10 parts per hundred resin (phr) TiO_2) by measuring one of the products of weathering oxidation, chlorocarboxylic acid ($-CHCl-CH_2-CO_2H$). They determined that after one year its penetration was approximately 40 µm (0.0016 inches). Similarly, low penetration is expected for oxidizing disinfectants, such as chlorine, chlorine dioxide, and chloramines (Summers 2008).

In addition, polyolefins degrade by chain scission. When this occurs in PE pipe materials, they lose molecular weight and strength. During PVC oxidation, chain scission may also occur. However, in this case the disinfectant reacts with the PVC to form low concentrations of HCl and cross-linked double bonds, which increases the molecular weight of the pipe (Summers 2008). Higher molecular weight PVC has a lower crack growth rate in long-term creep rupture studies (Baer et al. 2004).

2.2 Disinfection and Disinfectant Trends

A brief introduction of disinfectants and a summary of disinfectant trends are presented below.

2.2.1 Brief Introduction to Disinfectants

Disinfectants are applied for either primary or secondary disinfection in a drinking water facility. Primary disinfection may use chlorine, chloramines, chlorine dioxide, ozone, or ultraviolet light within the water treatment plant. Additional disinfectants may be added to distributed water from the plant to maintain a residual amount of disinfectant throughout the distribution system. This is known as secondary disinfection. Water utilities in the U.S. typically use either chlorine or chloramines for secondary disinfection, while chlorine dioxide is more common in Europe.

The use of a particular or combination of disinfectants for primary and secondary disinfection is dictated by raw water quality, finished water quality goals, and regulatory requirements. From a regulatory perspective, water utilities in the U.S. must balance the need to disinfect the water for microbial inactivation and requirements to minimize disinfection by-products (DBPs) resulting from the use of these disinfectants. As these regulations become more stringent, alternative disinfection processes (that is, ozone, chloramines, and chlorine dioxide) have been sought to decrease DBP formation while still providing adequate disinfection.

In the U.S., the maximum average residual disinfection limits in the distribution system for chlorine and chloramines are 4 mg Cl_2/L and for chlorine dioxide is 0.8 mg ClO_2/L (Table 2.1). The minimum average disinfectant residuals are 0.2 and 0.5 mg/L for chlorine and chloramines, respectively. No minimum is set for ClO_2. In comparison, European systems usually maintain a residual of less than 0.1 mg/L ClO_2.

Chlorine dioxide, while it can be used as a residual in U.S. distribution systems, is very difficult to maintain and simultaneously comply with other regulatory requirements. Chlorite (ClO_2^-), a by-product chlorine dioxide uses in drinking water, is regulated by the United States Environmental Protection Agency (EPA) at a maximum contaminant level (MCL) of 1.0 mg/L. The reactions that accompany disinfection can cause 70 to 75 percent of the chlorine dioxide to revert to $ClO_{2\,-}$ (Gates et al., 1998). Therefore, if the oxidant demand is greater than about 1.4 mg/L, chlorine dioxide may not be used as a disinfectant because the by-product formation might exceed the maximum level allowed (EPA, 1999). Since chlorine dioxide has an upper limit for application, its usage may not be feasible if relatively high doses are required to maintain a residual in the distribution system. Therefore, it is typically used as a preoxidant for CT disinfection credit and to control taste and odor, iron and manganese, or hydrogen sulfide and phenolic compounds (EPA, 1999).

Table 2.1 EPA Maximum Residual Disinfection Requirements Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Disinfectant	MRDLG[1]	MRDL[2]
Chlorine	4.0 (as Cl2)	4.0 (as Cl2)
Chloramines	4.0 (as Cl2)	4.0 (as Cl2)
Chlorine Dioxide	0.8 (as ClO2)	0.8 (as ClO2)

Notes:
1. Maximum residual disinfectant level goal
2. Maximum residual disinfectant level

2.2.2 Disinfectant Use Surveys

The Disinfection Systems Committee of the American Water Works Association (AWWA) Water Quality Division periodically surveys surface and groundwater systems and reports on drinking water disinfection practices. Surveys were conducted in 1978, 1989, 1998, and in 2007 (Connell et al., 2000 and Routt et al., 2007). Results from these surveys are shown in Table 2.2. The results of the 2007 survey are preliminary and are expected to be finalized and published in the Disinfection Survey Committee Report in Journal AWWA sometime in 2008.

The results since 1978 indicate a general trend towards the use of alternative disinfectants (that is, chloramines, chlorine dioxide, ozone). The 2007 survey indicated that chloramines use has decreased since 1998. However, since groundwater systems are less likely to use alternative disinfectants (Seidel et al., 2005; EPA 2005), the apparent decrease in chloramine use and minimal increase in other alternative disinfectants relative to chlorine may be a result of proportionately more ground water systems and fewer very large surface water systems being surveyed in 2007 as compared to 1998 (Routt et al., 2007).

It should be noted that the general trends in disinfectant use represent the number of systems using each type of disinfectant and may not be representative of the amount of pipe exposed to a particular disinfectant. This may be because:

- Some systems use more than one type of disinfectant for treatment. For example, systems may use chlorine dioxide for primary disinfection and chloramines for secondary disinfection.
- Larger systems use different disinfection technologies than smaller systems. For example, of the utilities surveyed in 1998, only 2 percent of the systems serving a population of 10,000 or less used chloramines, whereas 29 percent of the larger systems used chloramines (Connell et al., 2000 and Macler et al., 2000).

Table 2.2 Estimated Use of Disinfectants
Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Chemical Disinfectant	1978 [1]	1989 [1]	1998 [1]	2007 [2]
Chlorine gas	91%	87%	83.8%	54.7%
Sodium Hypochlorite	6%	7.12%	20.3%	36.1%
Chloramines		20%	29.4%	15.2%
Chlorine Dioxide	1%	4.5%	8.1%	7.5%
Ozone		0.4%	5.6%	6.9%
Other [3]	2%	0.75%	1%	6.5%

Notes:
1. Data from Connell et al., 2000.
2. Data from Routt et al., 2007.
3. Calcium hypochlorite, potassium permanganate.
4. The total percentage for each survey year may exceed 100 percent because water systems may use more than one type of disinfectant for treatment.

The AWWA conducted a secondary disinfection (disinfection used in the distribution system) practices survey in 2004 to determine the percentage of utilities currently using chloramines and those intending to convert to the use of chloramines in the future (Seidel et al., 2005). Data from this survey indicated that chloramines are used for secondary disinfection by 37 percent of utilities that treat surface water and 12 percent of utilities that treat ground water (Table 2.3). Of the utilities surveyed that use chlorine, 3 percent plan to convert chloramines and 12 percent are considering conversion to chloramines (Seidel et al., 2005).

Table 2.3 Estimated Use of Secondary Disinfectants[1]
Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Secondary Disinfectant	Surface Water	Ground Water
Chlorine	62%	80%
Chloramines	37%	12%

Notes:
1. Data from Seidel et al., 2005.

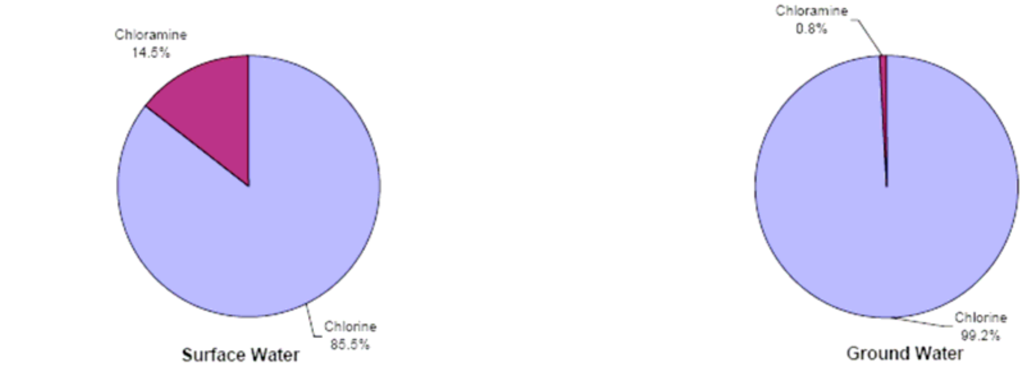
2.2.3 Regulatory Impact on Disinfectant Use

The Stage 2 Disinfectants and Disinfection By-Product Rule (D/DBPR) was promulgated in 2006 to address risks from DBPs and may require water systems to make necessary treatment changes starting in 2012 (Federal Register 2006). The EPA conducted an economic analysis of the costs of the Stage 2 D/DBPR (EPA, 2005) in order to estimate the impact of the new rule on water systems. A portion of this analysis characterized the types and frequency of disinfection technologies currently being used at treatment plants and predicted their future use. Three phases of potential changes in disinfectant use were presented:

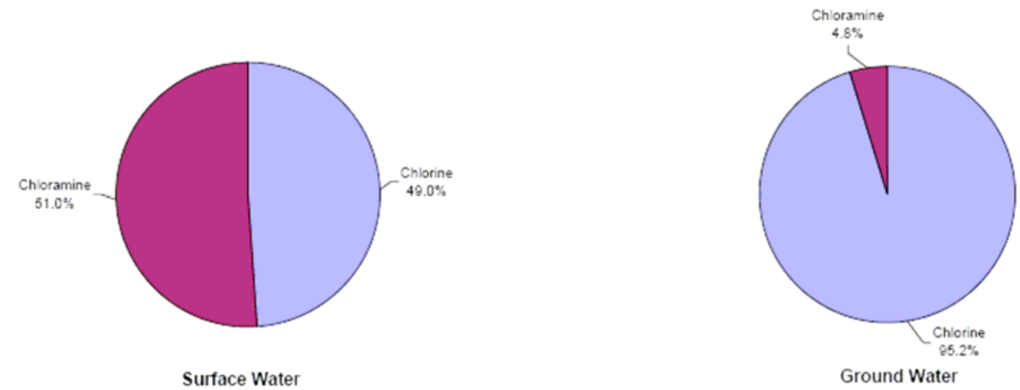
- Pre-Stage 1 D/DBPR Baseline. Characterization of technologies used prior to the Stage 1 D/DBPR compliance deadline (between January 2002 and January 2004, depending on system size). This condition established a baseline for the following projections.
- Pre-Stage 2 D/DBPR Projection. Prediction of technologies used after the Stage 1 D/DBPR compliance deadline.
- Post-Stage 2 D/DBPR Projection. Prediction of technologies used after the Stage 2 D/DBPR compliance deadline (between 2012 and 2015).

Estimates of disinfectant use in community water systems for all system sizes are shown in Figure 2.4. These data indicate that chloramine disinfection is more commonly used to treat surface water as well as predict a shift towards the use of chloramines for secondary disinfection. Only a small increase in the use of chlorine dioxide was predicted (Table 2.4). It should be noted that chlorine dioxide will most likely be used for primary, not secondary, disinfection.

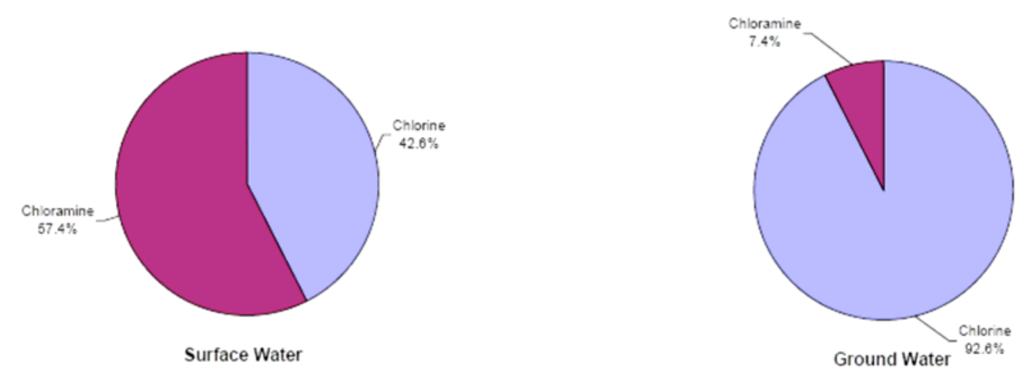
Pre-Stage 1 - Technologies in place prior to the Stage 1 D/DBPR compliance deadline of December 2003



Pre-Stage 2 Projection - Prediction of technologies in place following the Stage 1 D/DBPR Compliance deadline of December 2003



Post-Stage 2 Projection - Prediction of technologies in place following the Stage 2 D/DBPR Compliance deadline



ESTIMATED AND PREDICTED SECONDARY DISINFECTION TECHNOLOGIES (USEPA 2005)

FIGURE 2.4

Table 2.4	**Estimated Use of Advanced Disinfection Technologies[1] Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution**					
Condition	**Surface Water**			**Ground Water**		
	ClO2	**Ozone**	**UV**	**ClO2**	**Ozone**	**UV**
Pre-Stage 1 – Baseline	3.1%	2.0%	---	---	0.1%	---
Pre-Stage 2 – Projection	4.5%	9.9%	---	---	0.8%	---
Post-Stage 2 – Projection	4.8%	9.9%	2.7%	---	0.9%	1.3%

Notes:
1. Data from EPA, 2005.

2.3 Lifetime Evaluations for Plastic Pipes

A summary of literature evaluating the lifetime of plastic pipes is presented in this section. Additional information of lifetime predictions is presented in Section 2.4.

2.3.1 Lifetime Prediction of PVC

Using good design and installation practices, current performance standards indicate that water utilities should expect a minimum 50-year service life from a PVC pipe system. Burn et al. (2005) conducted a survey of 44 water utilities in Australia, Canada, and the U.S. with significant lengths of PVC in their system to evaluate the long-term performance of PVC pipes used for potable water distribution. The authors discussed Stage 1 failures (ductile-mechanical) and Stage 2 failures (brittle-mechanical) with regard to PVC pipe failure, but did not discuss Stage 3 failures (brittle-chemical) in potable water distribution piping. In addition, none of the PVC failures that were reviewed in the study mentioned the effects of chemical disinfection used for potable water distribution.

Major conclusions of the study included:

- PVC pipe has been used in new water distribution systems since the 1970s with few premature failures.
- The majority of physical failures in PVC were caused by poor installation practices.
- Most physical field failures were brittle in nature, indicative of failure due to slow crack growth (Stage 2 failure mode).
- North America should include a fracture toughness performance requirement since current pipe standards only test for ductile failure (Stage 1 failure mode).

- Water utilities should expect a minimum 50-year design life from PVC with good design and installation practices

2.3.2 Lifetime Prediction of PE

PE pipes have been used for water transmission in Europe since the 1950s, in Australia since the late 1970s, and in North America since the late 1980s. Similar to PVC pipe systems, PE pipe systems are expected to have a 50-year service life when using good design and installation practices. Davis et al. (2007) conducted a study to gather historical failure data from 87 water utilities in Australia, the UK, and the U.S. to assess the service life of PE pipe for potable water distribution systems. In general, the authors discussed Stage 1 failures (ductile-mechanical) and Stage 2 failures (brittle-mechanical) in relation to PE pipe failures, but did not discuss Stage 3 failures (brittle-chemical) in potable water distribution piping.

More specifically, the authors observed that:

- The majority of PE failures that occurred were related to third-party damage or poor preparation and contamination of joints and do not correspond to failure of PE pipes under normal service loading conditions.
- Slow crack growth (SCG) was deemed the major determinant of the potential life of a buried PE pipe under actual service conditions.
- Newer PE pipe materials have recently been developed (PE 4710 and PE100) which have higher resistance to SCG than older materials.
- Water utilities in the U.S. using PE for large diameter water supply pipe reported zero failures. However, it is important to note that these pipes are usually less than 10 years old.
- Historical failure rates correlate to the theoretical 50-year design life as predicted by ASTM D 2837.

Recent research into the premature failure of PE pipes used for potable water distribution has been performed in Europe (Colin et al., 2006; Audouin et al., 2007) and in Canada (Chung et al., 2008). In some cases, these PE pipes failed after two to ten years of service. Lab tests seem to indicate that the PE pipes failed due to the Stage 3 failure mode (brittle-chemical), which was not reviewed in the AwwaRF study (Davis et al., 2007). These ongoing research projects are expected to better characterize the failure modes and validate lifetime prediction tests for PE used in potable water distribution systems with chlorine disinfectants as specified in ASTM F 2263.

2.4 Plastic Pipe Standards

Plastic pipe standards provide guidance in the selection of pipe materials. The two most important items of interest in pipe standards are pressure ratings (as related to mechanical strength) and lifetime prediction. Since plastic materials tend to creep (deform permanently under stress) over time, the maximum pressure a plastic pipe is capable of sustaining decreases with time. The generally accepted design life for plastic pipes is 50 years. Testing materials for 50 years is impractical, so standard tests have been developed to extrapolate 10,000 hours (1.14 years) of test data to 50 years. Pressure ratings are selected based on the extrapolation of the 10,000-hour test data to 100,000 hours (11.4 years).

Since creep is not the only determining factor in pressure capacity and lifetime prediction, other test methods have been developed to test other influences on pipe lifetime, including:

- UV degradation
- Thermal degradation
- Chemical degradation
- Cyclic loading due to transient pressure surges
- Changes in the failure mode of a pipe material

Several pipe standards have been developed to evaluate the mechanical performance of plastic pipe and are listed in Table 2.5.

Table 2.5 Standards for Plastic Pipe Design and Material Characterization Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Standard Designation	Title
ASTM D 1784	Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
ASTM D 2837	Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials
ASTM D 3350	Polyethylene Plastics Pipe and Fittings Materials
ASTM F 2023	Evaluating the Oxidative Resistance of PEX Tubing and Systems to Hot Chlorinated Water

Table 2.5 Standards for Plastic Pipe Design and Material Characterization Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Standard Designation	Title
ASTM F 2263	Evaluating the Oxidative Resistance of PE Pipe to Chlorinated Water (at 73° F)
AWWA C905	Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 in. through 48 in. for Water Transmission and Distribution
AWWA C906	Polyethylene (PE) Pressure Pipe and Fittings, 4 in. through 63 in. for Water Distribution and Transmission
AWWA M23	Manual of Water Supply Practices; PVC Pipe - Design and Installation
AWWA M55	Manual of Water Supply Practices; PE Pipe - Design and Installation
PPI-TR-3	HDB/HDS/SDB/PDB/MRS Policies
PPI-TR-4	HDB/HDS/SDB/PDB/MRS Listed Materials
PPI-TR-9	Design Factors for Pressure Applications
PPI-TN-16	Rate Process Method for Projecting Performance of Polyethylene Piping Components
PPI-TN-19	Chemical Resistance of Thermoplastics Piping Materials
PPI-TR-34	Effects of Disinfection on Newly Constructed Polyethylene Water Mains
PPI-TN-41	High Performance PE Materials for Water Piping Applications
PPI-Statement-A	Relative Oxidative Aggressiveness of Chloramines and Free Chlorine Disinfectants Used in Treated Potable Water on Cross-linked Polyethylene (PEX) Pipe

These standards address several complex and interrelated issues with regard to the mechanical strength and lifetime of PVC and PE pipe materials. The following sections present summaries of these standard test methods, specifications, and design guidance documents relevant to PVC and PE pipe use in drinking water distribution systems.

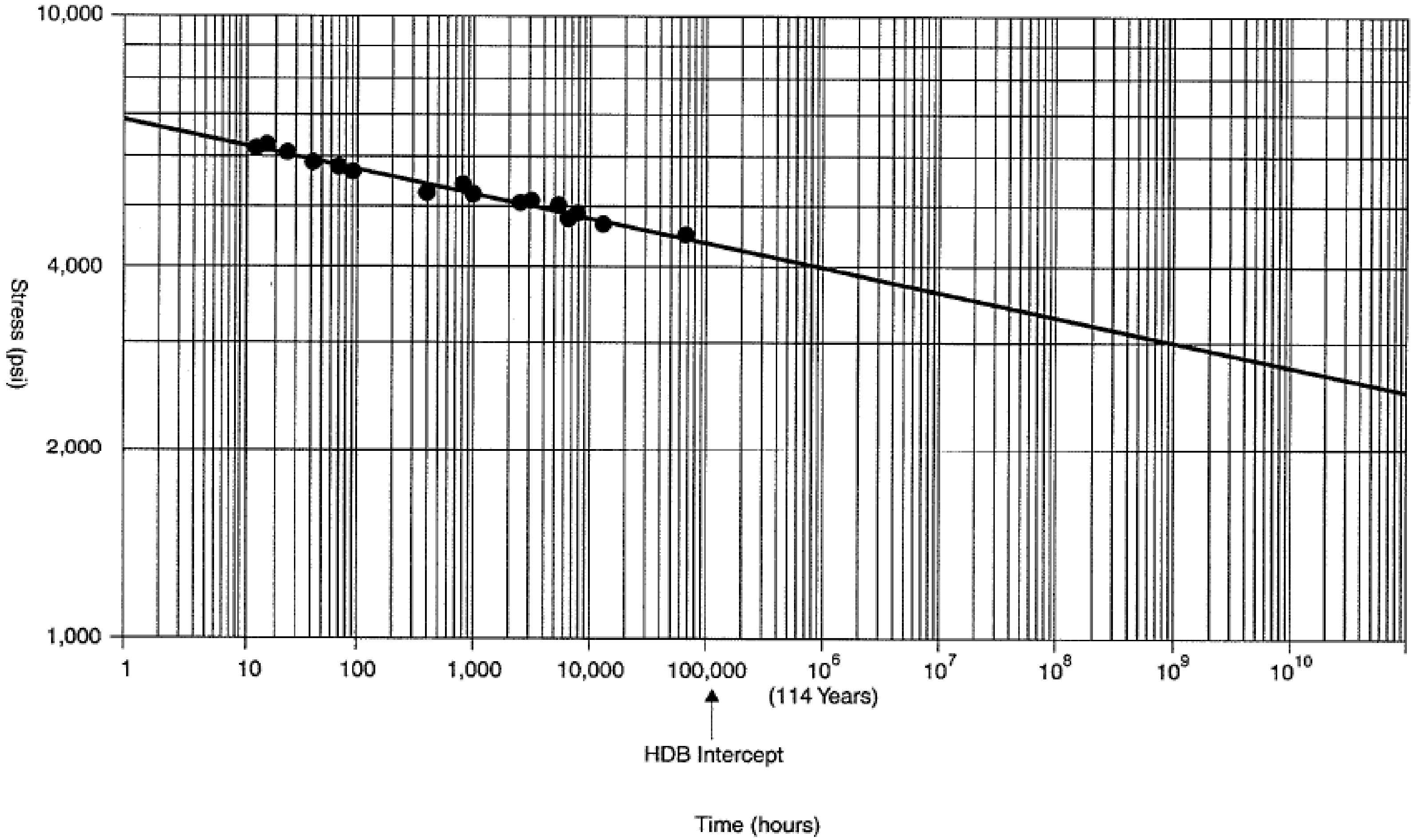
2.4.1 Standard Test Methods

2.4.1.1 Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials (ASTM D 2837)

ASTM D 2837, Standard Test Method for Obtaining Hydrostatic Design Basis for *Thermoplastic Pipe Materials*, is a method to characterize the mechanical performance of pressurized plastic pipe materials with water at 73 degrees Celsius. This standard is applicable to PE and PVC pipe materials. ASTM D 2837 presents a method to select an HDB according to a material's resistance to Stage 1 and 2 (ductile-mechanical and brittle-mechanical, respectively) failure. Pressure testing is performed with pure water for 10,000 hours (approximately 1.14 years) and the HDB is selected based upon linear extrapolation of the test data to 100,000 hours (approximately 11.4 years). HDB is established assuming that Stage 3 (brittle-chemical) failure will not occur. An example of data used for selecting a HDB of 4,000 psi for PVC pipe based on ASTM D 2837 is shown in Figure 2.5.

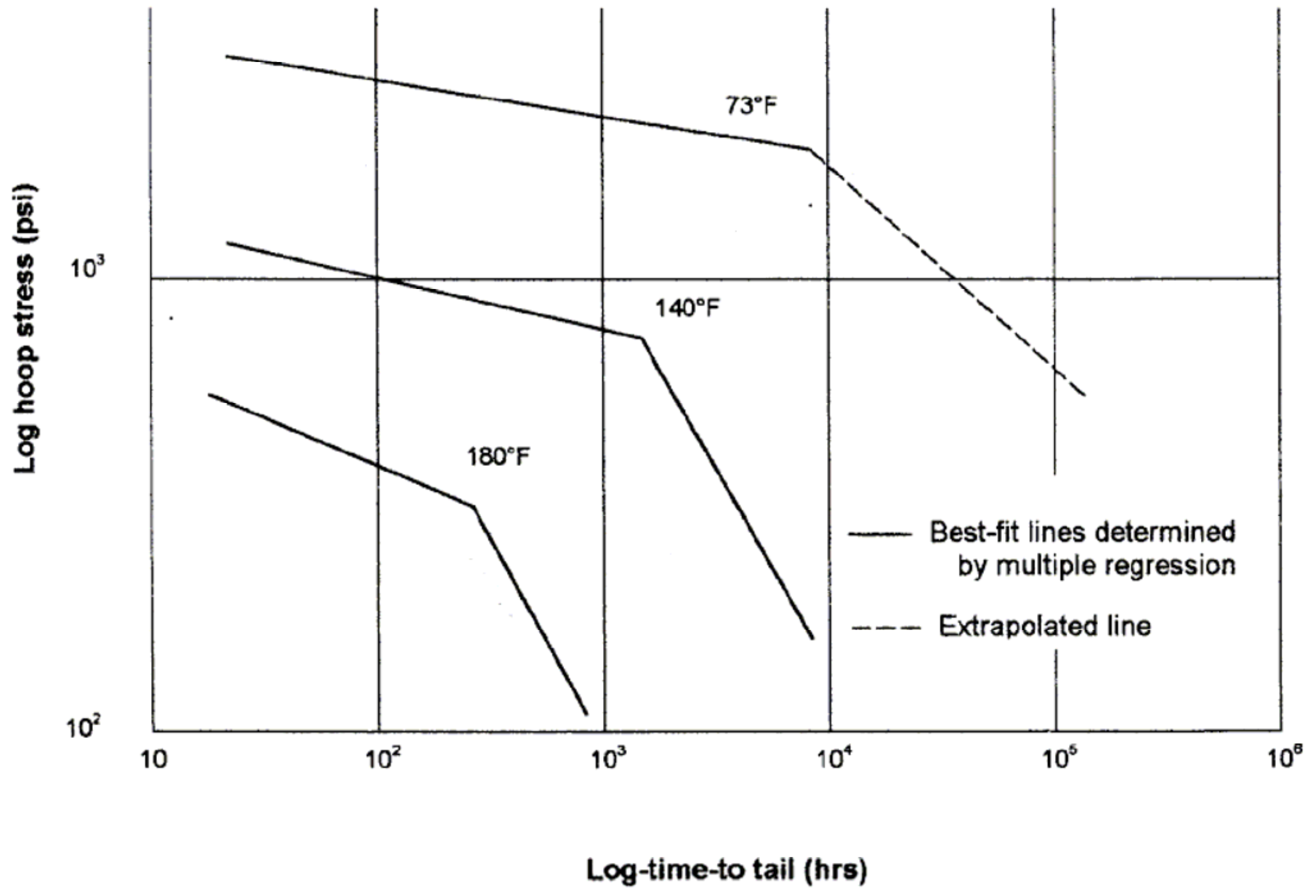
ASTM D 2837 assumes that the experimental stress-rupture test data, when plotted on a log hoop stress-log time plot, define a straight-line relationship for the test period of 10,000 hours (approximately 1.14 years). This straight-line relationship is assumed to be valid beyond the experimental period (10,000 hours) through at least 100,000 hours (the time intercept where the material's HDB is calculated). In the case of polyvinyl chloride (PVC), polybutylene (PB), and PEX, extensive long-term testing has validated the straight-line assumption. In the case of MDPE and HDPE piping materials, ASTM D 2837 requires additional testing and application of the rate process method to validate the straight-line assumption to 100,000 hours in order to establish an HDB. However, ASTM D 2837 does not require additional testing to verify that the straight-line assumption is valid for 50 years (438,000 hours), though some MDPE and HDPE pipe materials listed in PPI-TR-4 do meet this requirement. This validation process is referred to as "substantiation" in PPI-TR-3. According to ASTM D2837, the recommended additional testing of MDPE and HDPE materials provides reasonable assurance that the failure mode does not transition from Stage 1 (ductile-mechanical) to Stage 2 (brittle-mechanical) within the 100,000-hour extrapolation and assumes that Stage 3 (brittle-chemical) failure will not occur. This test procedure utilizes the rate process method to forecast Stage 2 failure in PE at 73 degrees Fahrenheit by characterizing Stage 2 failure in PE at elevated temperatures (140 and 180 degrees Fahrenheit). ASTM D 2837 notes that Stage 2 failure is caused by the initiation and growth of a crack and is denoted by a gradual "downturn" or a relatively sharp "knee" in the slope of the stress-rupture line as shown in Figure 2.6.

ASTM D 2837 requires validation of the linear assumption to 100,000 hours since the HDB is determined by the stress intercept at 100,000 hours. If the pipe failures transition from Stage 1 to Stage 2 failures before the 100,000 hours, the slope extrapolation will be inaccurate. ASTM D 2837 provides the following warning:



HDB SELECTION AT 100,000 HOURS BASED ON TESTING PVC ACCORDING TO ASTM D 2837

FIGURE 2.5



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STRESS RUPTURE LINES FOR PE

FIGURE 2.6

Note:
1. Rupture data from PE pipes tested at higher temperatures is used to predict ruptures at lower temperatures

> "Should there occur a significant downturn, (that is, a downward shift in the stress-rupture slope) prior to the 100,000 hour intercept, an extrapolation based on a trend defined by 10,000 hours of data may produce an overstated long-term hydrostatic strength (and hence an overstated HDB)."

ASTM D 2837 acknowledges that Stage 3 failure may occur in some plastic pipes. However, since the pipes are tested with pure water, Stage 3 failures are not considered in ASTM D 2837. This concept is evident in the following statement from ASTM D 2837: "Stress-rupture occurs in two stages (Stage 1 and Stage 2) exclusive of potential effects of polymer chemical degradation, or aging, that may occur in consequence of the effects of environments that are aggressive to the polymer." Therefore, ASTM D 2837 assumes that Stage 3 failure will not occur. This is a safe assumption if the pipes are put in service transporting pure water only.

ASTM D 2837 notes that when PE pipe materials are used in high temperature applications or in aggressive environments, a substantial "downturn" may occur at some point beyond the 10,000-hour test period. As with the hoop stress, this would also cause an overestimation of the HDB. ASTM D 2837 recommends long-term testing or extensive field experience with similar materials to obtain sufficient assurance that the inherent assumption of continuing linearity through at least 100,000 hours (approximately 11.4 years) is appropriate.

The hydrostatic design stress (HDS) is calculated in ASTM D 2837 by multiplying the HDB by a service (design) factor selected for the application on the basis of manufacturing variations, installation process, environment, temperature, hazard involved, life expectancy desired, and degree of reliability selected. ASTM D 2837 states: "The service factor should be selected by the design engineer after evaluating fully the service conditions and the engineering properties of the specific plastics under consideration." ASTM D 2837 provides possible design factors ranging from 0.10 to 0.90 but does not recommend any of them for specific situations. It is left up to the design engineer to select an appropriate design factor. Design factor selection is offered by other standard documents such as PPI-TR-9, AWWA C905 and AWWA C906, though none of these sources provide a design factor for pipes transporting water with chemical disinfectants.

2.4.1.2 Evaluating the Oxidative Resistance of PEX Tubing and Systems to Hot Chlorinated Water (ASTM F 2023)

ASTM F 2023, The Standard Test Method for Evaluating the Oxidative Resistance of *Crosslinked Polyethylene (PEX) Tubing and Systems to Hot Chlorinated Water*, presents a test method to evaluate the long-term oxidative resistance of PEX tubing to hot chlorinated water. The test method utilizes a pressurized flow-through test of hot chlorinated water to assess the Stage 3 brittle-oxidative failure performance of PEX. Only Stage 3 failures are used in ASTM F 2023 for lifetime prediction of PEX. If the pipes fail due to Stage 1 or Stage 2 failure modes, the test data is considered unusable.

ASTM F 2023 notes that other disinfectants such as chlorine dioxide and chloramines are used in other potable water systems, but have not been evaluated with this test method. Nevertheless, research performed by Chung et al., 2007b appears to show that all three disinfectants (chlorine, chlorine dioxide, and chloramines) have similar oxidation and degradation mechanisms for hot, pressurized water in PEX. Even though the macroscopic mechanisms appear similar between the three oxidants, the overall aggressiveness differs substantially. Chung et al. (2007b) also notes that comparisons of lab testing to field failures of PEX piping materials transporting hot chlorinated water have verified ASTM F 2023 as a valid test procedure for predicting the lifetime of PEX pipe materials in the presence of chlorine. The mechanism of degradation by chlorine, chloramines, and chlorine dioxide on PEX was similar and occurred in the following sequence:

1. Antioxidant is consumed on the inner surface.
2. Once the antioxidant is depleted below a critical level, oxidation and degradation of the inner surface occur.
3. As oxidation and degradation continues, the inner surface becomes brittle and cracks begin to form.
4. Further exposure leads to high crack density and deeper cracks.

ASTM F 2023 uses the rate process method (discussed above) or the three-parameter model of ISO 9080 to forecast the time to failure for PEX pipe materials. ISO 9080 is an international standard that describes a method for estimating the long-term hydrostatic strength of thermoplastics materials by statistical extrapolation. Generally, the rate process method is used in ASTM F 2023 because it requires less material testing than ISO 9080. ISO 9080 is not reviewed in this desktop study. PEX materials that pass the minimum lifetime requirements in ASTM F 2023 and ASTM F 876 are denoted in PPI-TR-4 with a “1” in the first digit. PEX materials that do not pass this requirement are denoted in PPI-TR-4 with a “0” in the first digit.

2.4.1.3 Evaluating the Oxidative Resistance of PE Pipe to Chlorinated Water (at 73 degrees Fahrenheit) (ASTM F 2263)

In the past, oxidation at low operating temperatures was not considered to have a significant effect on the life of PE pipes (Chung et al., 2007a). As the impact of disinfectants on the oxidative degradation process became better understood, ASTM F 2263 was developed to evaluate the long-term, chlorine resistance of MDPE and HDPE pipe used in cold water systems. ASTM F 2263 is very similar to ASTM F 2023 (discussed above) in that it helps predict the expected lifetime of a plastic pipe subjected to the oxidative environment of a potable water distribution system with chlorine disinfectants. ASTM F 2263 utilizes a pressurized flow-through test method of cold chlorinated water to assess the Stage 3 brittle-oxidative failure performance of MDPE and HDPE. If the pipes fail due to Stage 1 or 2 failure modes, the test data is considered unusable. ASTM F 2263 differs from ASTM F 2023 in that it is not used to test and validate materials listed in PPI-TR-4. Nevertheless, comparisons of lab testing to field failures of MDPE and HDPE piping materials transporting cold chlorinated water have verified that ASTM F 2263 seems to be a valid test procedure for predicting the lifetime of PE pipe materials in the presence of chlorine. (Chung et al., 2008b)

2.4.2 Standard Specifications and Design Manuals

2.4.2.1 Polyethylene Plastics Pipe and Fittings Materials (ASTM D 3350)

ASTM D 3350 prescribes a cell classification system for MDPE and HDPE pipe based on standard materials tests. The cell classification consists of the letters "PE" followed by six numbers and a single letter. The six numbers are material property codes and the single letter corresponds to the color and UV stabilizer of the material. The material properties represented by each digit are listed in Table 2.6.

ASTM D 3350 offers no guidance as to classifying the resistance of a material by secondary disinfectants.

Table 2.6 PE Cell Classification according to ASTM D 3350 Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

First Number	Second Number	Third Number	Fourth Number	Fifth Number	Sixth Number
Density	Melt Index	Flexural Modulus	Tensile Strength	Slow Crack Growth Resistance	Hydrostatic Strength Classification

2.4.2.2 Rigid Poly(Vinyl Chloride) Compounds and Chlorinated Poly(Vinyl Chloride) Compounds (ASTM D 1784)

ASTM D 1784 provides a five-digit cell classification for PVC pipe materials according to their physical properties similar to the system used for PE pipe. The material properties represented by each digit are listed in Table 2.7.

ASTM D 1784 offers no guidance as to classifying the resistance of a material by secondary disinfectants.

Table 2.7 PVC Cell Classification according to ASTM D 1784 Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution				
First Number	**Second Number**	**Third Number**	**Fourth Number**	**Fifth Number**
Base Resin Material	Impact Strength	Tensile Strength	Modulus of Elasticity in Tension	Deflection Temperature Under Load

2.4.2.3 Polyvinyl Chloride Pressure Pipe and Fabricated Fittings, 14 through 48 inches for Water Transmission and Distribution (AWWA C905)

AWWA C905 provides direction and guidance for manufacturing, testing, selecting, and purchasing PVC pressure pipe and fabricated fittings for underground water transmission and distribution systems. Design considerations are provided in AWWA M23 (discussed below). AWWA C905 provides pipe pressure ratings (PR) based on dimension ratio (DR), HDB of at least 4,000 psi as established by PPI TR-3 and ASTM D 2837, and a safety factor (F) which is set 2.0:

$$PR = \frac{2}{DR - 1} \cdot \frac{HDB}{F}$$

AWWA C905 also provides temperature coefficients used to de-rate the PR for temperatures greater than 73 degrees Fahrenheit. AWWA C905 requires that PVC pipe be extruded from PVC compound with cell classification 12454 or better based on ASTM D 1784. Those compounds must also qualify for a HDB of 4,000 psi or better for water at 73 degrees Fahrenheit per the requirements of PPI-TR-3 and ASTM D 2837.

In addition, AWWA C905 presents the importance of pipe material selection when there is a possibility of exposure to low molecular weight petroleum products or organic solvents or their vapors. However, it does not mention the danger of pipe material exposure to secondary disinfectants.

2.4.2.4 PVC-Pipe Design and Installation (AWWA M23)

AWWA M23 provides users with both general and technical information to aid in design, procurement, installation, and maintenance of PVC pipe and fittings. This manual deals with PVC corrosion, permeation, chemical resistance, and environmental effects. AWWA M23 requires all PVC compounds to have an HDB equal to or greater than 4,000 psi.

AWWA M23 notes that PVC is resistant to most types of corrosion and lists the results of immersion tests of unstressed strips of PVC. Similar to PPI-TR-19, AWWA M23 lists PVC as “generally resistant” to chlorine water up to 140 degrees Fahrenheit. No information is provided as to the effects on the mechanical properties or design lifetime of the pipe when using chlorinated water in a pressurized pipe.

2.4.2.5 PE-Pipe Design and Installation (AWWA M55)

AWWA M55 provides both technical and general information to aid in the design specification, procurement, installation, and understanding of HDPE pipe and fittings. This manual notes that PE plastics generally possess low water absorption, moderate to low gas permeability, good toughness and flexibility at low temperatures, relatively low heat resistance, and “excellent resistance to many chemicals.” AWWA M55 notes that higher temperatures lower the HDB for HDPE, but does not mention how any chemicals affect the HDB.

AWWA M55 reinforces the importance of considering the internal and external chemical environment that the HDPE pipe will be exposed to and the impact it may have on the design life of the pipe. The manual mentions chemical resistance charts that only involve immersion tests. As such, the charts only provide a relative indication of the suitability of PE and do not assess the impact that continual exposures may have on various aspects of long-term performance nor do they address the effect of stress (pressure). AWWA M55 references PPI Technical Report TR-19, which is reviewed below but does not provide chemical resistance for pressurized HDPE systems.

2.4.2.6 Polyethylene Pressure Pipe and Fittings, 4 through 63 inches for Water Distribution and Transmission (AWWA C906)

AWWA C906 provides purchasers, manufacturers, and suppliers with the minimum requirements for PE pressure pipe and fittings (4 through 63 inches) for water distribution and transmission. This standard provides pipe pressure classes (PC) based on DR, HDB as established by PPI TR-3 and ASTM D 2837, and a DF, which is set at 0.5.

$$PC = \frac{2}{DR - 1} \cdot HDB \cdot DF$$

AWWA C906 also provides temperature coefficients used to de-rate the PR for temperatures greater than 73 degrees Fahrenheit. AWWA C906 uses the HDB as developed according to PPI-TR-3 and ASTM D 2837 and requires the DF to be set at 0.5 for all water applications. This differs from the revised provisions in ASTM D 2837, which allows for a DF of 0.63 for higher performance PE materials. The larger DF allows for PE pipes with thinner sidewall to be used for a given pressure application or allows a given sidewall thickness to be used a higher pressures.

AWWA C906 presents the importance of pipe material selection when there is a possibility of exposure to low molecular weight petroleum products or organic solvents or their vapors. However, AWWA C906 does not mention the danger of pipe material exposure to secondary disinfectants or other known oxidants.

2.4.3 <u>Plastic Pipe Design and Installation Guidance Documents</u>

2.4.3.1 HDB/HDS/SDB/PDB/MRS Policies (PPI-TR-3)

PPI-TR-3 presents the policies and procedures used by the Hydrostatic Stress Board (HSB) of the Plastics Pipe Institute, Inc. (PPI) to develop recommendations of long-term hydrostatic strength (LTHS) ratings for commercial thermoplastic pipe materials, which includes PE and PVC. LTHS ratings are used to develop HDB recommendations. These recommendations are published and regularly updated in PPI TR-4 and are incorporated into ASTM D 2837, AWWA M23, AWWA C905, and AWWA C906.

Concerning the transition from Stage 1 to Stage 2 failure mode in plastic pipes over time, PPI-TR-3 provides several methods (including the rate process method) to validate the continuation of the linear stress regression curve extrapolation to at least 100,000 hours (approximately 11.4 years). A recommended HDB at 73 degrees Fahrenheit is only given to a material that is validated by the ductile stress regression extrapolation. This means that PPI-TR-3 assigns the HDB assuming that Stage 1 failures (ductile-mechanical failures) will be the only failures that occur within the 100,000 hour period, thereby excluding Stage 3 failures (brittle-chemical failures).

PPI-TR-3 allows ASTM F 2023 to test the resistance of PEX piping materials to Stage 3 failures (brittle-chemical failures) due to the presence of chlorine. However, PPI TR-3 does not provide a way to test the resistance of MDPE or HDPE pipe materials to chlorine, though ASTM F 2263 was developed for this purpose.

Establishment of HDB and HDS do not include consideration of an oxidative service environment, such as the use of secondary disinfectants. PPI-TR-3 acknowledges that the HDS recommendations are only valid for conditions equivalent to those under which the test data was obtained. In this case, the pipes were not tested in the presence of an oxidative environment. PPI-TR-3 also acknowledges that under some conditions, such as a more aggressive environment, may significantly reduce pipe durability, in which case, a more conservative (smaller) DF should be chosen. PPI-TR-3 notes that sustained pressure testing at elevated temperatures in accordance with ASTM D 1598 and evaluated per ASTM D 2837 may not be sufficient to fully evaluate the oxidative stability performance of plastic materials.

PPI-TR-3 does not specifically mention the oxidative environment due to the presence of secondary disinfectants in a potable water distribution system. However, the report does mention the risk of degradation due to sunlight (UV) exposure. PPI-TR-3 allows for some HDPE materials to qualify for a higher design factor of 0.63 over the standard 0.5. This provision allows for pipe designs with thinner sidewalls for a given pressure application than was allowed in the past. To receive the higher 0.63 design factor, HDPE materials must meet the following requirements:

1. 50 year substantiation of stress regression line

2. Minimum slow crack growth performance by ASTM F 1473 of 500 hours as required by ASTM D 3350.

3. LCL (Lower confidence limit)/LTHS ratio of at least 90 percent as per ASTM D 2837 More information is available in PPI-TN-41 on the justification of the change of design factors for some HDPE material from 0.5 to 0.63.

2.4.3.2 HDB/HDS/SDB/PDB/MRS Listed Materials (PPI-TR-4)

PPI-TR-4 lists thermoplastic piping materials with a PPI recommended hydrostatic design basis (HDB) rating for thermoplastic piping materials or pipe. PPI-TR-4 provides HDB and HDS recommendations for PVC, MDPE, HDPE, and PEX pipe materials among others. Examples of HDB and HDS listings are shown in Table 2.8. These listings are established in accordance with PPI-TR-3.

PPI-TR-4 assigns a "1" for the first digit of PEX listings only to indicate which ones have passed the resistance to chlorine test as specified by ASTM F 2023. PEX pipe materials that do not pass the resistance to chlorine test are assigned a "0" for the first digit in the PEX listing. PPI-TR-4 does not provide any indication of chlorine resistance for PE or PVC piping materials, though ASTM F 2263 was developed to test the chlorine resistance of MDPE and HDPE to cold chlorinated water. PE and PVC are listed in PPI-TR-4 according to their cell class as specified in ASTM D 3350 and ASTM F 1784.

Table 2.8 Examples of HDB and HDS Listings from PPI-TR-4 Evaluating the Compatibility of Chemical Disinfectants with Plastic Pipe Materials Used for Potable Water Distribution

Pipe Material Designation Code	Maximum HDS at 73 ° F (psi)	HDB at 73 ° F (psi)	ASTM Specification
PE 3708	800	1,600	D 3350
PE 3710	1,000	1,600	D 3350
PE 4608	800	1,600	D 3350
PE 4710	1,000	1,600	D 3350
PEX 0006 [1]	630	1,250	F 876
PEX 1006 [1]	630	1,250	F 876
PEX 0008 [1]	800	1,600	F 876
PEX 1008 [1]	800	1,600	F 876

Notes:
1. The first digit in PEX listings is for chlorine resistance tested in accordance with ASTM F 2023. A digit "1" in the indicates the PEX tubing has been tested and meets the F 876 requirement for minimum chlorine resistance at the end use condition of 25 percent at 140 degrees Fahrenheit and 75 percent at 73 degrees Fahrenheit. A digit "0" indicates it does not meet this requirement or it has not been tested.

2.4.3.3 Design Factors for Pressure Applications (PPI-TR-9)

PPI-TR-9 provides a summary of industry recommended design factors used with the HDB determined in accordance with ASTM D 2837. The design factors were developed based on years of international field experience, engineering tests, investigations, and safety considerations. The design factors are considered by PPI to be conservative within the limits for which they are recommended.

Design factors take several variables into account including manufacturing and testing variables, installation, transported medium fluid, life expectancy, degree of reliability, and temperature. PPI notes that experience to date indicates that variations due to manufacturing and testing usually varies within plus or minus ten percent. The other variables are accounted for with separate design factors such as DF_T for elevated temperatures or DF_C for chemical exposure.

The choice of a DF_C can be an important decision for pipe design depending on the intended service environment and expected lifetime of the pipe. PPI-TR-9 notes that some fluids may have a significant effect on the long-term strength of thermoplastic pipe materials. These effects must be considered during plastic pipe design. PPI-TR-9 provides DF_C coefficients for liquid hydrocarbon exposure but does not provide DF_C coefficients for exposure to secondary disinfectants.

2.4.3.4 Rate Process Method for Projecting Performance of Polyethylene Piping Components (PPI-TN-16)

PPI-TN-16 was developed to provide general information on use of the rate process method (RPM) to evaluate mechanical performance of PE pipe and fittings. The RPM is used to forecast the effective long-term performance of PE pipe materials. This RPM requires elevated-temperature sustained-pressure testing of pipe for Stage 2 (brittle-mechanical) failure. Details of the RPM are presented elsewhere (Palermo, 1985). The RPM was incorporated in two ASTM standards.

- ASTM D 2837, Standard Test Method for Obtaining Hydrostatic Design Basis for *Thermoplastic Pipe Materials* added a "validation" requirement (up to 100,000 hours) for PE piping materials

- ASTM D 2513, Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing, and Fittings added a "validation" requirement (up to 100,000 hours) for the pipe producer.

PPI-TN-16 also notes the importance of ensuring that all the failures observed during a test are of the same type (i.e. all ductile or all brittle). This is an important distinction to make especially in light of the three known modes of failure: Stage 1 (ductile-mechanical), Stage 2 (brittle-mechanical), and Stage 3 (brittle-chemical), which can occur under different operating conditions. Therefore, the RPM cannot be used for lifetime prediction when the failures observed are of different types. This is reinforced in ASTM D 3350 (discussed above), which warns of the possibility of overestimating the HDS and design life if the failure mode changes.

The RPM is used to forecast the LTHS and HDB at 100,000 hours in ASTM D 2837, and the RPM is used in PPI-TR-3 to determine whether the extrapolation of the 73 degrees Fahrenheit stress regression curve is linear to the 438,000-hours (50-year) intercept. This concept is referred to as substantiation in PPI-TR-4. MDPE and HDPE materials are denoted with a "*" in PPITR-4 as to whether or not they meet the substantiation requirement.

2.4.3.5 Chemical Resistance of Thermoplastics Piping Materials (PPI-TR-19)

PPI-TR-19 provides information on the transport of various chemicals using thermoplastic piping materials for non-pressure applications. Determination of the suitability for specific applications under stress (pressurized service) is beyond the scope of PPI-TR-19. PPI-TR-19 provides information regarding PE and PVC resistance to the effects of chlorinated water but does not provide any chemical resistance information for pressure applications. PPI-TR-19 states that PVC is "generally resistant" to exposure to chlorinated water to 1403 degrees Fahrenheit whereas MDPE, HDPE, and PEX are listed as having "limited resistance" to exposure to chlorinated water up to 120 degrees Fahrenheit. "Generally resistant" is defined by PPI-TR-19 as:

- Swelling less than 3 percent,

OR

- Weight loss less than 0.5 percent

AND

- Elongation at break not significantly changed

"Limited resistance" is defined by PPI-TR-19 as:

- Swelling 3 to 8 percent

OR

- Weight loss 0.5 to 5 percent

AND/OR

- Elongation at break decreased by less than 50 percent

PPI-TR-19 notes that chemicals that do not normally affect the properties of an unstressed thermoplastic may cause completely different behavior (such as stress cracking) when under thermal or mechanical stress (such as constant internal pressure or frequent thermal or mechanical stress cycles). Therefore, unstressed immersion test chemical resistance information is applicable only when the thermoplastic pipe will not be subject to mechanical or thermal stress that is constant or cycles frequently. PPI-TR-19 recommends long-term testing that duplicates service conditions as closely as possible to properly evaluate the long-term effects of chemicals on pressurized plastic pipe.

2.4.3.6 Effects of Disinfection on Newly Constructed Polyethylene Water Mains (PPI-TR-34)

PPI-TR-34 was published to provide information on the effects of chlorine disinfection (per AWWA-C651) on the durability of MDPE and HDPE piping systems. The disinfection process outlined in AWWA-C651 is intended for:

- Disinfecting newly constructed potable water mains
- Disinfecting mains that have been removed from service for planned repairs or for maintenance that exposes them to contamination
- Disinfecting mains that have undergone emergency repairs due to physical failure
- Disinfecting mains that, under normal operation, continue to show the presence of coliform organisms

The purpose of PPI-TR-34 was not to test the long-term resistance of MDPE and HDPE piping systems to chlorine as specified by ASTM F 2263, but to test the short-term resistance of high chlorine concentrations due to temporary disinfection. Testing was conducted on pipe specimens filled with 185 mg/L chlorine water solution and condition for 72 hours at room temperature. Chloramines were not tested as part of PPI-TR-34, though PPI Statement A mentions testing PEX with chloramines according to ASTM F 2023. PPI-TR-34 was developed based on the following tests performed on MDPE and HDPE pipes that had been exposed to high concentrations of chlorine for short durations:

1. Quick Burst Test according to ASTM D 1599
2. Sustained Hydrostatic Burst Test according to ASTM D 1598
3. Tensile and Elongation Test according to ASTM D 1928
4. OIT using a Differential Scanning Colorimeter (DSC)
5. A High Speed Tensile Impact Test call the “McSnapper” Test for Evaluating the Integrity of Heat Fusion Joints
6. PENT Testing According to ASTM F 1473 to Evaluate Slow Crack Growth Resistance PPI-TR-34 presents research by Studsvik Material AB in Sweden who has noted changes in the antioxidant concentration profiles and molecular/physical structure when PE is used in hot water environments. Studsvik performs long-term hydrostatic burst testing using chlorine for clients on a proprietary basis.

PPI-TR-34 also presents an incident in Japan that involved the use of lower density PE materials in a water distribution system that utilized chlorine disinfection. The PE pipe material began to blister causing material loss throughout the distribution system. Since then, acceptable levels of blistering for PE transporting chlorinated water have been established in Japan.

The major findings of the testing reported in PPI-TR-34 indicate that short-term chlorine disinfection, when conducted within the guidelines of AWWA-C651, does not have a significant adverse effect on the performance of PE pipe. No indications of any downward trends in the mechanical properties of PE were evident in the short-term exposure tests.

2.4.3.7 High Performance PE Materials for Water Piping Applications (PPI-TR-41)

PPI-TN-41 presents the reasoning behind the recent shift in the DF from 0.5 to 0.63 for some HDPE pipe materials. This change allows the use of higher pressures for pipes with the same DR or to obtain greater flow capacity for the same pressure rating with higher DR (thinner wall) pipes. Changes were made to ASTM D 2837 to allow for a new cell class of PE materials. These included changes in the pipe materials designation code:

- Base resin density - First digit in the code
- SCG - Second digit in the code
- HDS - Third digit in the code

A new base resin density classification did not provide for higher density values but was split to create a fourth class as follows:

- Previous cell class 3- greater than 0.941 to 0.955 g/cc
- New cell class 3 - greater than 0.941 to 0.947 g/cc
- New cell class 4 - greater than 0.947 to 0.955 g/cc

PPI-TN-41 states that SCG is the dominant field failure mode for PE pipes. The PENT test according to ASTM F 1473 measures relative resistance to SCG. PPI-TN-41 references research which shows that PENT values between 10 to 20 hours should correlate to a field life of at least 100 years with very few failures. PPI determined that a requirement of at least 500 hours, PENT slow crack resistance would provide assurance that high performance HDPE pipes will be highly unlikely to fail in the slow crack growth mode. The existing and new cell classes for PENT tests are listed below:

- Current cell class 4 - PENT value of at least 10 hours
- Current cell class 6 - PENT value of at least 100 hours
- New cell class 7 - PENT value of at least 500 hours

Increased HDS for some PE materials is allowed provided that the following conditions are met:

1. 50-year substantiation of the stress regression line
2. Minimum SCG performance by ASTM F 1473 of 500 hours as required by ASTM D 3350.
3. LCL/LTHS ratio of at least 90 percent as per ASTM D 2837

The higher HDS is allowed by using a DF of 0.63 rather than 0.5. This increased DF allows thinner sidewall HDPE pipes to be used for pressure applications. The change in DF did not account for the possible oxidative effects of secondary disinfectants on the HDPE.

2.4.3.8 Relative Oxidative Aggressiveness of Chloramines and Free Chlorine Disinfectants Used in Treated Potable Water on PEX Pipe (PPI-Statement-A)

PPI Statement-A presents and explains the results of testing performed on PEX pipe with chlorine and chloramines. The testing was performed by Jana Laboratories, Inc. according to ASTM F 2023. Samples of commercially available PEX pipe were tested to failure in a continuous flow test setup designed to accelerate failure by using elevated temperatures. The procedure utilized a test fluid containing free chlorine at 4.0 mg/L and a test fluid containing chloramines at 4.0 mg/L. Test fluids were controlled to pH 6.8. Testing was conducted at elevated temperatures of 221 and at 239 degrees Fahrenheit at 60 psig constant pressure until failure. The results of this testing showed pipe failure times approximately 40 percent longer when tested with chloramines compared to testing with free chlorine at the tested conditions. Based on these results, PPI believes the testing of PEX with free chlorine will conservatively estimate the time-to-failure for PEX pipes when used with chloramines.

3.0 SUMMARY

The following presents a summary of pipe interactions with chemical disinfectants, disinfection and disinfectant trends, lifetime evaluations of plastic pipes, and plastic pipe standards.

3.1 Pipe Interactions with Chemical Disinfectants

- A summary of the aging conditions used to estimate the effects of disinfectants on PE pipe materials from the studies discussed is shown in Table 3.1. All except for two studies (Dear and Mason 2006, Colin et al., 2006) investigated chlorine concentrations relevant for distribution systems.

- Stage 3 failure in PE can be caused by oxidation due to the presence of disinfectants. Chlorine dioxide is more aggressive than chlorine, and chlorine is more aggressive than chloramines.

- Chlorine dioxide was observed to deplete the antioxidant in PE pipe material much more rapidly than chlorine or chloramines. The attack was restricted to a layer of about 1 mm in thickness along the inner pipe wall with subsequent free radical attack on the PE chain structure creating chain scission and reduced mechanical properties.

- Lower penetration of disinfectants (chlorine, chlorine dioxide, and chloramines) and loss of stabilizer is expected in PVC pipe material due to lower diffusion rates than PE pipe material as based on their respective glass transition temperatures. However, no refereed publications were identified which investigated the influence of potable water disinfectants on PVC.

- The presence of disinfectants may increase the strength (molecular weight) of PVC.

- There are three commonly accepted failure modes for plastic pipe: Stage 1, 2, and 3. However, Chung *et al* (2007) has proposed two additional stages of failure for PE pipe, which include Mode 2 failure (Mechanical Initiation-Oxidative Propagation) and Mode 3 failure (Oxidative Initiation-Mechanical Propagation). These new modes of failure were observed in PE pipes used for potable water distribution.

Table 3.1 Aging Conditions Used to Estimate the Effect of Disinfectants on PE Pipe Materials
Compatibility of Chemical Disinfectants with Plastic Pipe Material

Source	Title	Year	Pipe Material	Temperature (°C)	pH	Time	Disinfectant	Findings
Vibien *et al*	Chlorine Resistance Testing of Cross Linked Polyethylene Piping Materials	2001	PEX	115	6.5-6.8	702-5890 hrs	Chlorine	PEX plumbing pipe is subjected to 4.3mg/l chlorine at elevated temperatures and experiences rapid oxidation of inner wall and subsequent brittle fracture of pipe, but extrapolated results of this accelerated aging indicate acceptable life at service temperatures
Hassinen *et al*	Deterioration of Polyethylene Pipes Exposed to Chlorinated Water	2004	HDPE	95-105	6.45	0-809 hrs	Chlorine	Antioxidants were rapidly consumed by relatively low chlorine concentrations (3 mg/L). Polymer degradation appeared to be confined to the inner surface and started when the antioxidant system was depleted at the inner pipe wall.
Lundback	Long Term Performance of Polyolefins in Different Environments Including Chlorinated Water: Antioxidant Consumption and Migration and Polymer Degradation	2005	HDPE	90-115	6.1-6.7	29-318 days	Chlorine	Chemical stabilizers were rapidly consumed by relatively low chlorine concentrations (0.5-1.5 ppm) - independent of concentration
Colin *et al*	Kinetic Modeling of the Aging of PE Pipes for the Transport of Water Containing Disinfectants	2006	MDPE,PE-80	20-40	NR	2-99 days/5-18 years	Chlorine Dioxide	PE antioxidant is quickly consumed uniformly in presence of chlorine dioxide to the ~1mm depth; exhumed field pipe shows same results; ClO2 reactions with PE and antioxidant are identified
Dear and Mason	Effect of Chlorine on Polyethylene Pipes in Water Distribution Networks	2006	MDPE	60-80	NR	200-10,752 hrs	Chlorine	Observation of exhumed, failed PE pipe and laboratory work at high Cl concentrations (3000-10,000 mg/l) shows that failure occurs by slow crack growth due to creep after initial inner layer of pipe is degraded by chain scission/oxidation; PE in plants can see 3000 mg/l Cl and life is expcted to be < 10 years
Castegnetti *et al*	Effect of Chlorinated Water on the Oxidative Resistance and the Mechanical Strength of PE Pipes	2007	HDPE, PE-100	25-80	6.5-7.5	0-19 weeks	Chlorine, Chlorine Dioxide	HDPE degrades in the presence of chlorine dioxide and chlorine under pressure conditions; elongation at fracture after 2 weeks is 50% versus >700% for control
Audouin *et al*	Durability of PE Pipes Transporting Chlorine Dioxide Disinfected Water- Kinetic Modeling of Embrittlement Process	2007	MDPE, PE-80	20-40	2.0-6.0	1200 hours	Chlorine Dioxide	Laboratory work confirms chlorine dioxide attack on PE resulting in chain scission of PE chains leading to "end of life" embrittlement due to free radical kinetics; embrittlement at 400 hours at 40 degrees C; predictive modeling in process
Chung *et al*	An Examination of the Relative Impact of Common Potable Water Disinfectants (Chlorine, Chloramines and Chlorine Dioxide) on Plastic Piping System Components	2007	PEX	ASTM F2023	6.8	ASTM F2023	Chlorine Dioxide, Chloramines, Chlorine	Crosslinked PE (PEX) fails in the presence of various disinfectants with inner wall degradation followed by mid and outer wall crack propagation in samples under pressure; chlorine and chlorine dioxide diffusion may make these disinfectants more aggressive in polymer degradation
Chung *et al*	The Mechanisms of Chlorine Dioxide Oxidation on Plastic Piping Systems	2008	HDPE	60-90	NR	28-348 hours	Chlorine Dioxide	Consumption of antioxidants leads to innner wall degradation with cracking extending through entire pipe wall material; temperature decreases lead to lifetime increases
Chung *et al*	Characterizing Long Term Performance of Plastic Piping Materials in Potable Water Applications	2008	HDPE	NA	NA	NA	Various	Study on failed PE pipe exhumed from field confirms laboratory work that inner wall degradation leads to mid and outer wall fracture and failure in PE pipes exposed to disinfectants

3.2 Disinfection and Disinfectant Trends

- Chlorine and chloramines are the most common secondary disinfectants employed in North America; chlorine dioxide is predominately used in the U.S. as a pre-oxidant or for primary disinfection credit. In Europe, however, chlorine dioxide use is more common in distribution systems due to a more selective use at lower doses.

- Disinfectant use since 1978 indicate a general trend towards the use of alternative disinfectants (that is, chloramines, chlorine dioxide, ozone) to chlorine.

3.3 Lifetime Evaluations of Plastic Pipes

- Historically, PE and PVC water mains have failed infrequently and are expected to have at least a 50-year design life.

- Recently, PE water mains are failing prematurely in France, possibly due to chemical ageing (Stage 3 failure mode) caused by oxidation. Jana Labs also has exhumed PE water mains that have failed prematurely under Stage 3 failure mode.

3.4 Plastic Pipe Standards

- There are three commonly accepted failure modes for plastic pipe: Stage 1, 2, and 3. However, Chung *et al* (2007) has proposed two additional stages of failure, which include Mode 2 failure (Mechanical Initiation-Oxidative Propagation) and Mode 3 failure (Oxidative Initiation-Mechanical Propagation). Pipe standards only address Stage 1, 2, and 3 failures. None of the pipe standards addresses Mode 2 or Mode 3 failures.

- PE tends to fail by the SCG mechanism (Stage 2 failure mode). Recently, HDPE materials with higher resistance to SCG have been developed allowing for a higher design factor. The higher design factor allows for thinner sidewall design. The higher design factor may be appropriate for avoiding Stage 1 and 2 failures beyond 50 years but may not be appropriate for avoiding Stage 3 failures prior to 50 years. It could be a cause for concern that thinner walled pipes are now allowed for use in potable water distribution system with the presence of oxidants.

- ASTM and AWWA pipe design standards do not take disinfection into account when establishing the HDB. The pipes are tested with pure water.

- Establishment of the "50-year design life" is a mathematical extrapolation assumes that no chemical aging will occur in PE and PVC. The 50-year design life assumes the PE failure mode will not change from Stage 1 (for substantiated materials according to PPI-TR-3), and Stage 2 for other PE materials in PPI-TR-4. If the failure mode does change the design life could be less than 50 years.

- ASTM D 2837 requires the design engineer to choose “appropriate” design factors to account for more aggressive environments. PPI-TR-9 provides design factors for PE and PVC pressure applications but not for disinfectants or oxidative environments

- Chemical dip tests are not helpful for testing a material’s resistance to oxidation when used in pressure applications as noted by several disclaimers in PPI-TR-19.

- Short-term tests involving the exposure of PE pipes to high concentrations of disinfectants, as referenced by PPI TN-34, are not helpful in examining long-term effects.

- ASTM F 2023 provides guidance for predicting PEX failure due to Stage 3 failure mode. PEX materials that pass or do not pass the lifetime predictor tests prescribed by ASTM F 876 are listed in PPI-TR-4.

- ASTM F 2263 provides guidance for predicting MDPE and HDPE failure due to Stage 3 failure mode. PPI-TR-4 does not reference ASTM F 2263, nor does it discuss how long the pipes will last with reference to Stage 3 failure modes. PPI-TR-4 only references a 50-year design life based on Stage 1 and Stage 2 failures.

- Design engineers need guidance in choosing a design factor for plastic pipe. According to ASTM D 2837, it is up to the design engineer to choose an appropriate design factor. Guidance is offered (for PE and PVC) by PPI-TR-9 for a chemical design factor for liquid hydrocarbon exposure but not for PE exposed to chemical disinfectants in a pressurized pipe.

- A summary of the testing and design standards for plastic pipe is presented in Table 3.2. Based on this summary, the following were observed:
  - No pipe standards presented information on the use of chlorine dioxide, and only one standard presented information on the use of chloramines.
  - Three standards (ASTM F 2023, PPI-TR-3, and PPI TR-4) present the resistance of PEX to pressurized chlorinated water.
  - ASTM F 2263 is the only standard that presents a test method for MDPE or HDPE with regard to Stage 3 failure. Nevertheless, this method is not used in any of the standards that establish HDB or design life for MDPE or HDPE pipes (ASTM D 2837, PPI-TR-3, PPI-TR-4).

Table 3.2 Plastic Pipe Standards Summary
Compatibility of Chemical Disinfectants with Plastic Pipe Material

Standard Designation	PVC	HDPE	PEX	Stage 1	Stage 2	Stage 3	Cl_2	CLA	ClO_2	Summary
ASTM D 1784	X			X						PVC cell classification based on material tests; no mention of disinfectants
ASTM D 2837	X	X		X	X	X				Establishes HDB and design lifetime, Acknowledges that Stage 3 failure may occur and cause overstatement of HDB and design life
ASTM D 3350		X		X	X					Provides MDPE and HDPE cell classification based on material tests; no mention of disinfectants
ASTM F 2023			X			X	X			Establishes useful service life for PEX in hot chlorinated water; materials that pass are listed in PPI-TR4
ASTM F 2263		X				X	X			Establishes useful service life for MDPE and HDPE in cold chlorinated water but not used by any other pipe standard
AWWA C905	X			X						Provides guidance for manufacturing, testing, and selecting PVC pipe; no mention of disinfectants
AWWA C906		X		X	X					Provides minimum requirements for MDPE and HDPE pressure pipe; no mention of disinfectants

Table 3.2 Plastic Pipe Standards Summary Compatibility of Chemical Disinfectants with Plastic Pipe Material

Standard Designation	PVC	HDPE	PEX	Stage 1	Stage 2	Stage 3	Cl_2	CLA	ClO_2	Summary
AWWA M23	X			X						Provides design guidance for PVC pressure pipe; no mention of disinfectants
AWWA M55		X		X	X	X				Provides design guidance for HDPE pressure pipe; provides no chemical resistance information for pressurized piping systems
PPI-TR-3	X	X	X	X	X	X	X			Provides HDB recommendations for MDPE, HDPE, PVC, and PEX. Provides lifetime prediction for PEX due to Stage 3 failures but not for MDPE, HDPE, or PVC.
PPI-TR-4	X	X	X	X	X	X	X			Provides list of materials with HDB designations based on PPI-TR-3; Indicates PEX materials resistant to Stage 3 failure, but not MDPE, HDPE or PVC.
PPI-TR-9	X	X		X	X					Provides design factors for elevated temperatures and pipe exposure to liquid hydrocarbons but not to disinfectants
PPI-TN-16		X		X	X	X				Provides information on use of the rate process method to changes in material properties

Table 3.2 Plastic Pipe Standards Summary
Compatibility of Chemical Disinfectants with Plastic Pipe Material

Standard Designation	PVC	HDPE	PEX	Stage 1	Stage 2	Stage 3	Cl_2	CLA	ClO_2	Summary
PPI-TN-19	X	X	X				X			Provide chemical resistance information for PVC, MDPE, HDPE, and PEX for non-pressure applications.
PPI-TR-34		X		X	X	X	X			Concludes that short-term, high concentrations of disinfection chemicals do not affect HDPE pipe strength.
PPI-TN-41		X		X	X					Explains reasoning behind new design factor of 0.63 based largely on higher resistance to slow crack growth.
PPI-Statement-A			X			X	X	X		Concludes PEX pipe lasts 40% longer with chloramines than chlorine.

Notes:
1. PVC – Polyvinyl chloride pipe
2. HDPE – High density polyethylene pipe
3. PEX – Cross-linked polyethylene pipe
4. Cl_2 – Free chlorine
5. CLA – Chloramines
6. ClO_2 – Chlorine dioxide
7. Stages 1, 2, 3 – See Section 1.3.1

4.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Although the impact of chemical disinfectants with PE pipe used for potable water distribution has recently been studied (Vibien et al. 2001, Hassinen et al. 2004, Lundback 2005, Colin et al. 2006, Dear and Mason 2006, Castegnetti et al. 2007, Audouin et al. 2007, Chung et al. 2007, and Chung et al. 2008), further investigation is warranted in order to accurately model the reactions of disinfectants with the plastic pipe materials (i.e., PE and PVC) as well as to accurately predict the impacts common drinking water disinfectants may have on the life expectancy and hydrostatic design basis of PE and PVC pipe. Specific topics for future research may include the following:

- In 2007, Chung *et al* performed lab testing based on ASTM F 2263 which showed that PE failed differently than PEX when exposed to pressurized cold chlorinated water. Chung *et al* (2007) identified two new failure modes for PE (Mode 1 and Mode 2). Future research could include examination of the effects of these two new failure modes on the life expectancy and hydrostatic design basis of PE pipe.

- ASTM F 2263 was developed to predict PE failure due to Stage 3 failure mode. PPI-TR-4 does not reference ASTM F 2263, nor does it discuss how long the pipes will last with reference to Stage 3 failures. Establishment of a "50-year design life" is a mathematical extrapolation that assumes Stage 3 failures will not occur. Future testing could be performed on PE pipes exposed to cold chlorinated water according to ASTM F 2263 and examine the effects on design life extrapolations.

- The "50-year design life" for PE pipe is a mathematical extrapolation assumes that no chemical aging (Stage 3 failure mode) will occur. The 50-year design life assumes the PE failure mode will not change from Stage 1 (for substantiated materials according to PPI-TR-3), and Stage 2 for other PE materials in PPI-TR-4. Future research could be performed into the effects of disinfectants possibly accelerating the onset of Stage 2 failure (the mechanical knee in the stress-time plot) and thus shortening the predicted 50-year design life.

- Design engineers need guidance in choosing a design factor for plastic pipe. According to ASTM D 2837, it is up to the design engineer to choose an appropriate design factor. Guidance is offered (for PE and PVC) by PPI-TR-9 for a chemical design factor for liquid hydrocarbon exposure but not for PE exposed to chemical disinfectants in a pressurized pipe. Future research could recommend appropriate design factors (if needed) for PE used for water distribution piping exposed to disinfectants.

- Evidence suggests that under typical distribution system conditions, disinfectants should not impact the life expectancy of PVC pipe. In fact, since PVC has higher glass transition temperature than PE, less penetration by oxidants that may diffuse through the pipe wall can be expected. PVC may also increase in molecular weight when exposed to low concentrations of disinfectants (Summers 2008), potentially resulting in a lower crack growth rate and a thus a stronger pipe. Therefore, further research is warranted to determine the impact that common potable water disinfectants may have on PVC pipe at concentrations typically found in distribution systems.

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