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July 8, 2010
Project No. F96502

Mr. Farsad Fotouhi
Vice President, Corporate Environmental Engineering
Pall Life Sciences
600 South Wagner Road
Ann Arbor, MI 48103-9019

Re: Analysis of High Density Polyethylene (HDPE) Horizontal Pipeline Life Expectancy

Dear Mr. Fotouhi:

The Michigan Department of Natural Resources and Environment (MDNRE) has requested that Pall Life Science (PLS) examine the life expectancy of the HDPE pipeline sleeve that was installed in the northern horizontal well. PLS requested that Fishbeck, Thompson, Carr and Huber, Inc. (FTC&H) provide a response to this request.

Background Information

The northern horizontal well and pipeline were installed in 1999 by Longbore Drilling Company of Houston, Texas. Two carbon steel pipes were installed into a 17-inch-diameter borehole. The well pipe is 6 5/8-inch outside diameter (O.D.), and the pipeline was 4-inch O.D. Carbon steel was selected for the well/pipeline material due to its collapse and tensile strength. Plastic pipe was not an option for either the well or pipeline, given the need for high tensile and collapse strengths in the material.

In fall 2005, PLS determined that the steel pipeline was leaking fluids. Concurrently, 1,4-dioxane concentrations in the horizontal well had declined significantly and were stabilizing. PLS worked with the MDNRE to develop a solution to the leaky pipeline. Ultimately, a decision was made to abandon the 4-inch-diameter pipeline, and insert a HDPE sleeve into the 6-inch well. This process eliminated further use of the northern horizontal well.

USA (Utility Services Authority) of Belleville, Michigan, was retained by PLS to insert (pull) a HDPE sleeve into the well pipe. This work was completed on December 6, 2005. The HDPE pipe used to sleeve the 6-inch horizontal pipe has the following specifications:

SDR-11 – ASTM D3035/FT160

NOM. SIZE	NOM. ID	NOM. OD	MIN. WALL	WGT/100 FT.	Pulled Tensile Safe (lbs.)
SDR 11 - ASTM D3035/F2160					
4"	3.682	4.500	0.409	225.483	5,870

Standard Working Pressure Rating (WPR) or for Water @ 73°F psi = 160 psi

Allowable surge pressure (occasional surge) = WPR + 50% = 240 psi

References: PE Pipe Handbook (second edition) Published by the Plastics Pipe Institute (PPI), 2007

The HDPE pipeline is used to convey approximately 200 gallons of water per day from the Evergreen System. Pipeline pressure is measured at both ends of the pipeline, which ranges between 70 and 90 pounds per square inch (psi). When the pipeline pressure reaches 100 psi, the pipeline is cleaned. Assuming a total blockage of the pipeline, the maximum pressure is anticipated to be approximately 200 psi. As such, the pipeline is operated well within its designed pressure ratings.

Fishbeck, Thompson, Carr & Huber, Inc.

Life Expectancy of Pipe

There have been several studies that indicate the life expectancy of HDPE pipe is at least 50 years and could be over 100 years. Two of these studies are referenced below:

According to the **PE Pipe Handbook (second edition)**, published by the Plastics Pipe Institute (PPI) (2007), the life expectancy of HDPE pipe is conservatively 50 to 100 years:

> *Durability – PE pipe installations are cost-effective and have long-term cost advantages due to the pipe's physical properties, leak-free joints and reduced maintenance costs. The PE pipe industry estimates a service life for PE pipe to be, conservatively, 50-100 years provided that the system has been properly designed, installed and operated in accordance with industry established practice and the manufacturer's recommendations. This longevity confers savings in replacement costs for generations to come. Properly designed and installed PE piping systems require little on-going maintenance. PE pipe is resistant to most ordinary chemicals and is not susceptible to galvanic corrosion or electrolysis.*
>
> See attachment: *Chapter 1 - Page 9*
> *plasticpipe.org/publications/pe_handbook.html*

According to project records, there were no known problems with the installation. USA, a well-known and very experienced pipeline company, uses industry-standard fusion welding procedures for its HDPE pipe installations. As such, it is reasonable to assume that the pipeline was installed using industry established practices and should have a normal life expectancy.

Long-Term Performance of Polyethylene Piping Materials in Potable Water Applications

Authors: S. Chung, S. Fong, K. Oliphant, P. Vibien – Jana (see attachment, plus link provided)

http://www.janalab.com/pdf/PE%20Chlorine%20Report%20-%20Final-2.pdf

This study suggests the life expectancy of HDPE pipe used in water applications with chlorine is over 100 years.

Other Considerations

PLS currently sends foam pigs through the pipeline as a means to remove iron buildup in the wall of the pipe. This process is done on an infrequent basis, when operating pressures near 100 psi. There is some potential for wall scouring at this time, depending on the characteristics of the material in the pipe. Based on internet reviews of the subject, there appears to be no issue with pigging causing HDPE damage.

According to chemical compatibility charts (the two charts are provided as attachments and links to the sites are also provided below), HDPE is resistant to 1,4-dioxane. These tests were on pure product; therefore, the likelihood of the HDPE being affected by diluted concentrations of 1,4-dioxane is less remote. 1,4-Dioxane is present in the water transferred in the HDPE pipeline. Current 1,4-dioxane concentrations in the pipeline are less than 1 milligram per liter.

http://pt.rexnord.com/products/guards/orange_peel_guards/hdpechemresistpdf01feb.pdf

http://www.porex.com/pdf/4728_chem_compat-11-28.pdf

In summary, it is FTC&H's opinion that the existing pipeline, provided it is not damaged by unforeseen external forces, will have a service life of at least 50 years.

If you have any questions or require additional information, please contact me at 269-544-6941 or jwbrode@ftch.com or contact Brian Vilmont at 616-464-3946 or bgvilmont@ftch.com.

Sincerely,

FISHBECK, THOMPSON, CARR & HUBER, INC.

James W. Brode, Jr., CPG

Brian G. Vilmont

Brian G. Vilmont, P.E.

lkj
Attachments
By e-mail

Chemical Compatibility Chart

RATING SYSTEM*

The following codes are used to rate chemical resistance:

G = Good
F = Fair
P = Poor
N = Not Recommended (some swelling or degradation will probably occur)

** Unless otherwise agreed upon in writing, Porex products are sold without a chemical resistance warranty. Buyer/user should perform appropriate tests to determine performance under specific operating conditions.*

SUBSTANCE AT 21°C (70°F)	HDPE UHMWPE	PP	PVDF	PTFE
Acetaldehyde	G	F	N	G
Acetic acid, 10%	G	G	G	G
Acetic acid, 100% (glacial)	G	G	G	G
Acetic anhydride	G	G	F	G
Acetone	G	G	P	G
Acide, aromatic	G	G	-	G
Acrylonitrile	G	G	F	G
Aallyl alcohol, 96%	G	G	G	G
Aluminum chloride	G	G	G	G
Alum	G	G	G	G
Amonia	G	G	N	G
Ammonia, gaseous	G	G	N	G
Ammonium salts	G	G	G	G
Amyl acetate	G	G	F	G
Anisole	F	F	-	G
Antimony trichloride	G	G	F	G
Aqua regia	N	F	F	G
Beer	G	G	G	G
Beeswax	G	G	-	G
Benzaldehyde	G	G	F	G
Benzene	F	F	G	G
Bensenesulphonic acid	G	G	F	G
Benzoic acid	G	G	G	G
Benzol chloride	F	F	F	G
Borax	G	G	G	G
Boric acid	G	G	G	G
Brine (saturated)	G	G	G	G
Bromine (liquid)	N	N	F	G
Bromochloromethane	N	N	-	-
Butanol	G	G	G	G
Butylacetate	G	F	G	G
Butylene glycol	G	G	G	G
Butyric acid	G	G	G	G
Calcium chloride	G	G	G	G
Calcium hupochlorite	G	G	G	G
Calcium nitrate, 50%	G	G	G	G
Camphor	G	G	-	-
Carbon disulphide	F	G	F	G
Carbon tetrachloride	P	N	G	G
Carbonic acid	G	G	G	G
Castol oil	G	G	G	G
Caustic potash	G	G	G	G
Caustic soda	G	G	N	G
Chloral hydrate	G	F	G	G
Chlorine (liquid)	N	N	G	G
Chlorine gas (dry)	F	N	G	G
Chlorine gas (wet)	F	P	G	G
Chloloracetic acid (mono)	G	G	G	G
Chlorobenzene	F	G	G	G
Chlorethanol	G	G	-	G

SUBSTANCE AT 21°C (70°F)	HDPE UHMWPE	PP	PVDF	PTFE
Chloroform	P	F	G	G
Chlorosulphonic acid	N	N	N	G
Chromic acid, 80%	G	G	G	G
Citric acid	G	G	G	G
Clophen A50 and A6	G	G	-	-
Coconut oil	G	G	G	G
Common salt (aqueous, saturated)	G	G	G	G
Copper salts	G	G	G	G
Corn oil	G	G	G	G
Creosote	G	G	G	G
Cresol	G	G	G	G
Cyclohexane	G	G	G	G
Cyclohexanol	G	G	G	G
Cyclohexnone	G	G	G	G
Dibutyl ether	F	F	-	-
Dibutyl phthalate	G	G	N	G
Dichloracetic acid, 50%	G	G	G	G
Dichloracetic acid, 100%	G	G	G	G
Dichloracetic acid methyl ester	G	G	-	G
Dichlorobenzene-o	F	F	G	G
Dichlorobenzene-p	F	F	G	G
Dichloroethylene	N	G	G	G
Diesel oil	G	F	G	G
Diethyl ether	F	F	F	G
Diisobutyl ketone	G	G	G	G
Dimethylamine	G	G	N	G
Dimethyl formamide	G	G	N	G
Dimethyl sulphoxide	G	G	F	G
Dioxane	G	G	N	G
Emulsifiers	G	G	-	G
Epichlorhydrin	G	G	N	G
Esters, aliphatic	G	F	-	G
Ethanol 96%	G	G	-	G
Ether	F	F	-	G
Ethyl acetate	G	G	N	G
Ethylene chloride (Dichloroethane)	F	F	G	G
Ethylenediaminetetraacetic acid	G	G	-	G
Ethylene gylcol	G	G	G	G
Fatty acids (C)	G	G	G	G
Ferric chloride	G	G	G	G
Fluorine	N	N	F	F
Fluosilicic acid	G	F	G	G
Formaldehyde (40% aqueous)	G	G	G	G
Formic acid	G	G	G	G
Frigen®	F	N	-	-
Fruit juices	G	G	-	G
Fruit pulp	G	G	-	G
Fuel oil	G	G	G	G
Furfuryl alcohol	G	G	F	G
Gelatine	G	G	-	G
Glycerine	G	G	G	G
Glycol (concentrated)	G	G	-	G
Glycolic acid, 55%	G	G	F	G
Glycolic acid, 70%	G	G	F	G
Glycolic acid butyl ester	G	G	-	G
Hylothane	F	F	-	-
Hydraulic fluid	G	G	-	G
Hydrazine hydrate	G	G	-	G
Hydrobromic acid, 50%	G	G	G	G
Hydrochloloric acid, all conc.	G	G	G	G
Hydrochloric acid gas (dry and wet)	G	G	G	G
Hydrocyanic acid	G	G	G	G
Hydrofluoric acid, 40%	G	G	G	G
Hydrofluoric acid, 70%	G	G	G	G
Hydrogen peroxide, 30%	G	G	G	G
Hydrogen peroxide, 90%	G	G	G	G
Hydrogene sulphide	G	G	G	G
Hydrosulphine (10%, aqueous)	G	G	-	G

Chemical Compatibility Chart

SUBSTANCE AT 21°C (70°F)	HDPE UHMWPE	PP	PVDF	PTFE
Iodine tinture, DAB 6 (German Phamacopoeia)	G	G	G	G
Isoocatane	G	G	-	G
Isopropanol	G	G	-	G
Isopropyl ether	F	F	-	G
Ketones	G	G	-	G
Lantic acid	G	G	G	G
Linseed oil	G	G	G	G
Liquid paraffin	G	G	-	G
Liquid paraffin	G	G	-	G
Magnesium chloride	G	G	G	G
Maleic acid	G	G	G	G
Malic acid, 50%	G	G	G	G
Menthol	G	G	-	G
Mercury	G	G	G	G
Mercuric chlorine (corrosive sublimate)	G	G	G	G
Methanol	G	G	-	G
Methoxybutanol	G	G	-	G
Methoxybutylacetate	G	G	-	G
Methylcyclohexane	F	G	-	G
Methylene chlorine	F	F	N	G
Methyl ethyl ketone	G	G	N	G
Methyl glycol	G	G	-	G
Monochloracetic acid	G	G	G	G
Monochloracetic acid ethyl ester	G	G	-	G
Monochloracetic acid methyl ester	G	G	-	G
Morpholine	G	G	F	G
Motor oil (HD oil)	G	G	-	G
Nephtha	G	F	G	G
Naphthalene	G	G	G	G
Nickel salts	G	G	G	G
Nitric acid, 25%	G	G	G	G
Nitric acid, 50%	F	F	G	G
Nitrobenzene	G	G	F	G
Nitotoluene	G	G	-	G
Nitrous gases	G	G	G	G
Oils (ethereal)	F	F	G	G
Oils (vegetable and animal)	G	G	G	G
Oleic acid, conc.	G	G	G	G
Oleum	N	N	N	G
Oxalic acid, 50%	G	G	G	G
Ozone	F	G	G	G
Perchloric acid, 20%	G	G	G	G
Perchloric acid, 50%	G	G	G	G
Perchloric acid, 70%	G	G	G	G
Petrol	G	F	G	G
Petro/Benzene mixture	G	G	G	G
Petroleum	G	G	G	G
Petroleum ether	G	G	G	G
Phenol	G	G	G	G
Phosphates	G	G	-	G
Phosphoric acid, 25%	G	G	G	G
Phosphoric acid, 50%	G	G	G	G
Phosphoric acid, 95%	G	G	G	G
Phosphorus oxychloride	G	G	G	G
Phosphorus pentoxide	G	G	G	G
Phosphorus trichloride	G	G	G	G
Photographic developers	G	G	G	G
Phthalic acid, 50%	G	G	G	G
Polyglycois	G	G	G	G
Potassium bichromate, 40%	G	G	-	G
Potassium chloride	G	G	G	G
Potassium cyanide (aqueous, saturated)	G	G	G	G

SUBSTANCE AT 21°C (70°F)	HDPE UHMWPE	PP	PVDF	PTFE
Potassium hydroxide (30% aqueous)	G	G	G	G
Potassium nitrate (aqueous, saturated)	G	G	G	G
Potassium permanganate	G	G	G	G
Propionic acid, 50%	G	G	-	G
Propionic acid, 100%	G	G	-	G
Propylene glycol	G	G	-	G
Pseudocumene	G	F	-	G
Pyridine	G	F	N	G
Sea water	F	G	G	G
Silicic acid	G	G	-	G
Silicone oil	G	G	-	G
Silver nitrate	G	G	G	G
Sodium benzoate	G	G	G	G
Sodium borate	G	G	G	G
Sodium carbonate	G	G	G	G
Sodium chloride	G	G	G	G
Sodium chloride, 50%	G	G	G	G
Sodium chloride bleach	F	G	G	G
Dodium dodecylbenzene-Sulponate	G	G	G	G
Sodium hydroxide-30% aqueous	G	G	G	G
Sodium hypochlorite, all concs.	G	G	G	G
Sodium nitrate	G	G	G	G
Sodium peroxide, 10%	G	G	G	G
Sodium peroxide, 10% saturated	F	F	G	G
Sodium sulphide	G	G	-	G
Sodium thiosulphate	G	G	G	G
Spermaceti	G	G	-	G
Spindle oil	F	G	-	G
Starch	G	G	-	G
Stearic acid	G	G	G	G
Succinic acid, 50%	G	G	G	G
Sugar syrup	G	G	-	G
Sulphates	G	G	-	G
Sulphur	G	G	-	G
Sulphur dioxide (dry)	G	G	G	G
Sulphur dioxide (wet)	G	G	G	G
Sulphuric acid, 10%	G	G	G	G
Sulphuric acid, 50%	G	G	G	G
Sulphuric acid, 98%	F	F	G	G
Sulphurous acid	G	G	-	G
Sulphuryl chloride	N	N	-	G
Synthetic detergents	G	G	-	G
Tallow	G	G	G	G
Tannic acid, 10%	G	G	G	G
Tartaric acid	G	G	G	G
Tetrabromoethane	P	P	G	G
Tetrachloroethane	P	F	-	G
Tetrahydrofuran	P	F	-	G
Toluene	P	G	G	G
Transformer oil	G	G	F	G
Tributyl phosphate	G	G	F	G
Trichloraecetic acid, 50%	G	G	G	G
Trichloroacetic acid, 100%	G	G	G	G
Trichloroethylene	P	F	G	G
Tricresyl phosphate	G	G	N	G
Triethanolamine	G	G	G	G
Turpentine oil	F	N	G	G
Urea, 33%	G	G	G	G
Vaseline®	F	G	G	G
White spirit	F	F	-	G
P-Xylene	F	N	G	G
Yeast	F	G	-	G
Zinc chloride	G	G	G	G

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Chemical Resistance Chart for HDPE (High Density Polyethylene)

The chemical resistance chart that follows is a general guide only. Please contact Orange Peel about specific applications.

Chemical Resistance Classification:

E – 30 days of constant exposure to reagent causes no damage
G – Little or no damage after 30 days of constant exposure to the reagent
F – Some effect after 7 days exposure to the reagent. Solvents may cause swelling and permeation losses
N – Not recommended for continuous use

First letter of each pair applies to conditions at 20°C (68°F);the second to those at 50°C (122°F).

Acetaldehyde – GF
Acetamide, Sat. – EE
Acetic Acid, 5% – EE
Acetic Acid, 50% – EE
Acetic Anhydride – FF
Acetone – EE
Acetonitrile – EE
Acrylonitrile – EE
Adipic Acid – EE
Alinine – EE
Allyl Alchohol – EE
Aluminum Hydroxide – EE
Aluminum Salts – EE
Amino Acids – EE
Ammonia – EE
Ammonium Acetate, Sat. – EE
Ammonium Glycolate – EE
Ammonium Hydroxide, 5% – EE
Ammonium Hydroxide, 30% – EE
Ammonium Oxalate – EE
Ammonium Salts – EE
n-Amyl Acetate – EG
Amyl Chloride – FN
Aniline – EG
Aqua Regis – NN
Benzaldehyde – EE
Benzene – GG
Benzoic Acid, Sat. – EE
Benzyl Acetate – EE
Benzyl Alcohol – FN
Bromine – FN
Bromobenzine – FN
Bromoform – NN
Butadiene – FN
Butyl Chloride – NN
n-Butyl Acetate – EG
n-Butyl Alcohol – EE
sec-Butyl Alcohol – EE
tert-Butyl Alcohol – EE
Butyric Acid – FN
Calcium Hydroxide, Conc. – EE
Calcium Hydroxide, Sat. – EE

Diethyl Ketone – GG
Diethyl Malonate – EE
Diethylamine – FN
Diethylene Glycol – EE
Diethylene Glycol Ethyl Ether – EE
Dimethyl Acetamide – EE
Dimethyl Formamide – EE
Dimethylsulfoxide – EE
1,4-Dioxane – GG
Dipropylene Glycol – EE
Ether – FN
Ethyl Acetate – EE
Ethyl Alcohol (Absolute) – EE
Ethyl Alcohol (40%) – EE
Ethyle Benzene – GF
Ethyl Benzoate – GG
Ethyl Butyrate – GF
Ethyl Chloride, Liquid – FF
Ethyl Cyanoacetate – EE
Ethyl Lactate – EE
Ethylene Chloride – GF
Ethylene Glycol – EE
Ethylene Glycol Methyl Ether – EE
Ethylene Oxide – GF
Fatty Acids – EE
Fluorides – EE
Flourine – GN
Formaldehyde, 10% – EE
Formaldehyde, 40% – EE
Formic Acid, 3% – EE
Formic Acid, 50% – EE
Formic Acid, 100% – EE
Freon TF – EG
Fuel Oil – GF
Gasoline – GG
Glacial Acetic Acid – EE
Glutaraidehyde – EE
Glycerine – EE
n-Heptane – GF
Hexane – GF
Hydrazine – NN
Hydrochloric Acid, 5% – EE

Nitric Acid, 1-10% – EE
Nitric Acid, 50% – GN
Nitric Acid, 70% – GN
Nitrobenzene – FN
Nitromethane – FN
n-Octane – EE
Orange Oil – GF
Ozone – EE
Perchloric Acid – GN
Perchloroethylene – NN
Phenol, Crystals – GF
Phenol, Liquid – NN
Phosphoric Acid, 1-5% – EE
Phosphoric Acid, 85% – EE
Picric Acid – NN
Pine Oil – EG
Potassium Hydroxide, 1% – EE
Potassium Hydroxide, Conc. – EE
Propane Gas – FN
Propionic Acid – EF
Propylene Glycol – EE
Propylene Oxide – EE
Resorcinol, Saturated – EE
Resorcinol, 5% -– EE
Sallcylaldehyde – EE
Sallcylic Acid, Powder – EE
Sallcylic Acid, Saturated – EE
Salt Solutions, Metallic – EE
Silicone Oil – EE
Silver Acetate – EE
Silver Nitrate – EE
Skydrol LD4 – EG
Sodium Acetate, Saturated – EE
Sodium Hydroxide, 1% – EE
Sodium Hydroxide, 100% – EE
Sodium HypoChlorite, 15% – EE
Stearic Acid, Crystals – EE
Sulphuric Acid, 1-6% – EE
Sulphuric Acid, 20% – EE
Sulphuric Acid, 60% – EE
Sulphuric Acid, 98% – GG
Sulphur Dioxide, Liquid – FN

Carbazole – EE
Carbon Disulfide – NN
Carbon Tetrachloride -– GF
Cedarwood Oil – FN
Cellosolve Acetate – EE
Chlorobenzene – FN
Chlorine, 10% in Air – EF
Chlorine, 10% (Moist) – GF
Chloroacetic Acid – EE
p-Chloroacetophenone – EE
Chloroform – GF
Chromic Acid, 10% – EE
Chromic Acid, 50% – EE
Cinnamon Oil – FN
Citric Acid, 10% – EE
Cresol – FN
Cyclohexane – FN
Cyclohexanone – FN
Cyclopentane – FN
DeCalin – EG
n-Decane – FN
Diacetone Alcohol – EE
o-Dichlorobenzine – FF
p-Dichlorobenzine – GF
1,2-Dichloroethane – NN
2,4-Dichlorophenol – NN
Diethyl Benzene – FN
Diethyl Ether – FN

Hydrochloric Acid, 20% – EE
Hydrochloric Acid, 35% – EE
Hydroflouric Acid, 4% – EE
Hydroflouric Acid, 48% – EE
Hydrogen Peroxide, 3% – EE
Hydrogen Peroxide, 30% – EE
Hydrogen Peroxide, 90% – EE
Iodine Crystals – NN
Isobutyl Alcohol – EE
Isopropyl Acetate – EG
Isopropyl Alcohol – EE
Isopropyl Benzene – GE
Isopropyl Ether – NN
Jet Fuel – FN
Kerosene – GG
Lacquer Thinner – FN
Lactic Acid, 3% – EE
Lactic Acid, 85% l – EE
Mercury – EE
2-Methoxyrthanol – EE
Methoxyethyl Oleate – EE
Methyl Acetate – FF
Methyl Alcohol – EE
Methyl Ethyl Ketone – EE
Methyl-y-butyl Ether – FN
Methylene Chloride – GF
Mineral Oil – EE
Mineral Spirits – FN

Sulphur Dioxide, Wet or Dry – EE
Sulphur Salts – GF
Tararic Acid – EE
Tetrahydrofuran – GF
Thlonyl Chloride – NN
Toluene – GG
Tributyl Citrate – EG
Trichloroacetic Acid – FF
1,2,4-Trichlorobenzene – NN
Trichloroethylene – FN
Triethylene Glycol – EE
2,2,4-Trimethylpentane – FN
Tripropylene Glycol – EE
Tris Buffer, Solution – EG
Turpentine – GG
Undecyl Alcohol – EG
Urea – EE
Vinylidene Chloride – GF
Xylene – GF
Zinc Stearate – EE

PLASTICS • PIPE • INSTITUTE

Thursday July 8. 2010

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PPI Main Page

PPI Divisions:

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Corrugated Pipe
Fuel Gas
Hydrostatic Stress Board
Municipal & Industrial
Plumbing & Heating

Second Edition Handbook of PE Pipe

Published by the Plastics Pipe Institute (PPI), the Handbook describes how polyethylene piping systems continue to provide utilities with a cost effective solution to rehabilitate the underground infrastructure. The book will assist in designing and installing PE piping systems that can protect utilities and other end users from corrosion, earthquake damage and water loss due to leaky and corroded pipes and joints.

Table of Contents
Foreword

Click here to purchase Handbook of PE Pipe

CHAPTER 1

Introduction

Since its discovery in 1933, PE has grown to become one of the world's most widely used and recognized thermoplastic materials.(1) The versatility of this unique plastic material is demonstrated by the diversity of its use and applications. The original application for PE was as a substitute for rubber in electrical insulation during World War II. PE has since become one of the world's most widely utilized thermoplastics. Today's modern PE resins are highly engineered for much more rigorous applications such as pressure-rated gas and water pipe, landfill membranes, automotive fuel tanks and other demanding applications.

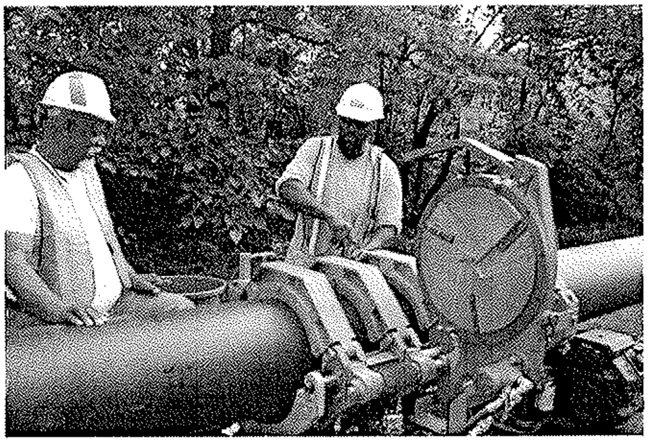

Figure 1 Joining Large Diameter PE Pipe with Butt Fusion

PE's use as a piping material first occurred in the mid 1950's. In North America, its original use was in industrial applications, followed by rural water and then oil field production where a flexible, tough and lightweight piping product was needed to fulfill the needs of a rapidly developing oil and gas production industry. The success of PE's pipe in these installations quickly led to its use in natural gas distribution where a coilable, corrosion-free piping material could be fused in the field to assure a "leak-free" method of transporting natural gas to homes and businesses. PE's success in this critical application has not gone without notice and today it is the material of choice for the natural gas distribution industry. Sources now estimate that nearly 95% of all new gas distribution pipe installations in North America that are 12" in diameter or smaller are PE piping.(2)

The performance benefits of polyethylene pipe in these original oil and gas related applications have led to its use in equally demanding piping installations such as potable water distribution, industrial and mining pipe, force mains and other critical applications where a tough, ductile material is needed to assure long-term performance. It is these applications, representative of the expanding use of polyethylene pipe that are the principle subject of this handbook. In the chapters that follow, we shall examine all aspects of design and use of polyethylene pipe in a broad array of applications. From engineering properties and material science to fluid flow and burial design; from material handling and safety considerations to modern installation practices such as horizontal directional drilling and/or pipe bursting; from potable water lines to industrial slurries we will examine those qualities, properties and design considerations which have led to the growing use of polyethylene pipe in North America.

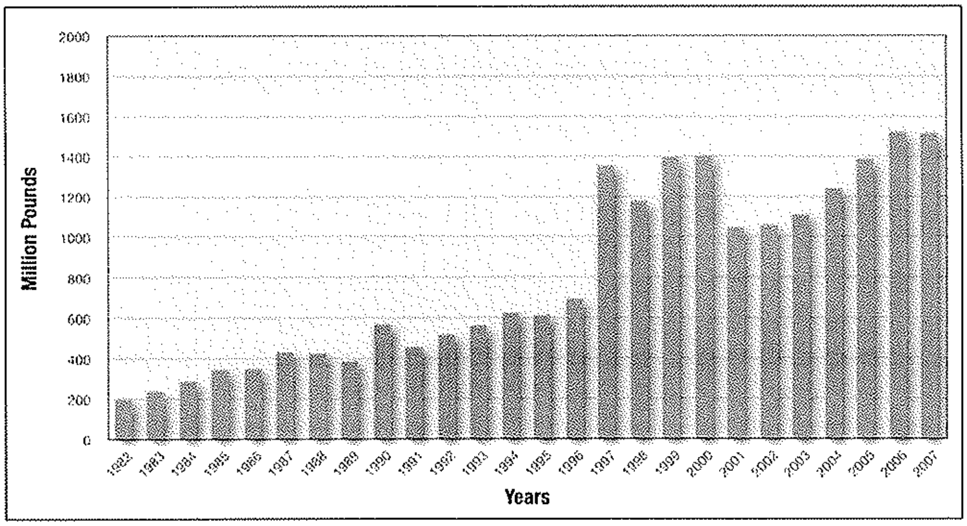

Figure 2 Historical Growth in North American HDPE Pipe Shipments[3]

Features and Benefits of PE Pipe

When selecting pipe materials, designers, owners and contractors specify materials that provide reliable, long-term service durability, and cost-effectiveness.

Solid wall PE pipes provide a cost-effective solution for a wide range of piping applications including natural gas distribution, municipal water and sewer, industrial, marine, mining, landfill, and electrical and communications duct applications. PE pipe is also effective for above ground, buried, trenchless, floating and marine installations. According to David A. Willoughby, P.O.E., "... one major reason for the growth in the use of the plastic pipe is the cost savings in installation, labor and equipment as compared to traditional piping materials. Add to this the potential for lower maintenance costs and increased service life and plastic pipe is a very competitive product."[4]

Natural gas distribution was among the first applications for medium-density PE (MDPE) pipe. In fact, many of the systems currently in use have been in continuous service since 1960 with great success. Today, PE pipe represents over 95% of the pipe installed for natural gas distribution in diameters up to 12" in the U.S. and Canada. PE is the material of choice not only in North America, but also worldwide. PE pipe has been used in potable water applications for almost 50 years, and has been continuously gaining approval and growth in municipalities. PE pipe is specified and/or approved in accordance with AWWA, NSF, and ASTM standards.

Some of the specific benefits of PE pipe are discussed in the parargraphs which follow.

- **Life Cycle Cost Savings** – For municipal applications, the life cycle cost of PE pipe can be significantly less than other pipe materials. The extremely smooth inside surface of PE pipe maintains its exceptional flow characteristics, and heat fusion joining eliminates leakage. This has proven to be a successful combination for reducing total system operating costs.
- **Leak Free, Fully Restrained Joints** – PE heat fusion joining forms leak-free joints that are as strong as, or stronger than, the pipe itself. For municipal applications, fused joints eliminate the potential leak points that exist every 10 to 20 feet when using the bell and spigot type joints associated with other piping products such as PVC or ductile iron. All these bell and spigot type joints employ elastomeric gasket materials that age over time and thus have the potential for leaks. As a result of this, the "allowable water leakage" for PE pipe is zero as compared to the water leakage rates of 10% or greater typically associated with these other piping products. PE pipe's fused joints are also self-restraining, eliminating the need for costly thrust restraints or thrust blocks while still insuring the integrity of the joint. Notwithstanding the advantages of the butt fusion method of joining, the engineer also has other available means for joining PE pipe and fittings such as electrofusion and mechanical fittings. Electrofusion fittings join the pipe and/or fittings together using embedded electric heating elements. In some situations, mechanical fittings may be required to facilitate joining to other piping products, valves or other system appurtenances. Specialized fittings for these purposes have been developed and are readily available to meet the needs of most demanding applications.
- **Corrosion & Chemical Resistance** – PE pipe will not rust, rot, pit, corrode, tuberculate or support biological growth. It has superb chemical resistance and is the material of choice for many harsh chemical environments. Although unaffected

by chemically aggressive native soil, installation of PE pipe (as with any piping material) through areas where soils are contaminated with organic solvents (oil, gasoline) may require installation methods that protect the PE pipe against contact with organic solvents. It should be recognized that even in the case of metallic and other pipe materials, which are joined by means of gaskets, protection against permeation is also required. Protective installation measures that assure the quality of the fluid being transported are typically required for all piping systems that are installed in contaminated soils.

- **Fatigue Resistance and Flexibility** – PE pipe can be field bent to a radius of about 30 times the nominal pipe diameter or less depending on wall thickness (12" PE pipe, for example, can be cold formed in the field to a 32-foot radius). This eliminates many of the fittings otherwise required for directional changes in piping systems and it also facilitates installation. The long-term durability of PE pipe has been extremely well researched. PE has exceptional fatigue resistance and when, operating at maximum operating pressure, it can withstand multiple surge pressure events up to 100% above its maximum operating pressure without any negative effect to its long-term performance capability.
- **Seismic Resistance** – The toughness, ductility and flexibility of PE pipe combined with its other special properties, such as its leak-free fully restrained heat fused joints, make it well suited for installation in dynamic soil environments and in areas prone to earthquakes.

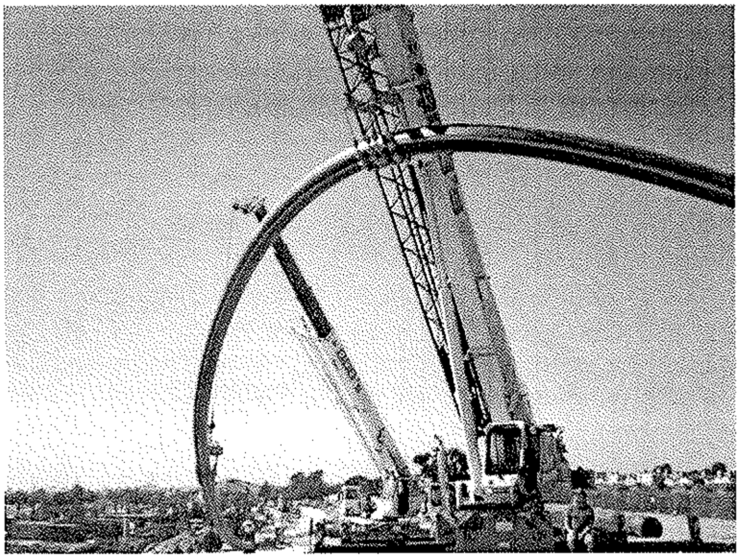

Figure 3 Butt Fused PE Pipe "Arched" for Insertion into Directional Drilling Installation

- **Construction Advantages** – PE pipe's combination of light weight, flexibility and leak-free, fully restrained joints permits unique and cost-effective installation methods that are not practical with alternate materials. Installation methods such as horizontal directional drilling, pipe bursting, sliplining, plow and plant, and submerged or floating pipe, can greatly simplify construction and save considerable time and money on many installations. At approximately one-eighth the weight of comparable sized steel pipe, and with integral and dependable leakfree joining methods, installation is simpler, and it does not need heavy lifting equipment. PE pipe is produced in standard straight lengths to 50 feet or longer and coiled in diameters up through 6". Coiled lengths over 1000 feet are available in certain diameters. PE pipe can withstand impact much better than PVC pipe, especially in cold weather installations where other pipes are more prone to cracks and breaks. Because heat fused PE joints are as strong as the pipe itself, it can be joined into long runs conveniently above ground and later, installed directly into a trench or pulled in via directional drilling or using the re-liner process. Of course, the conditions at the construction site have a big impact on the preferred method of installation.
- **Durability** – PE pipe installations are cost-effective and have long-term cost advantages due to the pipe's physical properties, leak-free joints and reduced maintenance costs. The PE pipe industry estimates a service life for PE pipe to be, conservatively, 50-100 years provided that the system has been properly designed, installed and operated in accordance with industry established practice and the manufacturer's recommendations. This longevity confers savings in replacement costs for generations to come. Properly designed and installed PE piping systems require little on-going maintenance. PE pipe is resistant to most ordinary chemicals and is not susceptible to galvanic corrosion or electrolysis.

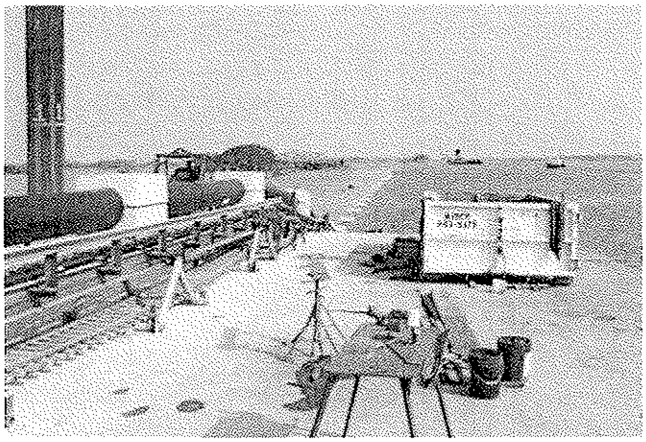

Figure 4 PE Pipe Weighted and Floated for Marine Installation

- **Hydraulically Efficient** – The internal surface of PE pipe is devoid of any roughness which places it in the "smooth pipe" category, a category that results in the lowest resistance to fluid flow. For water applications, PE pipe's Hazen Williams C factor is 150 and does not change over time. The C factor for other typical pipe materials declines dramatically over time due to corrosion and tuberculation or biological build-up. Without corrosion, tuberculation, or biological growth PE pipe maintains its smooth interior wall and its flow capabilities indefinitely to insure hydraulic efficiency over the intended design life.
- **Temperature Resistance** – PE pipe's typical operating temperature range is from 0°F to 140°F for pressure service. However, for non-pressure and special applications the material can easily handle much lower temperatures (e.g., to – 40°F and lower) and there are specially formulated materials that can service somewhat higher temperatures. Extensive testing and very many applications at very low ambient temperatures indicates that these conditions do not have an adverse effect on pipe strength or performance characteristics. Many of the PE resins used in PE pipe are stress rated not only at the standard temperature, 73° F, but also at an elevated temperature, such as 140°F. Typically, PE materials retain greater strength at elevated temperatures compared to other thermoplastic materials such as PVC. At 140° F, PE materials retain about 50% of their 73°F strength, compared to PVC which loses nearly 80% of its 73° F strength when placed in service at 140°F.(5) As a result, PE pipe materials can be used for a variety of piping applications across a very broad temperature range.

The features and benefits of PE are quite extensive, and some of the more notable qualities have been delineated in the preceding paragraphs. The remaining chapters of this Handbook provide more specific information regarding these qualities and the research on which these performance attributes are based.

Many of the performance properties of PE piping are the direct result of two important physical properties associated with PE pressure rated piping products. These are ductility and visco-elasticity. The reader is encouraged to keep these two properties in mind when reviewing the subsequent chapters of this handbook.

- **Ductility**

  Ductility is the ability of a material to deform in response to stress without fracture or, ultimately, failure. It is also sometimes referred to as increased strain capacity and it is an important performance feature of PE piping, both for above and below ground service. For example, in response to earth loading, the vertical diameter of buried PE pipe is slightly reduced. This reduction causes a slight increase in horizontal diameter, which activates lateral soil forces that tend to stabilize the pipe against further deformation. This yields a process that produces a soil-pipe Introduction 11 structure that is capable of safely supporting vertical earth and other loads that can fracture pipes of greater strength but lower strain capacity.

  Ductile materials, including PE, used for water, natural gas and industrial pipe applications have the capacity to safely handle localized stress intensifications that are caused by poor quality installation where rocks, boulders or tree stumps may be in position to impinge on the outside surface of the pipe. There are many other construction conditions that may cause similar effects, e.g. bending the pipe beyond a safe strain limit, inadequate support for the pipe, misalignment in connections to rigid structures and so on. Non- ductile piping materials do not perform as well when it comes to handling these types of localized high stress conditions.

Materials with low ductility or strain capacity respond differently. Strain sensitive materials are designed on the basis of a complex analysis of stresses and the potential for stress intensification in certain regions within the material. When any of these stresses exceed the design limit of the material, crack development occurs which can lead to ultimate failure of the part or product. However, with materials like PE pipe that operate in the ductile state, a larger localized deformation can take place without causing irreversible material damage such as the development of small cracks. Instead, the resultant localized deformation results in redistribution and a significant lessening of localized stresses, with no adverse effect on the piping material. As a result, the structural design with materials that perform in the ductile state can generally be based on average stresses, a fact that greatly simplifies design protocol.

To ensure the availability of sufficient ductility (strain capacity) special requirements are developed and included into specifications for structural materials intended to operate in the ductile state; for example, the requirements that have been established for "ductile iron" and mild steel pipes. On the other hand, ductility has always been a featured and inherent property of PE pipe materials. And it is one of the primary reasons why this product has been, by far, the predominant material of choice for natural gas distribution in North America over the past 30 plus years. The new or modern generation of PE pipe materials, also known as high performance materials, have significantly improved ductility performance compared to the traditional versions which have themselves, performed so successfully, not only in gas but also in a variety of other applications including, water, sewer, industrial, marine and mining since they were first introduced about 50 years ago.

For a more detailed discussion of this unique property of PE material, especially the modern high performance versions of the material, and the unique design benefits it brings to piping applications, the reader is referred to Chapter 3, Material Properties.

Visco-Elasticity

PE pipe is a visco-elastic construction material.(6) Due to its molecular nature, PE is a complex combination of elastic-like and fluid-like elements. As a result, this material displays properties that are intermediate to crystalline metals and very high viscosity fluids. This concept is discussed in more detail in the chapter on Engineering Properties within this handbook.

The visco-elastic nature of PE results in two unique engineering characteristics that are employed in the design of PE water piping systems, creep and stress relaxation.

- **Creep** is the time dependent viscous flow component of deformation. It refers to the response of PE, over time, to a constant static load. When PE is subjected to a constant static load, it deforms immediately to a strain predicted by the stressstrain modulus determined from the tensile stress-strain curve. At high loads, the material continues to deform at an ever decreasing rate, and if the load is high enough, the material may finally yield or rupture. PE piping materials are designed in accordance with rigid industry standards to assure that, when used in accordance with industry recommended practice, the resultant deformation due to sustained loading, or creep, is too small to be of engineering concern.
- **Stress relaxation** is another unique property arising from the visco-elastic nature of PE. When subjected to a constant strain (deformation of a specific degree) that is maintained over time, the load or stress generated by the deformation slowly decreases over time, but it never relaxes completely. This stress relaxation response to loading is of considerable importance to the design of PE piping systems. It is a response that decreases the stress in pipe sections which are subject to constant strain.

  As a visco-elastic material, the response of PE piping systems to loading is time-dependent. The apparent modulus of elasticity is significantly reduced by the duration of the loading because of the creep and stress relaxation characteristics of PE. An instantaneous modulus for sudden events such as water hammer is around 150,000 psi at 73°F. For slightly longer duration, but short-term events such as soil settlement and live loadings, the short-term modulus for PE is roughly 110,000 to 130,000 psi at 73° F, and as a long-term property, the apparent modulus is reduced to something on the order of 20,000-30,000 psi. As will be seen in the chapters that follow, this modulus is a key criterion for the long-term design of PE piping systems.

This same time-dependent response to loading also gives PE its unique resiliency and resistance to sudden, comparatively short-term loading phenomena. Such is the case with PE's resistance to water hammer phenomenon which will be discussed in more detail in subsequent sections of this handbook.

Summary

As can been seen from our brief discussions here, PE piping is a tough, durable piping material with unique performance properties that allow for its use in a broad range of applications utilizing a variety of different construction techniques based upon project needs. The chapters that follow offer detailed information regarding the engineering properties of PE, guidance on design of PE piping systems, installation techniques as well as background information on how PE pipe and fittings are produced, and appropriate material handling guidelines. Information such as this is intended to provide the basis for sound design and the successful installation and operation of PE piping systems. It is to this end, that members of the Plastics Pipe Institute have prepared the information in this handbook.

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TECHNICAL REPORT

LONG-TERM PERFORMANCE OF POLYETHYLENE PIPING MATERIALS IN POTABLE WATER APPLICATIONS

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Long-Term Performance of Polyethylene Piping Materials in Potable Water Applications

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Abstract

Polyethylene (PE) piping materials have demonstrated a strong track record in potable water applications since their introduction in the early sixties. In the decades since the introduction of those early materials, advances in polymer science have driven considerable evolution in both the pressure-carrying capabilities and the long-term service lifetime forecast. Due to the dramatic improvements in PE piping materials, projecting performance of current PE piping materials based on past performance is likely to provide an overly conservative picture. In order to forecast performance of current generation PE piping, the industry has been actively developing accelerated methodologies for validating the long-term performance of PE piping materials in potable water applications. This paper reports on the current state of the research and presents a methodology to project long-term PE pipe performance as a function of specific water quality, operating temperature and operating stress. Based on this methodology, case studies for four specific utilities and an average utility are presented that show that greater than 100 years performance is projected in these systems for the higher performance PE 3408 and PE 4710 materials examined.

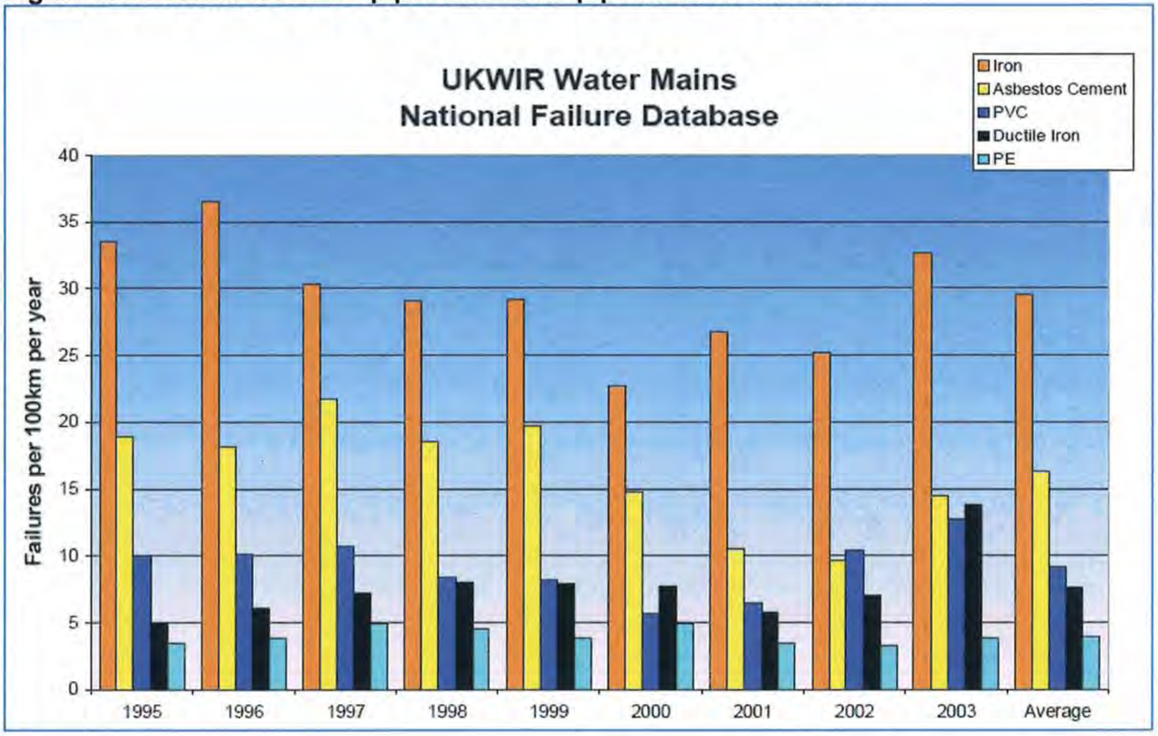
Introduction

Polyethylene (PE) piping materials have enjoyed a long and successful history in natural gas and water piping applications. In the safety-critical natural gas piping industry, PE pipe is the material of choice in North America, holding a 95% market share in new distribution piping networks. For the water industry, PE pipe dominates the European market at 65% share. In the UK, PE pipe holds almost the entire water market with an 85% market share. In North America, PE pipe holds a much smaller, though growing, share of the water piping market.

The first PE water piping systems in the US were installed in the early sixties. Since then, PE piping systems have enjoyed a consistently high satisfaction rating from water utilities. Chambers[1] first reported on the strong performance of PE piping materials in water service applications in 1984. The report was based on data from an American Water Works Association (AWWA) survey combined with telephone interviews, site visits and laboratory analysis. At the time of the survey, the utilities had been using PE pipe for as long as 20 years. Overall satisfaction with PE pipe was 95% (with the exclusion of pipe from one specific manufacturer). Thompson and Jenkins conducted an AWWARF sponsored survey entitled 'Review of Water Industry Plastic Pipe Practices'[2], published in 1987. The findings were similar to those reported by Chambers, with median satisfaction ratings of 85-90% for both PE and PVC. The most recent data found in the literature is that reported for the UK water industry as shown in Figure 1. Data compiled from the UK National Failure Database from 1995 to 2003 shows that PE pipe has the lowest failure rate of all water distribution piping materials. Similar experience was recently reported by the Aarhus Water Company in Denmark at the Plastics Pipes XIII conference in Washington, DC, in October of 2006. Once again, PE water pipe had the lowest failure rates of all materials in the Aarhus system[3].

In the decades since the installation of the first PE piping systems, there have been significant advances in polymer science and the resulting PE piping performance. The pressure carrying capabilities and forecasted long-term service lifetime have both increased significantly. This has been driven by a proactive approach by the industry to characterize, understand and increase system performance.

Figure 1: Performance of PE pipes and other pipe materials in the UK[4]



Despite the successful history and advances in material performance, some have questioned the long-term resistance of PE pipe to chlorinated potable water. This question has been fuelled by competitive interests and recently reported failures in Europe (where a combination of factors led to very aggressive service conditions). The successful history of PE pipe in potable water applications seems to be at odds with the reported failures and competitive attacks. The question arises: What is the true performance of PE pipe in potable water applications and can that performance be validated and predicted for given applications?

The successful history of PE water piping in Europe[3,5,6] and North America[1,2,3] provides some substantiation of PE's performance in potable water applications. However, looking to the performance of existing PE systems to predict the performance of the newer improved materials, would provide only a conservative estimate of minimum performance. With the enhancements made to materials, formulations and manufacturing methods, the performance of current generation systems would be expected to be much higher than the original PE installations.

In order to demonstrate and validate the long-term performance of PE piping systems in potable water applications based on lab-generated data, the PE piping industry has been proactively working to develop accelerated methodologies through the last decade. Jana Laboratories Inc. has led several worldwide studies examining the impact of potable water on piping systems and has issued numerous publications charting the progress in this area by detailing the mechanisms involved[7], developing aggressive accelerated testing approaches[8] and validating the developed methodologies[9,10]. This report provides a summary of the current state of those efforts, reporting on a methodology to project long-term performance of PE piping materials in potable water applications, the validation of that methodology and the resulting performance projections based on the currently available data.

The model developed shows that specific performance is a function of the water quality, water temperature and operating stress. All of these parameters vary by the specific utility. For the case study utilities examined, the current models project that high performance PE piping materials can very conservatively provide greater than 100 years resistance to chlorine and chloramines treated potable water.

Determining the Engineering Properties of PE Piping Materials

The plastic piping industry has been very proactive in developing methodologies to define the long-term performance properties of plastic piping materials in engineering terms. Since the 1950s the industry has worked at developing and refining the methodologies for projecting long-term performance[11,12], culminating in the standards and approaches utilized today. Throughout this development, material performance, particularly for PE piping materials, has also advanced significantly. Through the combined evolution of assessment and validation methodologies and material performance, the performance envelope for plastic piping materials has continually grown.

In validating long-term performance, plastic piping materials such as polyvinyl chloride (PVC), polypropylene (PP) and PE are typically tested under accelerated conditions in order to define a performance envelope. With the application of design factors to this performance envelope, a safe design window for the specific application is defined. Typically three different regimes: Stage I, Stage II and Stage III, are distinguished in defining the performance envelope as shown in Figure 2 and discussed below.

Stage I

Stage I is the Ductile-Mechanical regime. The mechanism observed in this regime is the long-term viscoelastic creep common to all plastics. ASTM D2837 *Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products* provides the methodology utilized in the US for determining the long-term performance of plastic piping materials. The development of this methodology was initiated in 1958 with the establishment of the 'Working Stress Committee' of the Thermoplastics Pipe Division of the Society of the Plastics Industry and culminated in the initial development of the standard in 1969. Potable water materials in the US, such as PVC, PEX and PE, have their pressure ratings, as determined by ASTM D2837, listed by the Plastics Pipe Institute (PPI)[13,14]. Recently, results were reported for a PE piping material that had physically been on test for over 50 years, which provided good long-term substantiation of this general methodology[15]. It is worth pointing out that the ductile failure mode is not observed in the field because the design stress for a PE pipe is well below its yield strength.

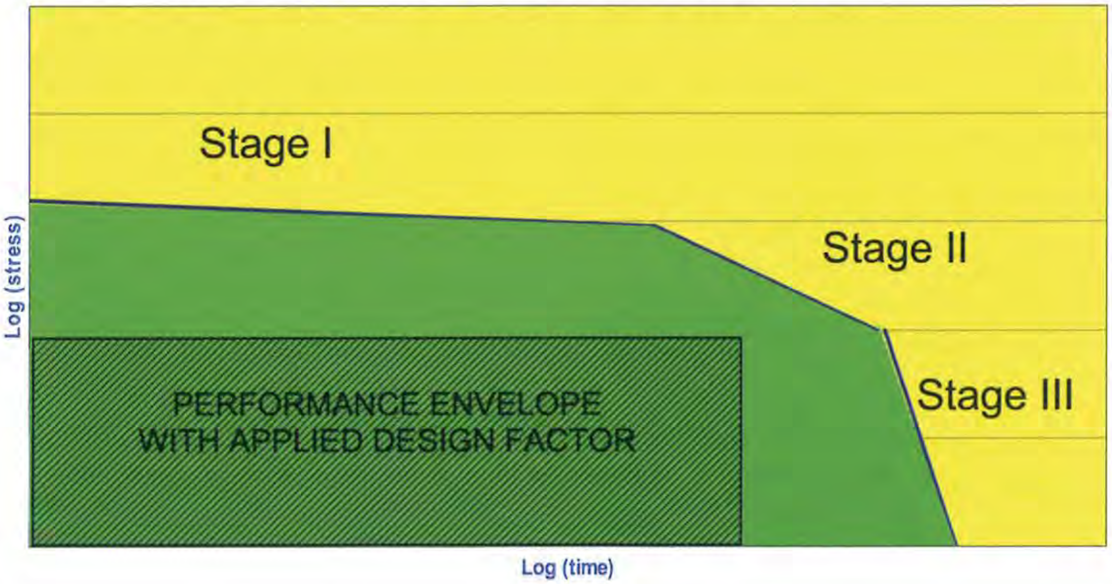
Stage II

Stage II is the Brittle-Mechanical regime. Methodologies for verifying that this regime will not be observed in service are also included in ASTM D2837. An accelerated method to measure the performance in the Brittle-Mechanical regime was developed and became an ASTM standard, F1473, in 1995 (known as the PENT test). As an example of the improvement in the performance of PE pipes over recent decades, the first PE gas pipe had a standard PENT value of approximately 1.5 hours. Today the minimum PENT requirement for a modern PE 4710 material is 500 hours, representing more than 300-fold improvement.

Stage III

Stage III is the Brittle-Oxidative regime. In this regime a material's resistance to oxidation is determined. The oxidative process can take many hundreds, even thousands, of years to occur. Therefore, developing validated methodologies to project Stage III performance based on shorter term testing is challenging. The oxidative process is also highly dependent on the specific environment. For potable water applications the primary variables are: water quality, water temperature and operating pressure. These variables need to be addressed in a successful methodology. The PE pipe industry has been proactively working to develop long-term validation methodologies for the Stage III regime specific to potable water applications through the last decade. The methodology developed is presented in this paper.

Figure 2: Defining the Performance Envelope of Plastic Piping Materials



Research Objectives

PPI proactively initiated a research project to review the state-of-the-art research on the factors that determine Stage III performance and develop a methodology that would be capable of validating long-term Stage III performance of PE pipe in potable water applications. The necessary features for the methodology were: 1. the methodology could be validated as providing realistic projections of performance, 2. the methodology had the ability to validate performance across the full range of end-use conditions, and 3. the methodology could validate the performance in a practical timeframe.

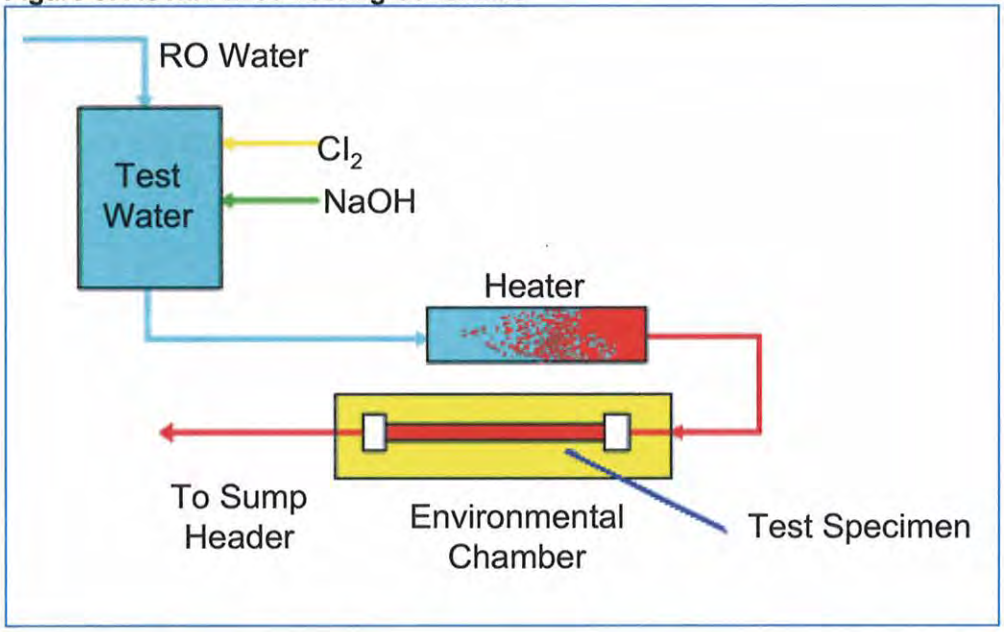
Methodology

To project field performance based on accelerated laboratory testing, three key criteria need to be met: First, the mechanisms observed in laboratory testing must be the same as those anticipated/observed in the field; Second, laboratory testing must be achievable in a practical timeframe and; Third, the approach must provide the ability for predictive extrapolations to end use conditions.

Numerous methodologies have been reported on for assessing the progression of field aging in the brittle-oxidative regime of plastic piping systems such as Oxidation Induction Time (OIT) analysis of stabilizers[16,17,18], Fourier Transform Infrared analysis of carbonyl concentrations[19], and other methods. These approaches, however, focus only on characterization of the progression of the mechanisms, and do not provide any guidance on the forecasted lifetime or the predicted remaining lifetime. The methodology developed in this study provides a significant advancement over these approaches in that it provides a means of forecasting specific pipe performance as a function of specific water quality, water temperature and system operating stress based on accelerated testing of actual pipe specimens to their ultimate performance lifetime.

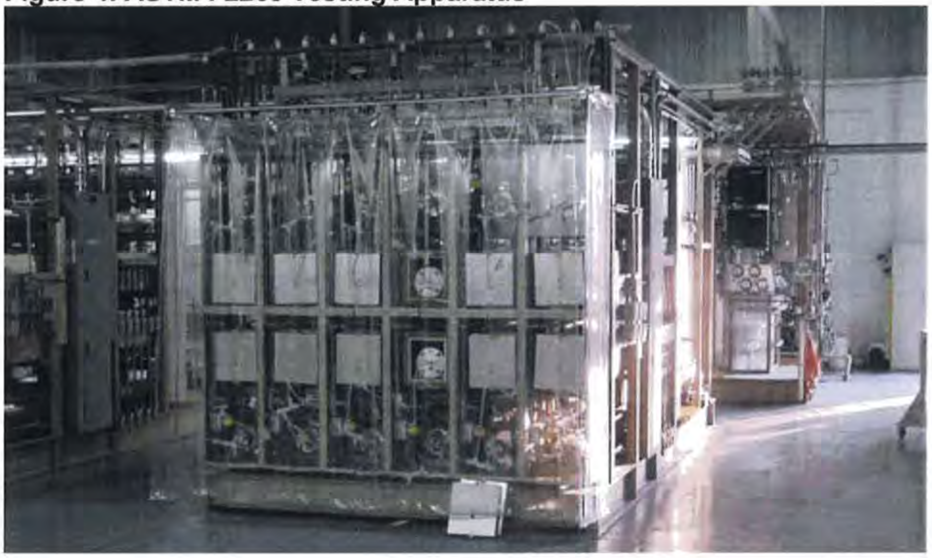
The methodology is based on that developed and successfully applied by Jana through the past decade for assessing the performance of engineering plastic materials in hot potable water applications. The basis for the testing is ASTM F2263 *Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water*[20]. This method involves accelerated testing at a specific water quality, multiple elevated temperatures and pressures and modeling the data using the Rate Process Method (RPM)[21]. Testing is conducted on materials in pipe form with internal pressurization and a continuous flow of controlled water quality. A schematic representation of the process is shown in Figure 3. The test apparatus is shown in Figure 4.

Figure 3: ASTM F2263 Testing Schematic



Conducting ASTM F2263 testing at multiple water qualities and modeling the impact of water quality enables the development of a model capable of predicting long-term performance of a specific PE pipe compound as a function of water quality, temperature and stress. The impact of water quality is modeled based on the Oxidation Reduction Potential (ORP). This is a measure of the overall oxidizing strength of the water and is primarily a function of the disinfectant (chlorine) level and the pH. A linear relationship between log (failure time) and ORP is utilized for the model[8,16].

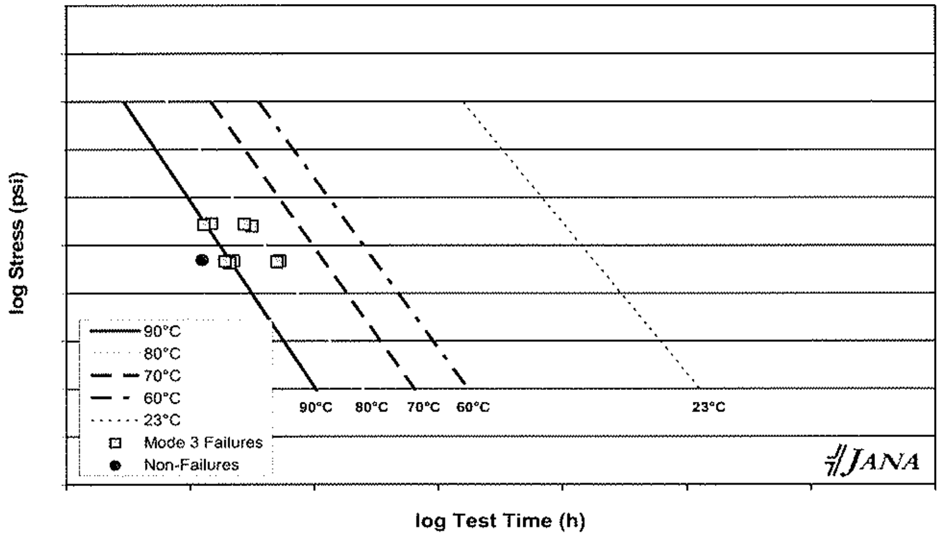
Figure 4: ASTM F2263 Testing Apparatus



The model was validated based on: consistency of the mechanisms observed in accelerated laboratory testing and field aging, fit of the laboratory data to the model, and comparison of the model predictions to observed field performance[7,8,9,10,22].

An example dataset is shown in Figure 5. As seen in the figure, the fit of the experimental data to the Rate Process Model is excellent. The testing is in progress and the data are, therefore, preliminary. A conservative approach has, therefore, been taken in discussions around the specific projections.

Figure 5: Data Set A: PE Pipe Rate Process Modelling



Case Studies

General operating data was obtained from four water utilities distributed throughout the United States (California, North Carolina, Florida and Indiana). This data was used in conjunction with the models developed to project performance at their specific operating conditions. As the model projections are specific to the operating conditions of these specific utilities, an analysis was also conducted for a model average utility. To simplify the analysis, the calculations were based on size DR11 piping and the results were not scaled for pipe size. This is a conservative approach as testing was conducted on small diameter tubing, which would be considered a 'worst case' size. Two separate datasets were analyzed for the high-performance materials and the average of the results is presented. Because the testing is in progress, extrapolations beyond one hundred years are conservatively represented as >100 years. For all of the case studies presented the extrapolations are in fact, considerably greater than 100 years.

Case Study 1 – Indiana

The water utility in Indiana services over 1 million people. Their standard operating conditions and the model projections based on these operating conditions are provided in Table 1.

The performance projections are well in excess of 100 years. This shows that, under the operating conditions of this utility, PE piping systems are projected to provide excellent service performance.

Table 1: Summary of Standard Operating Conditions and Projected Performance by Utility

Utility Operating Variable	Indiana	Florida	North Carolina	CPAU (California)	Average US Utility
Average Disinfectant Residual (ppm)	1.6	1.4	0.9	1.9	-
Average pH	7.7	9.3	8.6	9.0	-
Estimated ORP (mV)[*]	650	650	680	650	650
Average Water Temperature (°F)	57	79	68	61	57
(°C)	14[a]	26	20[b]	16	14[c]
Average Operating Pressure (psig)	70	70	70	65	70
Projected Performance in the Brittle Oxidative Regime (y)	>100	>100	>100	>100	>100

[*] Estimated value based on disinfectant residual, pH and disinfectant type.

[a] Average value. Water temperature ranges from 1 to 29°C.

[b] Average value. Water temperature ranges from 13 to 28°C.

[c] Average value. Water temperature ranges from 3 to 29°C.

Case Study 2 – Florida

The water utility in Florida services over 2 million people. Their standard operating conditions and the model projections based on these operating conditions are provided in Table 1.

Performance is projected to be in excess of 100 years, indicating that PE piping systems will provide excellent service performance under these conditions.

Case Study 3 – North Carolina

The water utility in North Carolina services over 700,000 people. Their standard operating conditions and the model projections based on these operating conditions are provided in Table 1.

Performance is again projected to be in excess of 100 years, indicating that PE piping systems will provide excellent service performance under these conditions.

Case Study 4 – City of Palo Alto Utilities (CPAU), California

The CPAU services 60,000 people in the Palo Alto area. Their standard operating conditions and the model projections based on these operating conditions are provided in Table 1.

The performance projections are well in excess of 100 years, indicating that PE piping systems will provide excellent service performance under these conditions.

Case Study 5 – Average US Water Utility

Case Study 5 examined an average water utility. The operating conditions presented in Table 1 were selected as representative of an average US utility based on an analysis of the 'AWWA Water Stats: The Water Utility Database'[23] and other literature and internet sources. The model projections based on these operating conditions are also provided in Table 1.

The performance projections for the Stage III regime are well beyond 100 years, indicating that at typical average water quality conditions, high performance PE piping systems are projected to provide excellent service performance. This data is in alignment with the successful PE water piping service history of over 40 years.

Conclusions

Considerable research has been undertaken to develop a methodology for validating the long-term performance of PE piping materials in potable water applications. The result is a validation methodology that is able to project PE pipe performance based on specific water quality, operating temperature and operating pressure. The methodology has been shown to provide a good fit to experimental data and model performance in the field.

Case Studies for four utilities and a modeled average utility show that greater than 100 years performance is projected for higher performance PE 3408 and PE 4710 materials. In fact, performance in the Stage III regime is projected well beyond 100 years, indicating excellent projected performance for water piping applications.

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