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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.

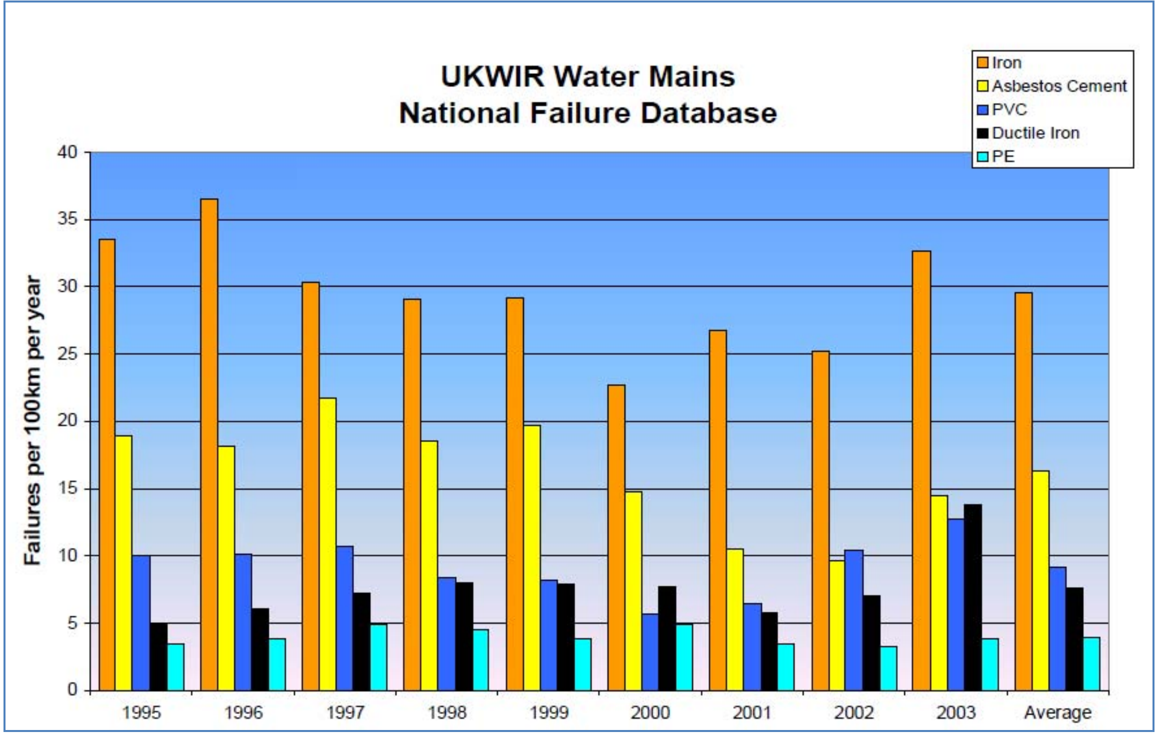
Introduction

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.

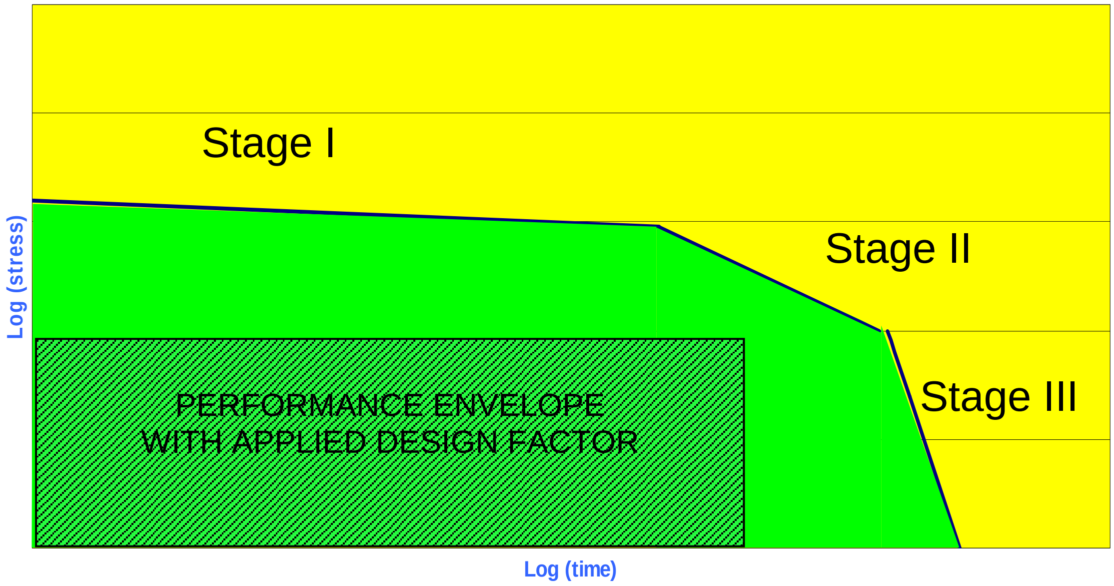
Stage II

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.

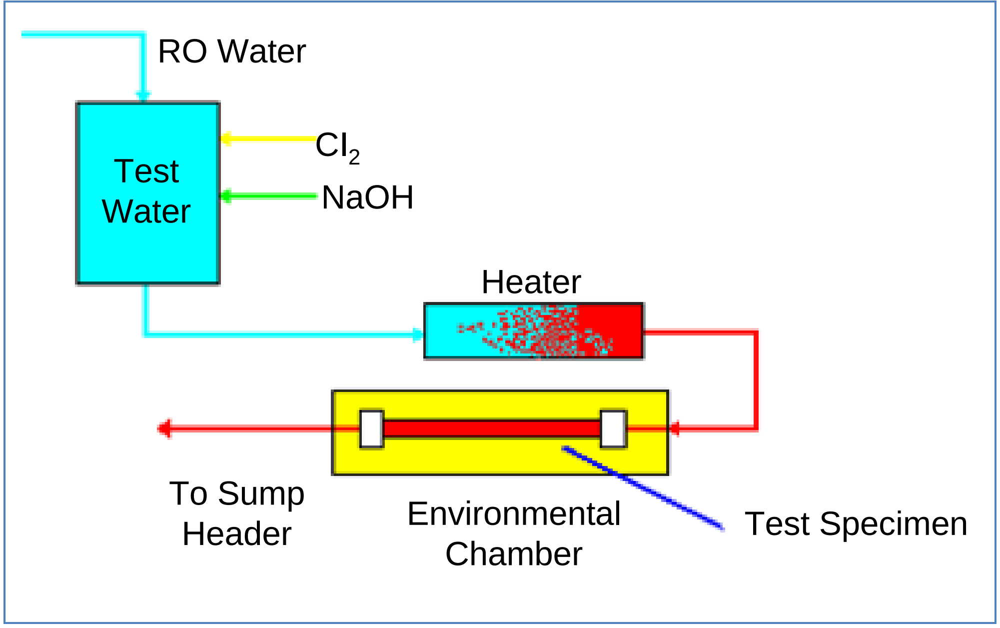
Methodology

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.

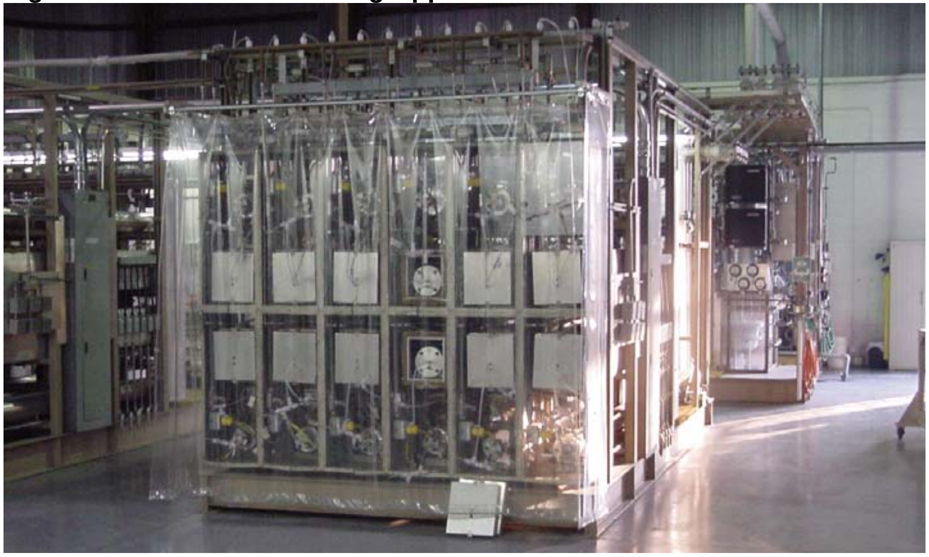
The methodology is based on that developed and successfully applied by Jana through the past decade for assessing the performance of engineering plastic materials in hot potable water applications. The basis for the testing is ASTM F2263 *Standard Test Method for Evaluating the Oxidative Resistance of 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].

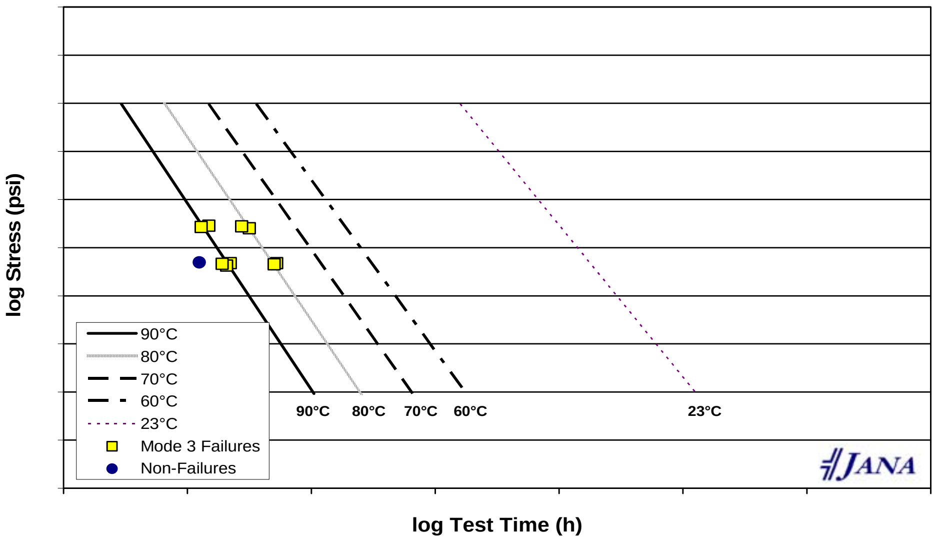
Figure 4: ASTM F2263 Testing Apparatus



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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