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TECHNICAL REPORT

POLYETHYLENE (PE) PIPE PERFORMANCE IN POTABLE WATER DISTRIBUTION SYSTEMS

PAST, PRESENT AND FUTURE

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Polyethylene (PE) Pipe Performance in Potable Water Distribution Systems
Past, Present and Future

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Abstract

The performance history of PE piping systems, from their first installation over 50 years ago through to the projected performance of current generation materials, is examined based on field performance data and model projections. High satisfaction ratings are reported by utilities for PE piping in both mains and service lines for materials installed through the last 30 years. It is also seen that, since the early PE materials, there has been a significant evolution in pipe performance. The development of a performance forecasting model and its use in projecting PE pipe performance is compared versus actual field performance from an extensive survey of water utilities. Exhumed from service current generation HDPE pipe materials are also characterized and assessed for residual lifetime. The results project that the pipes examined will perform well beyond another 100 years at their current operating conditions.

Introduction

There has been a significant evolution in the performance properties of PE piping since their first introduction to potable water piping systems in the US over 50 years ago. Advances in base materials, additives and pipe extrusion have all made the materials of today very different than those of a half century ago. A comprehensive study was undertaken to develop methodologies for projecting long-term performance of PE pipe in potable water applications in order to examine how this evolution has impacted performance and to provide a sound basis for validating the performance of the current generation materials going into the ground today.

Several connected research programs were undertaken to develop a model capable of estimating performance across the full range of end-use conditions and to validate that model to ensure it provides realistic field performance projections. The first of these programs resulted in the development of a standardized accelerated test methodology (ASTM F2263 *Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water*)[1]. Upon the development of this methodology, a second set of research projects was undertaken to conduct long-term testing to generate data for modeling. Under this project, over 200 PE pipe specimens were tested and examined in detail, with some specimens remaining on test for periods approaching two years. A third research project was concurrently undertaken to collect exhumed PE pipe samples from a wide variety of water distribution installations and examine them so as to compare the observed long-term field aging mechanism to that of the accelerated laboratory specimens. Over 300 PE pipe field samples were collected and analyzed, confirming that the test methodology, as developed, generated the same long-term aging mechanisms as observed in the field[2]. A fourth project was then undertaken to obtain actual utility historical field performance data through telephone interviews with over 200 US water utilities regarding their experience with HDPE pipe. The completion of this project has resulted in the development of a validated methodology capable of replicating the long-term aging mechanism in service that can project and validate HDPE pipe performance.

A detailed discussion of the long-term aging mechanisms and the methodology developed for projecting long-term performance has been presented previously[3,4]. This report provides an overview of the overall research program, examining both the actual observed field performance and the predicted performance of PE materials for pipe systems spanning almost the entire 50 year history of PE in potable water. It is seen that there has indeed been considerable evolution in PE pipe performance, that the methodology developed to project performance does indeed project performance that is consistent with past performance of older generation PE materials, and that use of the performance validation methodology provides the ability to realize a future with leak-free water distribution pipelines that exceed their designed service life. It is also seen that utility satisfaction with PE mains and PE service lines installed through the last 20 years are exceptionally good (95% and 93%, respectively).

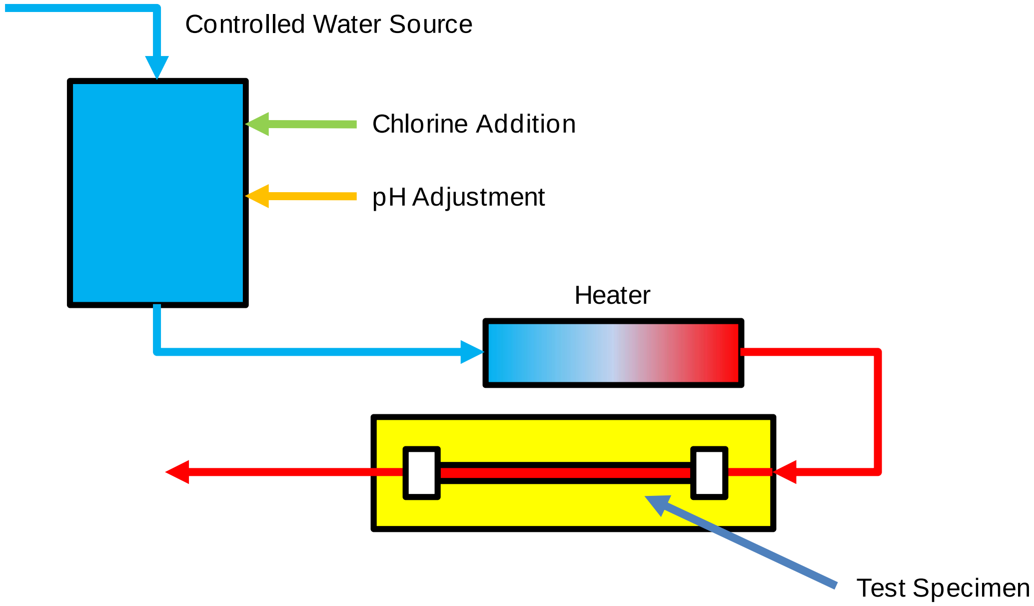
The accelerated aging and performance modeling approach is described briefly followed by a discussion of the observed field performance based on utility phone surveys. The modeling approach for past and current generation materials is then compared with the observed field survey results to create a clear picture of the evolution observed in PE pipe performance. The methodology is then applied to exhumed from service current generation piping where excellent long-term performance is projected in the application.

Modeling PE Pipe Performance

As reported previously, a methodology for predicting and validating the long-term performance of PE piping materials in potable water applications has been recently developed[3,4]. The methodology is based on modeling the long-term aging mechanisms observed in the field through accelerated testing under laboratory conditions. With this methodology, it is now possible to forecast and ensure long-term performance of greater than 50 or 100 years before the pipe goes into the ground[3,4].

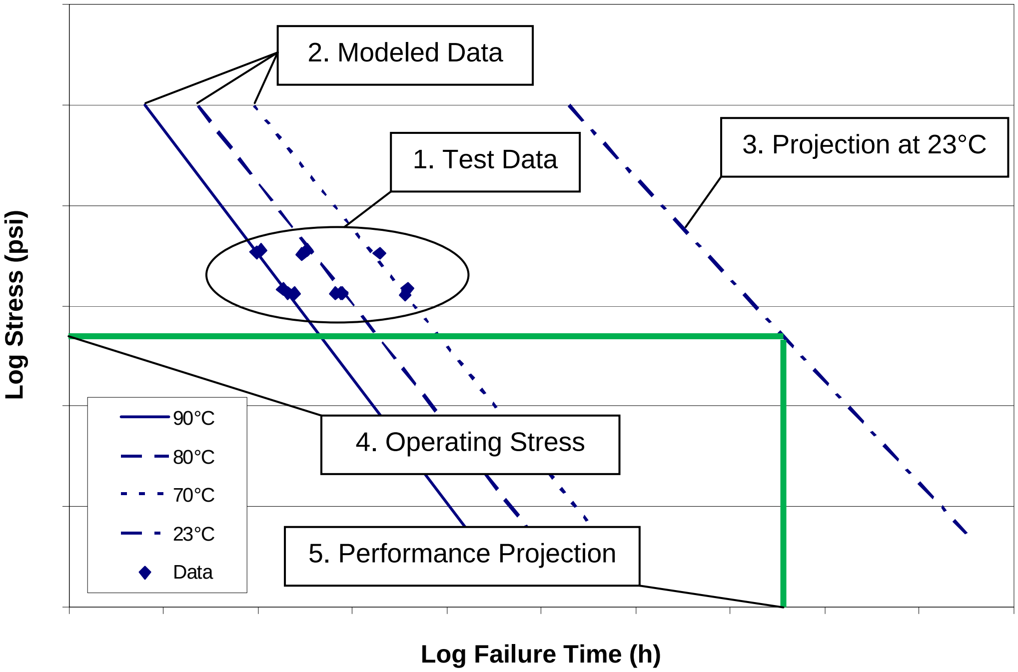
Figure 1 provides a schematic representation of the accelerated testing approach. Actual pipe specimens are exposed to a stream of continuously flowing chlorinated water at elevated temperatures. The flowing chlorinated water provides for exposure to a controlled, aggressive, oxidative environment that conservatively covers the full range of chlorination approaches in potable water applications (testing is conducted with 4.2 +/- 2 ppm chlorine). The elevated temperature accelerates the long-term aging mechanism so that testing representative of field aging can be conducted in the laboratory in a reasonable timeframe (typically < 2 years of continuous accelerated exposure).

Figure 1: Schematic Representation of Accelerated Testing Approach for Validation of PE Pipe



Through developing a model based on the resulting data and inputting a utility's operating conditions, performance projections specific to the utility can be made. **Figure 2** shows a typical dataset with the test data points, modeled performance and projections at end-use conditions. The test data is developed through accelerated testing (Step 1) and fit to the Rate Process Model (RPM) (Step 2). This model is then used to project performance at the end-use temperature (Step 3). From the actual end-use operating stress (Step 4), the projected long-term aging performance of the PE pipe material can then be projected (Step 5) for the specific water quality for which the testing was conducted (additional models were developed to be able to shift data generated at the very aggressive test water quality to the much less aggressive conditions typically found in actual end-use applications).

Figure 2: Projecting Long-Term Aging of PE Pipe in Potable Water Applications



Using this approach, models have been developed for multiple and different PE pipe materials and for both current and past generation PE materials. The results of this modeling are presented, in conjunction with actual field performance data from utility surveys, in the sections that follow.

Survey of PE Pipe Field Performance

The first PE pipe materials were installed in potable water applications in the early 1960s. Surveys of the performance of these past generation PE materials were conducted in the 1980s. While there have been some performance reports since the 1980s[8-10], there has not been any recent comprehensive study of US water utility experience with the PE piping in their potable water distribution systems. To obtain more current field performance data, an extensive phone survey of utilities was conducted. Roughly 300 water utilities experienced with PE water service lines and 60 utilities experienced with PE water mains were identified to serve as the basis for the survey. A total of 208 utilities with PE service line experience and 38 utilities with PE main experience responded to the survey. A follow-up survey was conducted with 63 of these utilities to gain further insight into their PE usage. This section provides a summary of the past studies along with an overview of the 2010 Survey. The detailed survey findings are discussed in subsequent sections.

Past Studies

Chambers[8] first reported on the performance of early generation 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 manufacturer). Thompson and Jenkins conducted an AWWA Research Foundation sponsored survey entitled 'Review of Water Industry Plastic Pipe Practices'[9], published in 1987. The findings were similar to those reported by Chambers, with median satisfaction ratings of 85 to 90% for both PE and polyvinyl chloride (PVC). More recent data has been reported for the UK water industry (where PE pipe usage rates are currently at 85%) showing that PE pipe has the lowest failure rate of all water distribution piping materials. Similar experience was recently reported by the Arhus Water Company in Denmark at the Plastics Pipes XIII conference in Washington, DC, in October of 2006, again showing PE water pipe to have the lowest failure rates of all materials in their system[7].

While the overall satisfaction with PE piping was high, there were reported issues with the performance of pipe from specific manufacturers (Yardley and Orangeburg)[8-10]. There were also other reported failures of these early generation materials that occurred more frequently in areas with higher water temperatures[8]; the pipe samples examined at the time demonstrated depletion of the stabilizers (added to the pipe for long-term protection against oxidative aging) at the inner pipe surfaces. These reports are consistent with the primary (Mode 3) long-term aging mechanism of PE pipe in potable water that has since been identified[3-5]. At the time, however, the long-term aging mechanisms of PE pipe in these applications were not well characterized and the authors of the studies were not able to clearly identify the true cause of the performance issues for these earliest generation materials.

2010 Study: Survey of Utility Experience with PE Pipe in US Potable Water Distribution

The 2010 survey details are presented in **Table 1** along with the details of past surveys. The 2010 survey is the most comprehensive phone survey of PE users conducted to date.

The utilities surveyed serviced a total of approximately 21 million people, or 7% of the US population. The size of the utilities responding to the survey ranged from utilities servicing 13,000 people to 4.3 million people with an average and median of 450,000 and 150,000, respectively. The geographic distribution of the utilities responding to the survey is shown in **Figure 3**. The percentage of the overall respondents that were from each of US geographic regions is shown in overlay. Overall, the utilities responding provide a good statistical sampling and a broad representation of PE pipe users.

The respondent utilities also cover the full breadth of PE pipe evolution. The distribution of utilities by date of first installation of PE service lines is shown in **Figure 4**, with the date of first installation ranging from the 1960s to the 2000s. The same information is provided for PE mains in **Figure 5**, where the utilities surveyed have installed PE pipe over the last 20 years.

Table 1: Details of Surveys

Survey	2010		Chambers (1984)[8]				Thompson and Jenkins (1987)[9]		AWWARF (1992)[10]
	Initial	Follow Up	Initial	Follow Up	Interview	Field Visit	Initial	Interview	
Contact Method	Phone	Phone	Mail	Mail	Phone	In Person	Mail	Phone	Phone
Utilities Contacted	250	134	3,546	431	23	8	3,000	16	31
Surveys Completed	210	64	1,119	165	23	8	404	16	31
Hit Rate (%)	84	48	32	40	100	100	13	100	100
Percentage of PE Users	99	98	39	100	100	100	41	100	100
PE Utilities Contacted	209	63	431	165	23	8	165	16	31

Figure 3: Geographic Distribution of Respondent Utilities to 2010 Survey: Percentage of State Population Served by Surveyed Utilities

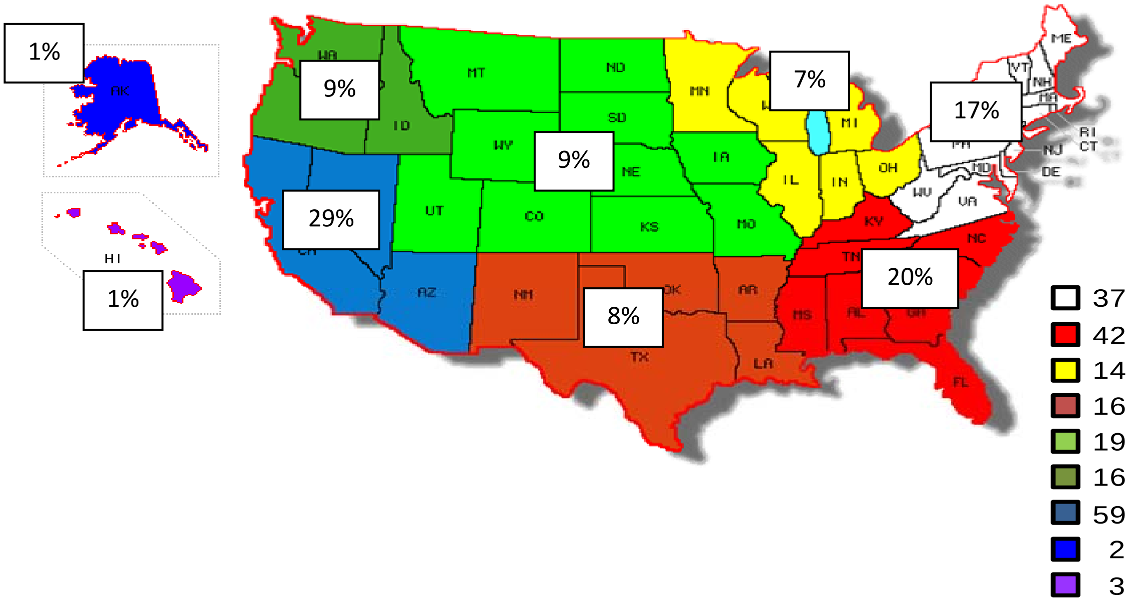


Figure 4: Distribution of Utilities by Date of Reported First Installation of PE Service Lines

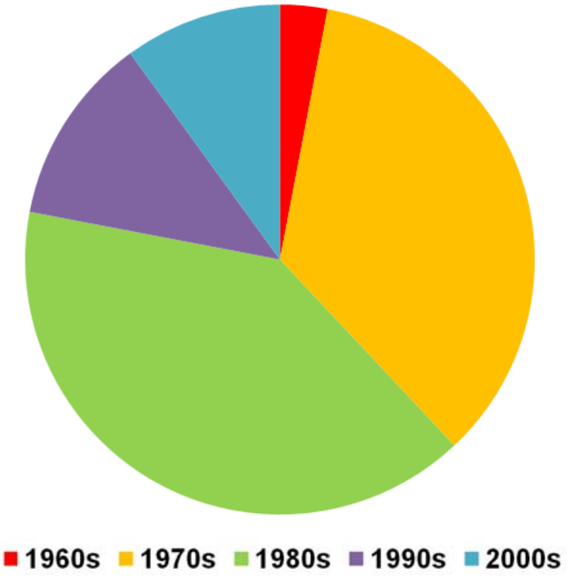
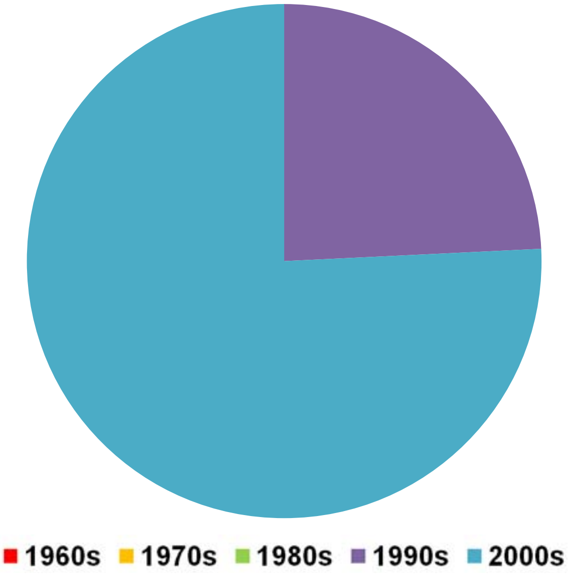


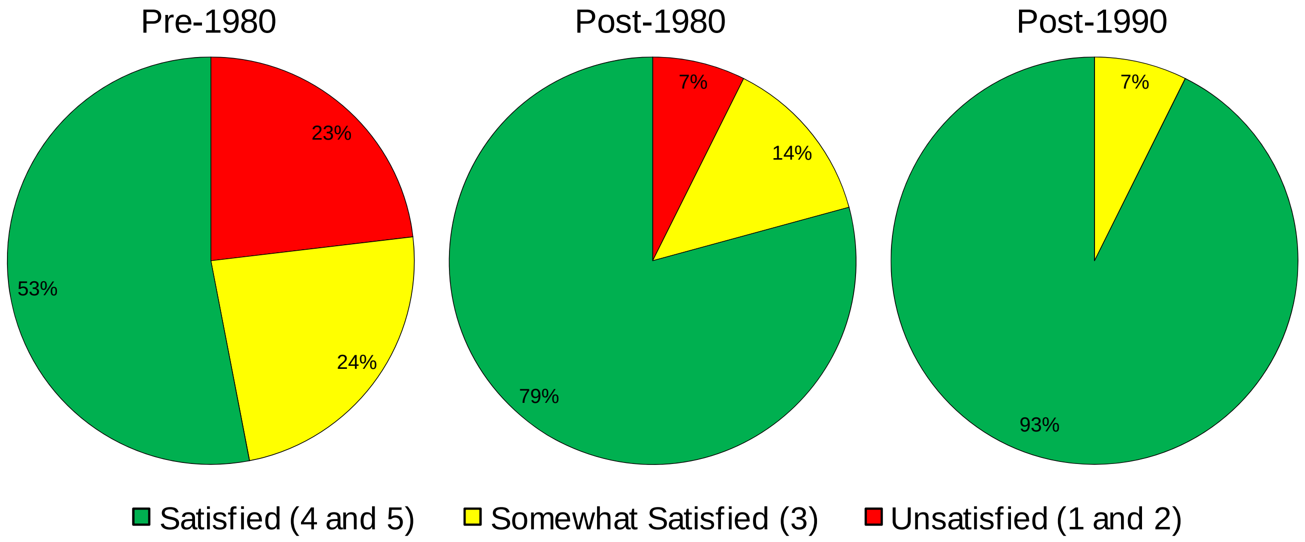
Figure 5: Distribution of Utilities by Date of Reported First Installation of PE Mains



Utility Rating of PE Performance

One of the key survey questions asked to utilities was: "On a scale of 1 to 5, with 1 being unsatisfied and 5 being very satisfied, how would you rate your experience with PE piping materials?". The results for first generation PE pipe (pre-1980 installations), mid-generation PE pipe (post-1980 installations) and recent generation PE pipe (post 1990 installations) are shown in **Figure 6**.

Figure 6: Comparison of Utility Satisfaction with PE Pipe by Generation

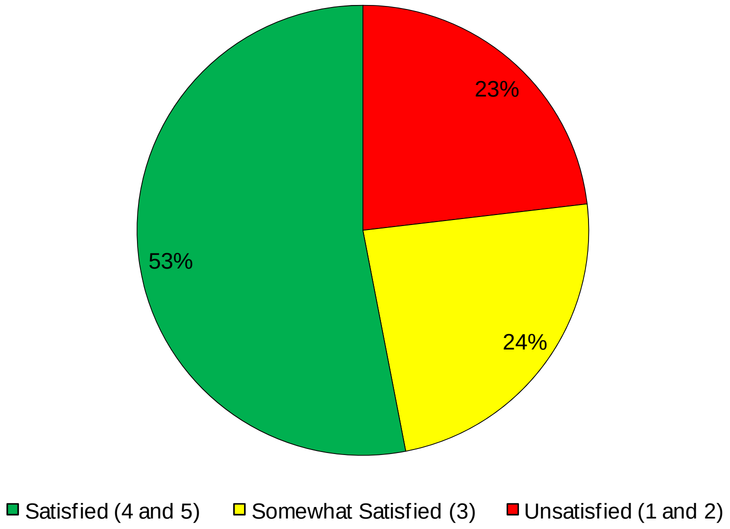


In looking back on the performance history of PE piping materials, an interesting story unfolds. Utility satisfaction ratings for mid-generation (post-1980 date of installation) PE materials are high (approximately 80%) and higher still for more recent generation PE materials (95% and 93% for mains and service lines, respectively). The satisfaction ratings fall significantly, however, for those utilities with a date of first installation pre-1980. The analysis that follows shows that this difference in satisfaction is primarily due not to the longer time in service for the earliest generation materials but to the significant evolution in performance of PE piping systems through the last half century.

The Early Days

Utility satisfaction with the earliest installations of small diameter PE service lines is seen to be noticeably different from that for later generations of PE materials. For materials with a date of first installation pre-1980, only 53% of utilities reported being satisfied or very satisfied (ratings of 4 or 5) with their PE service lines, 24% reported being somewhat satisfied (rating of 3) and 23% reported being unsatisfied, as shown in **Figure 7**.

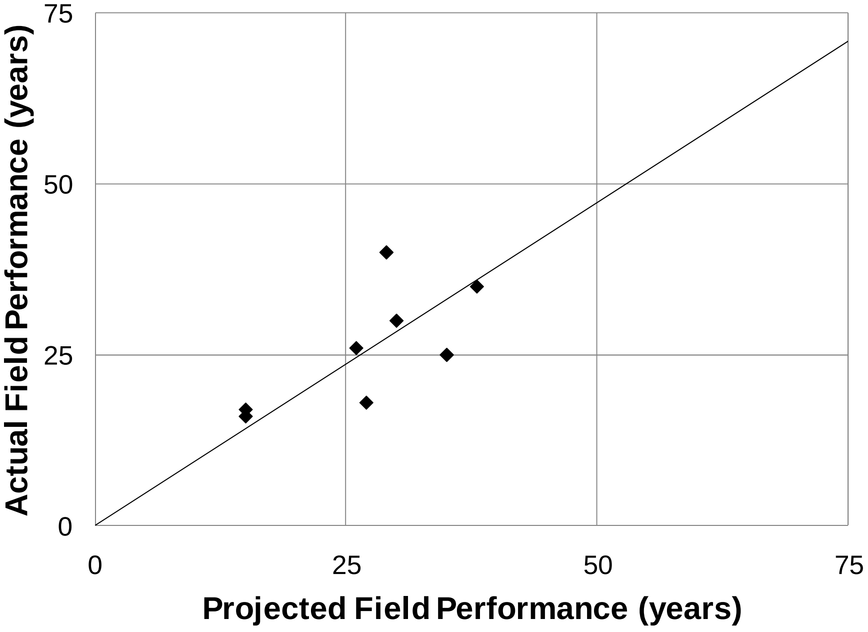
Figure 7: Utility Satisfaction Ratings for PE Service Lines – Pre-1980 Date of First Installation



Clearly the satisfaction with the oldest generation small diameter PE service lines is nowhere near what it is for current generation materials. Is this simply due to the age of the materials or is there a fundamental difference in material performance? To answer this question, performance models were developed for older generation PE service lines. These were coupled with the reported time in service where utilities saw a significant increase in leak frequency for utilities where all this information was available. The results are shown in **Figure 8**. Similar projections for the same utilities for current generation PE materials are provided in the section that follows.

Of the eight utilities examined, five of the eight are as aggressive as or more aggressive than Las Vegas Valley Water District, identified as one of the more aggressive areas in the US due to its desert-like conditions and the resultant high ground temperatures. Very good agreement is seen between the projected performance and actual field performance (the average time in service to a significant increase in leak frequency for the eight utilities was 26 years, with a model projection of 27 years), indicating that the model is capable of providing realistic projections of actual field performance. It is also observed that the performance of the earliest generation PE service lines in these aggressive applications is below the desired minimum of 50 to 100 years. As is seen in the next section, it is also well below the performance projected for current generation materials.

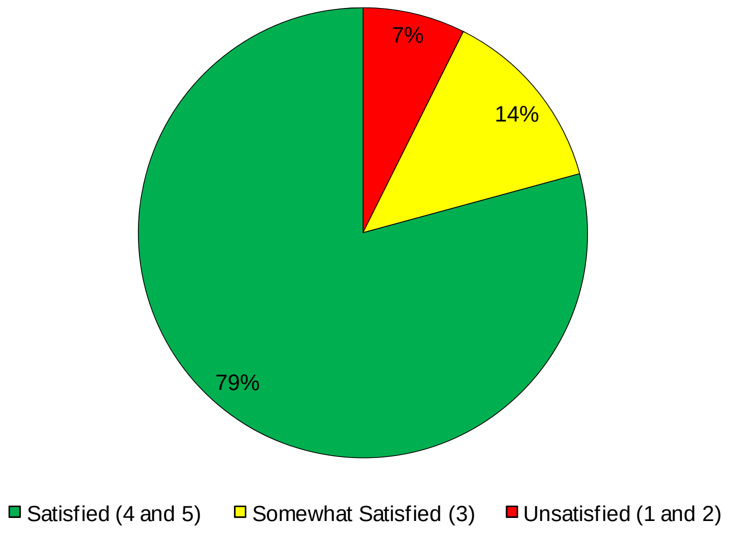
Figure 8: Comparison of Observed and Modeled Performance for Pre-1980 PE Pipe Materials



The Last 30 years

The results with a date of first installation of PE pipe through the last 30 years (post-1980) are summarized in **Figure 9**. Seventy-nine percent of utilities reported being satisfied or very satisfied (ratings of 4 or 5) with their PE service lines, 14% reported being somewhat satisfied (rating of 3) and 7% reported being unsatisfied.

Figure 9: Utility Satisfaction Ratings for PE Service Lines with Date of First Installation 1980 to Present



The Last 20 years

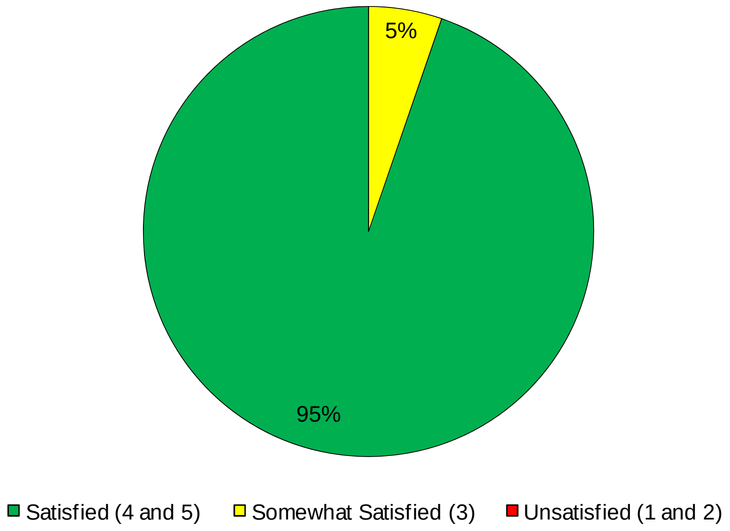
When we look back over the past 20 years, we can gain insight into the performance of PE pipe materials in both service lines and mains (utilities started installing PE pipe in mains predominately through the last 20 years), and, for both, utilities report very high levels of satisfaction.

PE Mains

The 38 utilities reporting on their PE mains usage responded to the same question on satisfaction rating (rate satisfaction with your PE mains on a scale of 1 to 5, with 5 being very satisfied and 1 being very unsatisfied). As shown previously in **Figure 5**, these utilities installed their PE mains through the last 20 years.

The reported satisfaction with PE mains was very high, with 95% of utilities reporting being satisfied or very satisfied (ratings of 4 or 5) with their PE mains and 5% reporting being somewhat satisfied (rating of 3), as shown in **Figure 10**.

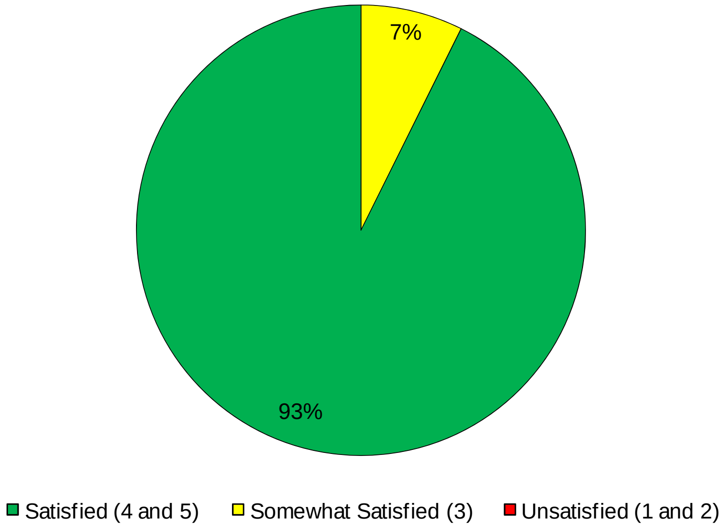
Figure 10: Utility Satisfaction Ratings for PE Mains



PE Service Lines

Similarly, the reported satisfaction with PE service lines for utilities with a date of first installation of 1990 to present was also very high, with 93% of utilities reporting being satisfied or very satisfied (ratings of 4 or 5) with their PE service lines and 7% reporting being somewhat satisfied (rating of 3), as shown in **Figure 11**. This is an increase in satisfaction for PE service lines relative to that presented for utilities with a date of first installation 1980 to present. This is explicitly addressed in the sections that follow.

Figure 11: Utility Satisfaction Ratings for PE Service Lines with Date of First Installation 1990 to Present



The Present – Continued Evolution

Since these earlier generation PE materials, there has been tremendous evolution in the long-term performance of PE pipe materials[11-17]. This performance evolution has significantly extended the performance envelope for PE pipe, as has been reported by many authors[11-16].

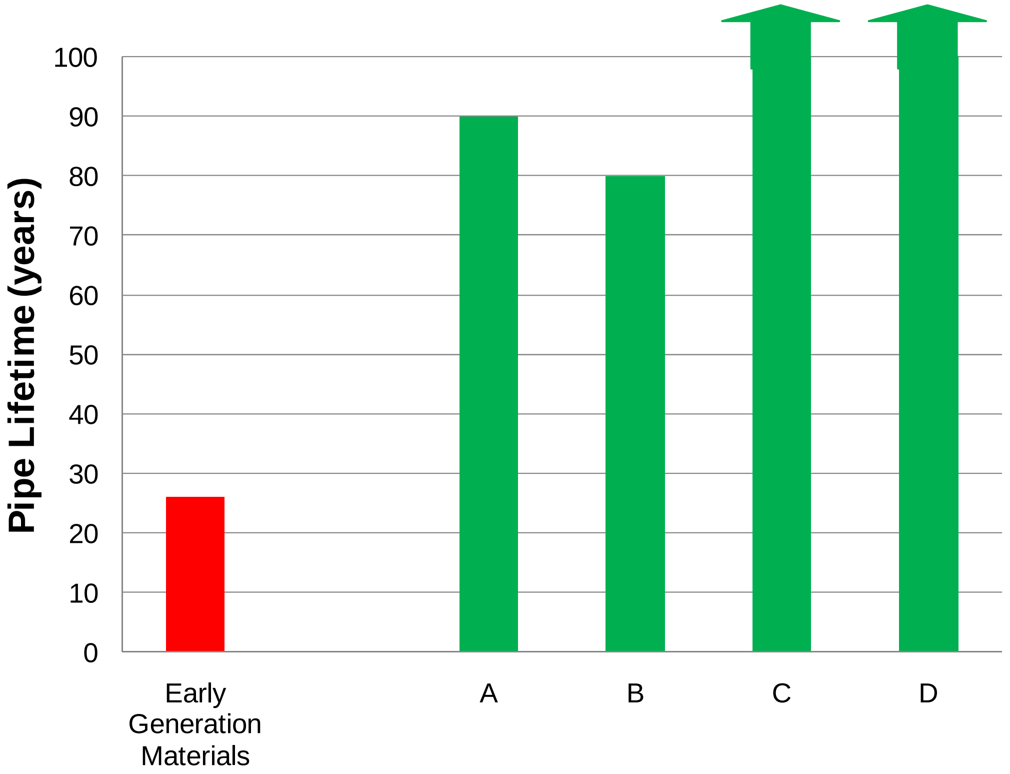
Given this evolution in PE pipe materials and the consequent evolution in performance, the question is raised: "What is the performance of current PE pipe materials?" To answer this question, the industry undertook a multi-year research program, initiated in 2007, to generate test data for making model predictions for current generation PE3608 and PE4710 materials. The resulting performance projections (as detailed below) show very good projected performance for the current generation of both PE3608 and PE4710 materials. To ensure that the model was applicable to current generation materials, the progression of the aging mechanisms in accelerated testing was studied on over 200 laboratory test specimens and compared to the observed field aging mechanisms of the over 300 field samples discussed above. The aging mechanisms of current generation PE materials, although occurring at a much slower pace than for past generation materials, are seen to be mechanistically identical to the field samples. In addition, current generation PE pipe materials installed within the last decade were exhumed, analyzed and subjected to accelerated laboratory testing. The results are seen to be consistent with the performance projection model and indicate greater than 100 years of residual lifetime under the current operating conditions.

Projecting Performance of Current Generation PE Materials

Testing of four current generation HDPE materials (including both PE3608 and PE4710) was conducted in general accordance with ASTM F2263 *Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water* and the data modeled as presented previously[1]. The resulting performance projection models were then used to forecast performance of these current generation PE materials at the specific conditions of those utilities for which field performance and projected performance of past generation materials was available (general performance projections and specific Case Studies for current generation materials have been presented previously[3,4]). The results are presented in **Figure 12**.

The projected performance of the current generation PE materials examined is seen to be significantly above that of both the past generation PE service line projections and actual observed field performance. All the current generation materials have average projected field performance greater than 50 years (the average for first generation (pre-1980) materials was 27 years). The data clearly show that significantly enhanced performance is projected for current generation materials relative to past generation materials and that current generation materials are projected to have good long-term performance even under aggressive end use conditions.

Figure 12: Comparison of Projected Performance for First Generation (pre-1980) and Current Generation PE Pipe Materials



Characterization of Exhumed Current Generation PE pipe

Current generation PE pipe materials installed in 2003 and 2005 were exhumed from service and characterized to ensure that long-term field aging for these materials has the same basic mechanisms as observed for past generation materials and in accelerated laboratory testing. The exhumed from service samples were also subjected to accelerated laboratory testing to enable projections of residual lifetime under the specific service conditions under which they are operating.

The results, presented below, confirm that the early stages of the long-term aging mechanism are the same as those observed in accelerated laboratory testing and for field specimens of older generation PE pipe. The exhumed pipe samples were also projected to have residual lifetimes well in excess of 100 years under the utility operating conditions in which the piping is installed, further confirming performance of current generation PE materials.

Test Program

The exhumed from service pipe specimens were 2" HDPE pipe installed in either 2003 (seven years service, 2" IPS SDR 11) or 2005 (five years service, 2" IPS SDR 11) from the same manufacturer, though produced at two different times. The specimens were analyzed to characterize the progression of the long-term aging mechanism through Oxidative Induction Time (OIT) measurements at the inner pipe bore, Fourier Transform Infra-Red (FTIR) at the inner pipe bore, and Bend-Back testing per AWWA C901. Specimens were also tested in general accordance with ASTM F2263 at 90°C, 450 psi hoop stress, 4.2 mg/L chlorine, a pH of 6.8 and Oxidation Reduction Potential (ORP) greater than 825 mV.

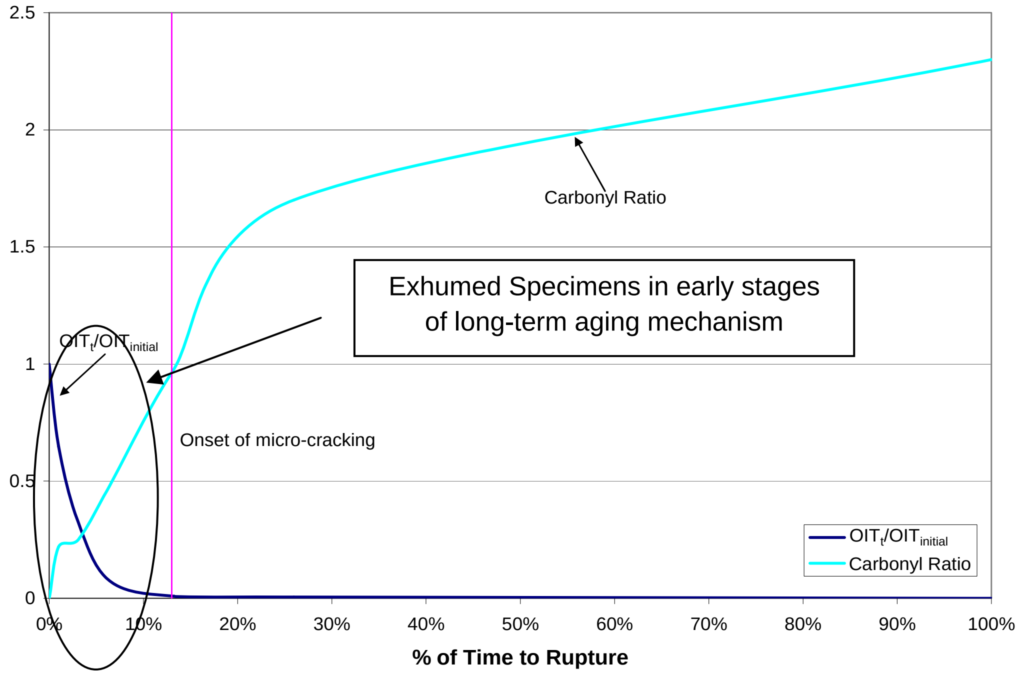
Observed Aging Mechanism in Current Generation Exhumed PE Pipe

The first stage in the long-term aging mechanism is a reduction of stabilizers at the inner pipe bore. An equilibrium condition is then established where stabilizers in the bulk of the pipe migrate to the inner pipe surface. The stabilizers are designed to function according to this mechanism. A common tool applied to examination of the process of stabilizer depletion at the inner bore is the Oxidative Induction Time (OIT) test[18-21]. This test indirectly measures the level of stabilization in the pipe material through measurement of the time for oxidation to occur at highly elevated temperatures (typically 190°C or 200°C) in a pure oxygen environment. While the methodology has its limitations[21], when these are considered the method can provide insight into the overall process of stabilizer depletion. There is also, at a certain point of stabilizer depletion at the inner pipe bore, the initiation of degradation of the inner pipe surface. The Carbonyl Ratio is a relative measure of the level of oxidation of PE materials. The Carbonyl Ratio is defined by the ratio of integrated area of the carbonyl band defined by approximately 1800 cm^{-1} and 1660 cm^{-1} over the area defined by approximately 1480 cm^{-1} and 1440 cm^{-1}. While the values should be examined on a qualitative basis rather than comparing actual values because of interferences from contaminants and additives in the polymer, higher Carbonyl Ratios generally indicate higher levels of oxidation. The Carbonyl Ratio is typically measured by performing micro Fourier Transform Infra-Red (FTIR) spectroscopy on the inner pipe bore. The Carbonyl Ratio has been successfully used to characterize the aging process of PE piping materials[5,7,22,23].

The long-term aging mechanism as characterized using OIT and FTIR has been presented by the authors previously[3,4]. **Figure 13** provides a typical long-term aging mechanism observed for laboratory exposed specimens. The OIT ratio, expressed as a percentage of the initial value, is seen to drop to a relatively low level at the inner bore early in the long-term aging mechanism. The onset of oxidation also occurs early in the long-term aging process, as shown by the Carbonyl Ratio. In general, the Carbonyl Ratio increases in the early phase of the aging process, reaches a plateau and then levels off[24,25]. The onset of the initial increase in the Carbonyl Ratio and the plateau regions is dependent on the pipe formulation and the end-use environment.

As will be seen in the analysis that follows, the exhumed from service specimens are in the early stages of the long-term aging mechanism (see **Figure 13**), as would be expected based on their time in service.

Figure 13: Overall Mode 3 Long-Term Aging Mechanism



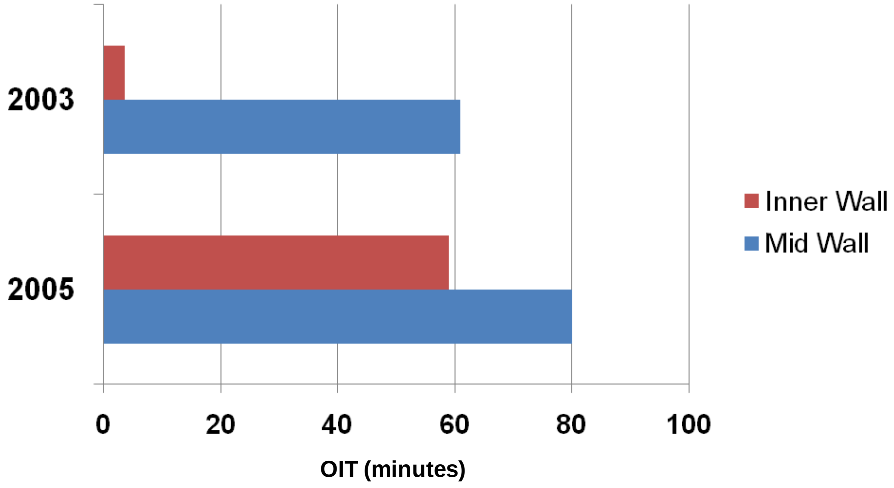
The OIT and Carbonyl Ratio for the exhumed pipe specimens are shown in **Table 4** with the OIT results shown graphically in **Figure 14**. For the 2005 specimen, the OIT at the inner wall is still high, indicating that this pipe is still in the very earliest phase of the overall aging process. For the 2003 sample, the equilibrium phase has initiated with a low inner wall OIT. The Carbonyl Ratio for both samples indicates that no detectable oxidation has occurred at the inner pipe wall of either sample.

Table 4: OIT and Carbonyl Ratio of Exhumed PE Pipe

Pipe Material	OIT		Carbonyl Ratio
	Mid Wall	Inner Surface	
2003	61	3.6	<0.03
2005	80	59	<0.03

Note: Samples removed from different sections of the same distribution system operating under similar conditions.

Figure 14: OIT Results for Exhumed From Service Current Generation PE Pipe Materials



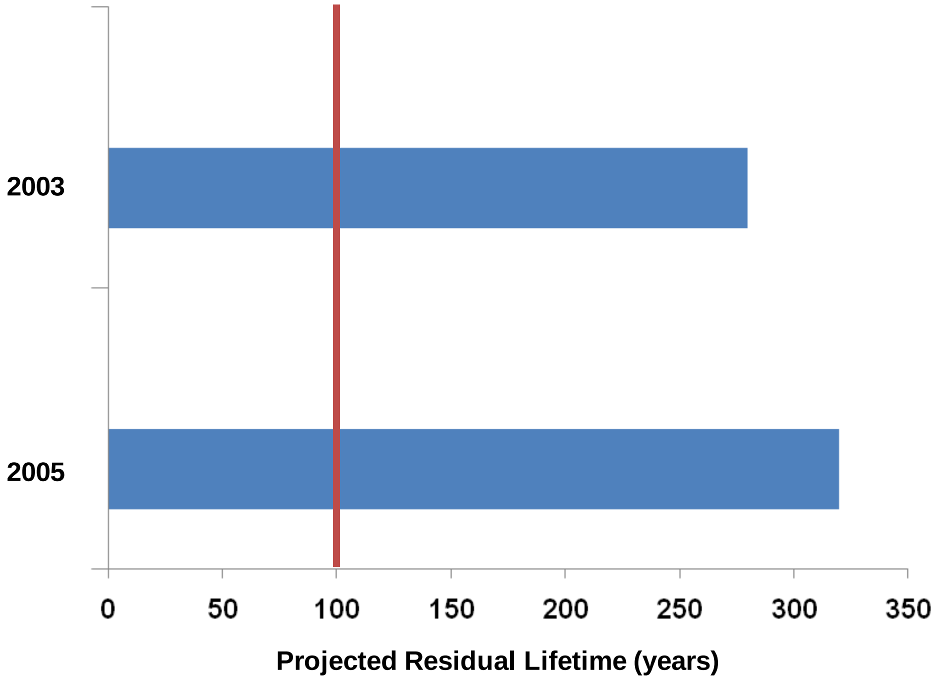
As it is not possible to tell exactly at which phase of the overall lifetime the pipe is at based simply on OIT and Carbonyl Ratio (or FTIR) analysis[3,4], accelerated laboratory testing of both the 2005 and 2003 exhumed pipe materials to ASTM F2263 was conducted to enable estimation of residual lifetime. Due to the limited sample of exhumed pipe available, testing was conducted at a single accelerated test condition and the results extrapolated to end-use conditions using shift functions developed specifically for the Mode 3 aging mechanism. The test results and projections are shown in **Table 5** with the projections shown graphically in **Figure 15**. The results were not adjusted for the lower average operating ORP (790 mV) of the utility in order to be conservative in the forecast. While the results should be considered directional only due to the limited test data, and specific projected numbers are not to be interpreted in any way as exact projections of residual lifetime, they indicate that both materials are projected to perform well beyond 100 years into the future at their current operating conditions.

Table 5: Accelerated Testing and Projection of Residual Lifetime for Exhumed PE Pipe

Pipe Material	Test Time (hrs)*	Estimated Residual Lifetime (years)**
2003	672	>100
2005	733	>100

* 90°C, 450 psi hoop stress nominal test stress (90 psig pressure)
** Based on 825 mV ORP, 100 psig pressure at utility operating water temperature

Figure 15: Projected Residual Lifetime of Exhumed from Service PE Pipe > 100 years



The Future – Leak-Free Pipelines?

With the development and validation of a methodology capable of projecting long-term performance of PE piping materials in potable water applications, the vision of leak-free potable water pipelines is now at hand. PE pipe materials have long provided leak-free operation in gas distribution pipelines, having a reliability record in that application significantly exceeding all other piping materials (steel, PVC, etc.)[26]. With the ability to now validate long-term performance in potable water applications through the performance forecasting methodology developed, it now becomes possible to design and verify potable water PE piping systems that will provide this same leak-free operation through their intended life.

This approach is already being undertaken by some utilities, such as the city of Palo Alto, CA[27]. The industry has also initiated several further projects to develop complete design tools and performance validation criteria based on the model presented in this paper.

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