

TECHNICAL REPORT

SERVICE LIFE EVALUATION OF POLYETHYLENE (PE) WATER PIPES



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Abstract

The question of remaining service life of in the ground piping systems is an important one for utility operators. For PE piping materials a number of different methodologies have been proposed to address this question. The industry-recommended approach is to utilize a recently developed methodology involving exhumation and testing of the pipe to ASTM F2263 and not a simple Oxidation Induction Time (OIT) or Carbonyl Ratio, as summarized below.

For PE piping systems, the primary aging mechanism in potable water applications is oxidation of the pipe by the disinfectants present in the potable water. Plastic pipe lifetimes are comprised of A, B, and C regimes corresponding to a precipitation period, a period of Fickien diffusion with chemical consumption of antioxidant, and a polymer degradation period. The duration of these regimes together constitutes the pipe service life. These processes are often measured through Oxidation Induction Time (OIT), to estimate stabilizer levels, and Carbonyl Ratio, to examine the on-set of material degradation. For actual pipes in service, a 95% reduction in the antioxidant levels at exposed surfaces (as determined by OIT) has been observed within the first 8% of the measured lifetime of PE pipe. In other words, pipe with 95% stabilizer depletion at the inner surface as measured by OIT still had 92% of its expected service life remaining. This represents the Regime B period. For Regime C, after an initial increase in oxidation products as measured by carbonyl ratio, there appears to be a plateau region of near constant carbonyl ratio that can extend for up to 80% of the overall pipe lifetime. Regimes B and C are also often observed to overlap. This means that pipes with low OITs and the presence of carbonyl groups (as measured by Carbonyl Ratio) at the inner pipe surface can still have 80% of their service life remaining. Therefore, simple use of either OIT or Carbonyl Ratio (or both together) as a direct indication of remaining service life is not possible and can be misleading.

Recently a methodology has been developed that provides a means of forecasting specific pipe performance as a function of water quality, water temperature and system operating stress based on accelerated testing of actual pipe specimens to their ultimate performance lifetime. This lifetime prediction method is equally applicable to new materials and piping exhumed after decades of service.

By exhuming in service piping, testing to ASTM F2263 and considering the utility's specific operating conditions, forecasts of residual pipe lifetime can be achieved. As the results are specific to the pipe materials exhumed, this testing is coupled with a system analysis and OIT and FTIR analyses to select the appropriate pipe for testing and to confirm applicability to the other pipeline sections. The system analysis provides direction on the areas of the system that would be considered most aggressive. The OIT and FTIR analyses provide confirmation of this assessment through ensuring the pipe is in the appropriate regime of the aging process. The overall result is a complete picture of residual lifetime for the pipeline operator.

As the methodology involves testing of actual pipe specimens removed from service, it provides a true and direct measure of residual lifetime. The current aging state of the pipeline is explicitly captured by the methodology.

Service Life Evaluation of Polyethylene (PE) Water Pipes

Plastic pipe has been one of the great engineering success stories of the last half-century. The corrosion resistance, durability, and installation and operating benefits of plastic piping systems have made plastic pipes the clear favorite for underground infrastructure applications such as natural gas distribution and municipal water distribution. The materials and manufacturing controls in these industries have developed to the point that today plastic pipes are expected to provide many decades of trouble free operation.

The excellent service life expectations for current plastic piping materials naturally lead to questions about the remaining service life of plastic piping materials that have been in service for 10, 20, 30 years or more. What can a system owner expect in the future? Will these pipes continue to perform well indefinitely? When may replacement begin to be indicated? These have long been important questions, and they become more important every year as management of underground assets becomes ever more critical and ever more challenging.

Effective methodologies are used by the plastics pipe industry to assure that current materials that are listed for pressure pipe applications will not experience either Stage I (ductile creep rupture) or Stage II (macroscopically brittle slow crack growth) failures indefinitely when the actual stress is maintained at or below the maximum recommended design stress. These methodologies are described in Plastics Pipe Institute Technical Reports TR-2¹ and TR-3². Materials that comply when tested are listed in PPI Technical Report TR-4³. ASTM Standard Test Methods are cited by the Technical Reports as the basis for obtaining the data needed to demonstrate performance.

More recently, methodologies have also been developed that allow for validation of Stage III (general oxidative resistance) performance.^{4,5,6,7} ASTM Standard Test Methods now exist for evaluating the Oxidative Resistance of polyethylene (PE) and crosslinked polyethylene (PEX) pipe to chlorinated water: ASTM F2023⁸ and F2263⁹.

The testing that is done to assure the performance of listed plastic piping materials is extensive and time consuming, and is performed on full pipe samples from commercial equipment. The testing is done in this manner to verify adequate service life at the design stress and temperature, because no comparably effective and reliable method has been developed. Conducting such extensive testing on installed piping systems is not practical and an alternate approach needs to be taken.

This paper provides a brief overview of such an approach based on recently developed validation methodologies for Stage III performance of PE piping materials⁴.

Field Aging Mechanism

The first step in characterizing residual lifetime is looking at how the materials in the piping system respond to their environment over time: how they age. For PE piping systems, the primary aging mechanism in potable water applications is oxidation of the pipe by the disinfectants present in the potable water. PE piping systems are highly engineered to provide the desired field service performance and resistance to this aging mechanism. For polyethylene (PE) piping materials the key components of the pipe formulation are the base resin and the stabilization package. The base resins have been tailored to provide the long-term strength properties desired in the end-use application. The stabilizer system is designed to

protect the polymer from long-term oxidation so that it can continue to function as designed in the application. The stabilizer system, in effect, plays a role analogous to a 'sacrificial anode', being consumed in protecting the polymer from the oxidants present in the potable water. The two together, resin and stabilizer system, act in concert to provide overall long term performance. A test used to measure the short-term effectiveness of certain stabilizers at high temperatures is called the Oxidative Induction Time (OIT) test.

J. Viebke and U.W. Gedde have proposed that plastic pipe lifetimes are comprised of A, B, and C regimes corresponding to a precipitation period, a period of Fickian diffusion with chemical consumption of antioxidant, and a polymer degradation period.¹⁰

Regime A is a special initial period of adjustment to the service temperature (or test temperature). If the initial concentration of a stabilizer is greater than its solubility at the test or service temperature, some stabilizer will precipitate when thermal equilibrium is established. Though the precipitate remains within the polymer, it is no longer functional in the Oxidative Induction Time (OIT) test, causing an initial sharp drop in the OIT value that is not related to oxidation or consumption of the stabilizer.

Regime B involves the stabilizer being consumed at the inner pipe surface. As the stabilizer concentration is reduced at the surface, a concentration gradient is established between the inner surface and the bulk polymer wall. This provides the driving force for diffusion from the bulk wall to the inner pipe surface, resulting in a constant replenishment of stabilizer at the inner pipe surface. E. M. Hoang and D. Lowe¹¹ found that a 95% reduction in the antioxidant levels occurred at exposed surfaces (as determined by OIT) within the first 8% of the measured lifetime of PE pipe. In other words, pipe with 95% stabilizer depletion at the inner surface as measured by OIT still had 92% of its expected service life remaining. Regime B with its low inner surface OIT levels, therefore, is seen to initiate early in the overall aging process.

In regime C, the polymer begins to oxidize at the inner surface. In reality, regimes B and C often overlap, with a combination of stabilizer diffusion and polymer oxidation occurring simultaneously.^{4,12} The Regime C oxidation of the inner pipe surface also appears to occur early in the overall lifetime of PE and other polyolefin pipe materials.^{4,5,6,7} After an initial increase in oxidation products, as measured by carbonyl ratio, there appears to be a plateau region of near constant carbonyl ratio that can extend for up to 80% of the overall pipe lifetime.^{13,14} Any methodology for forecasting residual lifetime needs to explicitly consider this aging mechanism.

Application of ASTM F2263 in Examining Field Aging of Plastic Pipe

Recently a methodology has been developed that provides a means of forecasting specific pipe performance as a function of water quality, water temperature and system operating stress based on accelerated testing of actual pipe specimens to their ultimate performance lifetime⁴. The basis for the testing is ASTM F2263 *Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water*. This method involves accelerated testing at a specific water quality and multiple elevated temperatures and pressures, and modeling the data using the Rate Process Method¹⁵.

It has been demonstrated that this validation methodology 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. This lifetime prediction method is equally applicable to new materials and piping exhumed after decades of service.

By exhuming in service piping, testing to ASTM F2263 and considering the utility's specific operating conditions, forecasts of residual pipe lifetime can be achieved. A similar approach has been previously successfully applied to gas pipe¹⁶. As the results are specific to the pipe materials exhumed, this testing is coupled with a system analysis and OIT and Fourier Transform Infra-Red (FTIR) analysis to select the appropriate pipe for testing and to confirm applicability to the other pipeline sections. The system analysis provides direction on the areas of the system that would be considered most aggressive. The OIT and FTIR analyses provide confirmation of this assessment through ensuring the pipe is in the appropriate regime of the aging process. The overall result is a complete picture of residual lifetime for the pipeline operator.

As the methodology involves testing of actual pipe specimens removed from service, it provides a true and direct measure of residual lifetime. The current aging state of the pipeline is explicitly captured by the methodology.

The Application of OIT in Examining Field Aging of Plastic Pipe

OIT and related approaches (such as Induction Temperature) have been widely used to examine field aging mechanisms in plastic piping systems.^{17,18,19} OIT measures the time for the on-set of degradation to occur on exposure of a small sample to an air or oxygen environment at elevated temperatures (typically 190 or 200°C). It is generally used as a proxy for the level of stabilizers present in the sample, with higher OIT values generally indicating a higher level of stabilizers.

As such, OIT has been effectively used to examine the Regime B component of the aging mechanism. J. Viebke and U.W. Gedde⁵ used OIT to characterize the Regime B component of aging in PE pipes, though the OIT data provided no basis for estimating the A or C time periods, and thus no basis for overall life estimation. Other authors have also reported on the use of OIT in characterizing the aging mechanism in potable water pipes.^{17,18,19}

As discussed previously, low inner surface OIT values are typically observed early in the overall pipe lifetime. By comparing these values for materials in different key areas of the system (as identified through a system analysis), appropriate specimens for testing in the ASTM F2263 methodology can be identified. The data can also be used to characterize different segments of the pipeline to ensure that the data generated by the ASTM F2263 testing is representative. OIT analysis has the advantage of being a quick test requiring limited sample and can be easily applied in such a screening capacity.

While OIT has been successfully used in characterizing the aging mechanism, as it is an indirect measure, its limitations need to be understood so that it is not misapplied. First, while OIT can provide a general indication, there is no direct correlation between OIT and oxidative resistance at end use conditions. This is because stabilizers, which are effective in increasing OIT, differ in their effectiveness at service temperatures, which are always much lower than the OIT test temperature. Stabilizers also differ in their resistance to extraction in various environments, which is not evaluated by the OIT test. Also, some stabilizers (such as Hindered Amine Light Stabilizers (HALS) and Hindered Amine Thermal Stabilizers (HATS)) are effective in preventing degradation and failure in PE even though they contribute nothing to

the measurable OIT of a polymer.¹¹ OIT values, therefore, provide only a general indication of the level of certain stabilizers which may be present. They are not able to provide a direct measure of pipe lifetime for either new pipe or in-service pipe.

With consideration of these limitations, however, OIT can be a useful tool in making general comparisons of samples of the same pipe material at different points in the distribution system to enable effective selection of samples for residual lifetime assessment.

The Application of Carbonyl Ratio in Examining Field Aging of Plastic Pipe

Carbonyl Ratio, defined by the area of the carbonyl band between 1812 and 1660 cm^{-1} , is a measure of the level of oxidation of PE materials. Similar to the OIT values, because of interferences from contaminants and additives in the polymer, the values should be examined on a qualitative basis rather than comparing actual values. 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 surfaces or thin microtomed sections, and thus can be used to compare different small areas within a material or on a surface.

Carbonyl Ratio has also been successfully used to characterize the aging process of PE piping materials.^{4,5,6,7} In general, the Carbonyl Ratio increases in the early phase of the aging process, reaches a plateau and then levels off.^{13,14} The onset of the initial increase in the Carbonyl Ratio and the plateau regions is dependent on the specific pipe formulation and the specific end-use environment. These onsets represent the onset of Regime C and the progression of the Regime C mechanism, respectively. The Regime C process is typically seen to overlap with the Regime B process and can extend for up to 80% of the overall pipe lifetime.^{13,14}

When OIT and Carbonyl Index analyses are used for comparison of similar materials within a single pipeline, their usefulness as relative measures of oxidation is greatest. In these cases, there are fewer interferences with the analyses; the stabilizers within the same brand and age of pipe are likely to be the same, and the initial quantities, solubility, and the polymer itself are also likely to be the same. Through coupling of Carbonyl Ratio and OIT analysis, therefore, it is possible to characterize the relative state of different specimens within the piping system to enable effective selection of pipe for exhumation and testing to ASTM F2263. The combination analysis can also be used to ensure that the exhumed pipe being tested for residual lifetime analysis is representative.

Again, as Carbonyl Ratio is an indirect measure of the aging process, its limitations need to be considered to ensure proper application. The Regime C process as measured through Carbonyl Index is seen to extend for up to 80% of the overall pipe lifetime; therefore, the Carbonyl Ratio of a pipe sample is not directly related to pipe lifetime. That is, pipe samples with the same Carbonyl Index could have 80% to 1% of their lifetimes remaining. Comparing Carbonyl Ratio values for different PE pipe formulations is also not a reliable direct comparison of the residual lifetime of those materials, as they could be at very different stages of the overall Regime C process.

Service Life Evaluation

The methodology is based on that developed and successfully applied 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)¹⁵. Testing is conducted on materials in pipe form with internal pressurization and a continuous flow of controlled water quality.

Combining targeted analysis of the relative oxidation within a pipeline by Carbonyl Ratio and OIT with ASTM F2263-based testing of exhumed specimens allows sound and defensible estimates to be made of remaining service life. Estimates made from this type of comprehensive analysis are sufficiently precise to guide the important tasks of buried resource management: prioritizing and scheduling the replacement of vulnerable runs while extracting the maximum economical life from as many feet of installed asset as possible.

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