A Technical Review of Jana Laboratories, Inc. Report Entitled, *Impact of Potable Water Disinfectants on PE Pipe*

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Report Submitted to:
Underground Solutions Inc.

Report Submitted By:
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Impact of Potable Water Disinfectants on PE Pipe

EXECUTIVE SUMMARY

Failures of HDPE water pipes in both Europe and North America have raised questions regarding the long-term viability of HDPE pipe for water service. Peer reviewed studies have been published that link many of the field failures to inner surface embrittlement from oxidative degradation. The three most common disinfectants in potable water - chlorine, chloramines and chlorine dioxide – are all oxidants that are known to shorten the life of HDPE pipe.

In order to address the problem and provide technically defensible long-term performance expectations for HDPE water pipe, the polyethylene pipe industry has commissioned Jana Laboratories, Inc. to develop accelerated test and analysis methodologies that can account for specific potable water environments. This paper is a technical review of one of Jana's more recent updates on their work.

The following summarizes the deficiencies that warrant further attention and consideration:

- Peer reviewed studies do not support the report's assumption that modern PE100's (HDPE 4710's) will provide for longer life expectancy than that for previous generation PE80's (HDPE 3408's & 3608's) when exposed to common water disinfectants. Actual testing has shown that the exact opposite can occur. Suez Environnement has tested a variety of PE80 and PE100 materials (pipe compounds) and found that the worst performing PE80 pipe had a normalized life expectancy longer than that of the best performing PE100 pipe. The reason for this is that anti-oxidant additives to the pipe compound control Stage III (oxidative degradation) life expectancy. The occurrence of Stage III failures is not significantly altered by the improved slow crack growth resistance (mechanical property) of newer-generation HDPE resins.
- Peer reviewed studies do not support the report's assumption that thicker-wall, larger-diameter HDPE pipe will provide for greater life expectancy. Research studies have shown there to be very little increase in crack propagation time-to-failure for thicker-wall HDPE pipe operated at the same hoop stress. The reason that differences in wall thickness have only a small effect on HDPE pipe longevity is because cracks grow more rapidly as their length increases. Consequently, once the HDPE pipe inner wall surface is sufficiently embrittled, a thicker pipe wall will not significantly extend its life.
- The report's estimates of mean failure time are inadequate and may differ significantly from actual, "true" life performance. In order to be statistically useful, reporting of 95% confidence intervals are essential and should have been included.
- Likewise, the use of a median Oxidation Reduction Potential (ORP - a measure of drinking water's effective oxidizing potential that considers pH and concentration of disinfectant) of 650 mV and average annual temperature are completely insufficient for establishing realistic longevity projections. Thousands of water systems have ORP values above 650 mV. Further, seasonal

temperature variations should not have been "averaged" by use of a single temperature in the calculations because temperature effects are substantial but not linear.

- The life projections in the report are based upon operating pressures that are less than half of the HDPE pipe's rated pressure class. At the rated pressure class, life expectancy will decrease by 80% or more.
- The report should have disclosed the HDPE compound(s) and anti-oxidant system(s) used in the testing and whether they were commercially available products or developmental materials not yet available for commercial use. It should also have disclosed the equation used to project the life of HDPE pipe with all of the parameters developed in the regression analysis of the data Jana had developed. Owners and their engineers who elect to specify HDPE water pipe need to be able to estimate pipe lifetime for their specific operating conditions. Without the life projection equation and associated statics, there is no way for a water utility to assess whether HDPE pipe will be a good choice.

It has been established that drinking water's oxidative potential plays a significant role in determining the life expectancy of HDPE pipe. The use of ASTM F2263 as a test method from which lifetime predictions might be made has great potential. However, in order for those predictions to have any value to owners and their design engineers they must take in to account aggressive operating conditions which cover all of the community water systems in the North America and not just a select few (i.e., only 5). In addition, specific information regarding each tested HDPE pipe material and its anti-oxidant system needs to be clearly disclosed.

INTRODUCTION

Earlier this year, Jana Laboratories, Inc. (Jana) released a report titled *Impact of Potable Water Disinfectants on PE Pipe*[2]. This document, which will throughout this paper be referred to simply as "the Jana report," appears to be a summary report of work performed over the last three or four years by Jana for the Plastics Pipe Institute, the polyethylene pipe industry's trade organization. Among other things, it discusses testing performed by Jana of high density polyethylene (HDPE) pipe in accordance with ASTM F2263, *Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene Pipe to Chlorinated Water.*[3] From the results of this testing, Jana made predictions of polyethylene pipe lifetime for the end use conditions they have identified in several "representative" water transmission and distribution systems in the United States. The predictions reflect very favorably on the potential for long term performance of HDPE pipe in potable water transmission and distribution applications. However, there are a number of omissions and errors within the report that could make these predictions questionable. That which follows is a review of some of these issues.

OXIDATIVE DEGRADATION OF HDPE PIPE IN POTABLE WATER APPLICATIONS

A well documented historical problem with HDPE pipe performance has been the effect of surface embrittlement on long-term performance, an issue that has drawn much attention and review. It is known that premature failure of PE pipe can occur when a thin layer of material on the inside surface of the pipe is degraded by oxidative degradation. This phenomenon, called Stage III failure in PE pipe, has been thoroughly studied and reported on by a number of researchers around the world. It was also the subject of a recent review.[1]

Since 2006, a number of peer-reviewed studies have linked earlier observed polyethylene oxidation research to field failures of HDPE pipes in both Europe and North America. Of particular interest are reports of premature polyethylene pipe failure in the presence of commonly used water disinfectants such as chlorine (hypochlorites), chlorine dioxide and chloramines. Studies in France by major water utilities (Suez Environnement and Veolia Environnement) have linked factors such as type and concentration of disinfectant, service temperature and internal pressure to HDPE pipe oxidation and failure.

In North America, the Las Vegas Valley Water District (LVVWD) has identified degradation of pipe due to oxidation from chlorination of the water as one of the reasons for significantly reduced service life of their HDPE service lines. LVVWD has experienced from approximately 900 to over 1200 PE water service line failures annually since the early 1980's. They concluded from their data analysis that failures were more likely to be due to wear our over time (due in part to oxidation of the pipe material) than to random failure. The characteristic life for their PE water service pipes was somewhere between 23 and 29 years, with a maximum life expectancy between 35 and 42 years.[33] Figure 1 below is a histogram of LVVWD failures in 1982 and in the period from 2003 – 2006.

It has been well established that for premature failure to occur by this process the thin, oxidized layer of pipe material must be both sufficiently embrittled and sufficiently deep into the pipe wall that its resistance to fracture initiation is dramatically reduced. Studies in this area have demonstrated that the depth of oxidation needs to be in the range of as little as two to four thousandths of an inch (0.002" – 0.004") into the pipe wall. The degree of degradation necessary in this layer for the effect to occur has been quantified by infrared spectroscopy. When these conditions are met, cracks will initiate in the embrittled layer at levels of stress that are typical of buried PE pressure pipe and in times that are much shorter than the time for crack initiation in the absence of such oxidation. These cracks will then propagate relatively rapidly through the pipe wall, resulting in a premature leak. The specific fluid being conveyed in the pipe plays a significant role in the degradation process. Details of HDPE water pipe failures from oxidation and surface embrittlement are documented in Reference 1. These include failures that occurred after one year of service in an Ohio utility, three years in a California location, six years in Nevada and seven years in Hawaii.

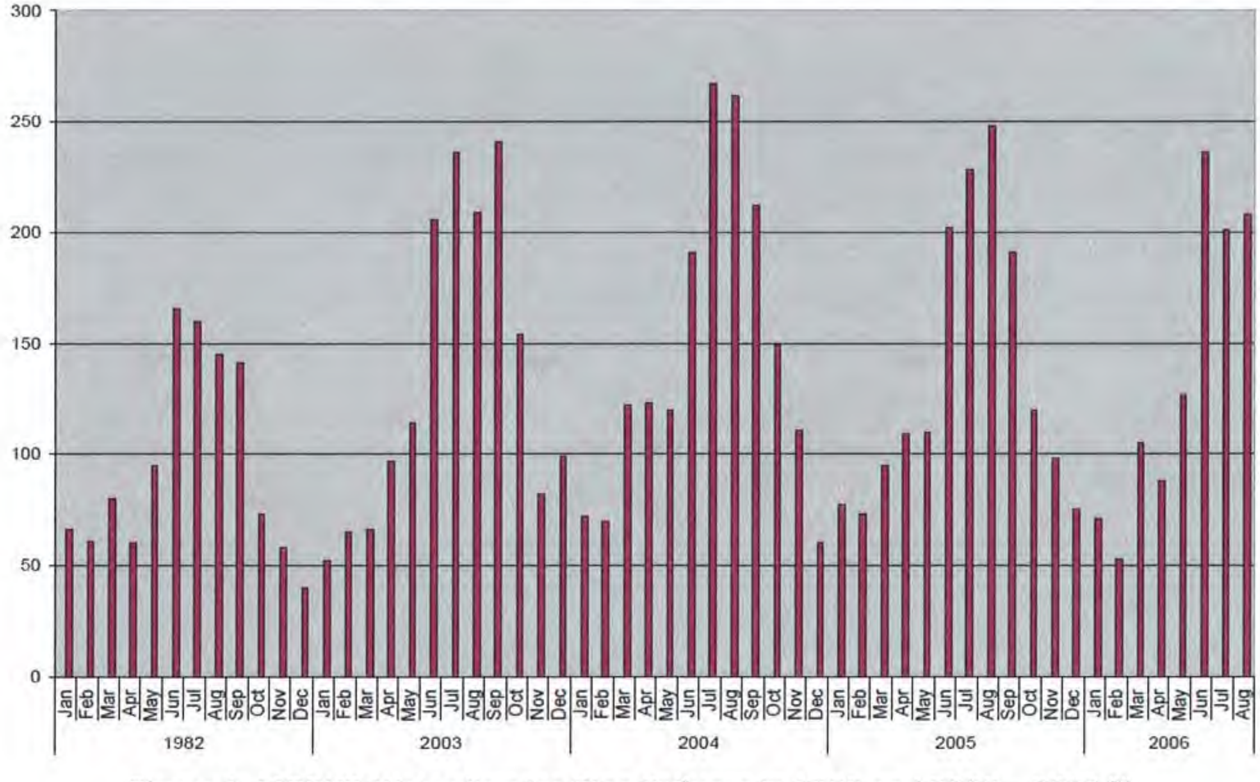

Figure 1: LVVWD Water Service Pipe Failures in 1982 and 2003 – 2006.[33]

PROBLEMS WITH JANA'S TESTING PROGRAM AND SERVICE LIFE PREDICTIONS

Life Prediction Equation Is Not Provided - The test program conducted by Jana involved performing tests by ASTM F2263 on new, unused PE pipe samples of small diameter tubing provided to them for that purpose. The tests were conducted at two different elevated temperatures on pipe through which water with varying pH and chlorine concentrations was flowing. The pH and chlorine concentration were monitored by measuring the oxidation reduction potential (ORP) of the water. The times to failure of these test pipes were recorded and the test results fitted to a "rate process" type equation. The actual equation is not provided in any of the reports Jana has issued on this work. It is presumed to be like that in PPI TN-16[4], but with an extra term added to include the effect of ORP on test pipe lifetime observed by Jana in tests carried out on crosslinked polyethylene (PEX) pipes[5]. The coefficients determined by this regression analysis were then used with the equation to predict mean failure times for pipes maintained at temperatures, pressures and with water ORP's outside of the range of the test conditions, but supposedly representative of values employed in actual water transmission and distribution practice. These predictions are presented in Table 1 of the Jana report.[6] However, the regression coefficients used in performing these predictions were not provided in the Jana report.

<u>Compounds and Stabilizer Systems Are Not Identified</u> - The composition of the polyethylene compound(s) used to manufacture the pipes that were tested was not identified. Without identification of the pipe compound and its stabilizer package, any predictions made using the regression equation developed from this program are of no real value. In fact, it is not clear whether all of the data used in the regression analysis were obtained on pipe made from the same polyethylene compound. The Jana report states, "Two separate datasets were analyzed for the high-performance materials and the average of the results is presented."[7] Does this mean that data were obtained on two different types of pipe? If so, why were only the average results presented? Why not present the failure time calculations for each "dataset" so that the reader of the report could independently assess how one pipe material compared to another? It is certainly true, as stated in the Jana report, that the lifetime of PE pipes in this type of service will depend strongly on not only water quality, temperature and stress[8] but also on the base PE resin and its stabilizer system[9]. If the two datasets were obtained on pipe manufactured from different compounds, then comparison of the results of each dataset could provide valuable information on the efficacy of the different base resin/stabilizer system combinations. Such information could be enormously valuable to a potential purchaser of PE pipe for a potable water application.

If, on the other hand, the two datasets were obtained on testing of the same pipe at different times, reporting the calculated results for each set would provide the reader of the report with an opportunity to assess the repeatability of the test results. If, for example, a calculation based upon one dataset predicted a relatively short lifetime, e.g. less than 50 years, while the same calculation based upon the second data set predicted a lifetime of several centuries, one might reasonably question the usefulness of either prediction. Clearly it is important to know the results of calculations performed with each individual dataset, and not just an average of the two.

Further, the reader of the Jana report is not told whether this pipe or the compound from which it was made (including the stabilizer package) was a commercially available product or a special, experimental composition made solely for this test program. The predictions offered for "Standard Operating Conditions" are all presented as being in excess of 100 years.[10] If the pipe tested by Jana was produced from a special, experimental compound that is not commercially available, then the predictions are misleading to a potential HDPE pipe user who can only purchase that which is commercially available. The lack of detailed information on the pipe that was tested makes the predictions offered in Table 1 of no value to engineers considering whether to specify PE pipe for a potable water system.

Higher Operating Pressures Yield Significantly Shorter Life Predictions - Yet another problem with the service life predictions presented in Table 1 of the report is that all but one of the lifetimes were calculated assuming an operating pressure of 70 psig (the other was calculated for a pressure of 65 psig). That pressure (70 psig) is only 43¾ % of the pressure class of DR 11 pipe.[11] While these pressures were judged by Jana to be "average" for a U.S. water utility, there is nothing in either AWWA C901 or C906 that would limit the pressure in an HDPE pipe to anything less than the 160 psig pressure class that the standards allow for DR 11 pipe. A more meaningful calculation would be to estimate the lifetime at the rated pressure class for the pipe being used. The predicted service life at pressures (stresses) at or near the HDPE pipe's pressure class will be much shorter than the predictions given in the Jana report.

Another way of looking at this issue of the effect of pressure on pipe lifetime is to modify an example given in the report.[12] The last paragraph in Section 3.3 provides this example; "To provide a sense of the impact of stress on the Mode 3 aging mechanism, at a given water quality and ground water temperature, the relative Mode 3 aging rate at 35 psig is approximately 5 to 10 times slower than that at 80 psig internal pressure." Some simple mathematics will show that this 5 to 10 times scaling factor for the effect of pressure can be applied to the effect of going from 70 psig to 160 psig pressure. Thus at a pressure of 160 psig, the current pressure class for DR 11 HDPE pipe if the 0.5 design factor is employed, the Mode 3 aging rate will be 5 to 10 times *faster* than at 70 psig pressure. This means that a predicted lifetime of $\geq$ 100 years at 70 psig pressure (Table 1 of the Jana report) would be reduced to only $\geq$ 10 to $\geq$ 20 years at a pressure equal to the pressure class rating of 160 psig. That is,

$$t_f = \geq 100 \text{ years (Jana Table 1)} \div (5 \text{ or } 10) = \geq 10 \text{ to } \geq 20 \text{ years for DR11 @ 160 psig}$$

where t_f is time to failure.

"True" Life Could Be Significantly Shorter Than Predicted Mean Value - This leads to another criticism of the predicted lifetimes presented in the report. The regression analysis carried out on the data generated by Jana's testing provides an estimate of the mean failure time for the operating conditions used in the regression equation. The fact that the estimated lifetime is a mean value means that many of the tested pipes, operated at the indicated conditions, would fail at greater times than the estimated life but *many others would fail at lesser times.* It is also possible to calculate a confidence limit on the mean failure time estimate, which the Jana report's authors did not provide.

Statistically, predictions like those made in Table 1 of the report are an estimate for the behavior of all pipes made from one specific HDPE compound based upon testing only a very few specimens of that pipe. While this procedure is used all the time, it has to be recognized that the mean lifetime predicted from the test data is only an estimate for the "true" mean life of the pipe. The true mean could only be determined if each and every piece of the lot of pipe from which the test specimens were taken pipe was tested. The true mean life of the pipe will be within a plus or minus range around the value calculated from the regression equation. That range is usually expressed as a "confidence interval," an interval of failure times around the predicted mean expressed with a certain level of confidence (typically 95%). The point to remember here is that statistically the "true" mean failure time for all pipes of the same composition and manufacture as the test pipes could be significantly less than the prediction. How much less is indicated by the lower limit of the confidence interval. Nelson, in his book on accelerated testing,[13] has written that, "Confidence intervals are essential ... they help engineers take heed that the estimates have great statistical uncertainty ... The estimates approximate the true parameter values. By their width, confidence intervals for parameters indicate the uncertainty in estimates."

Further, while the predicted mean may be impressively long there will be a distribution of failure times around that mean; i.e. not all pipes tested or operated under identical conditions will fail at exactly the same time. For a water utility operator, it is extremely important to know what the spread of that distribution of failure times will be. A water utility is going to be facing serious problems long before 50% of their service lines or mains fail for any reason. It is possible to estimate the percentiles of the distribution of failure times from the results of tests like those described in the report. Information like the confidence limits on the predicted mean failure times and the percentiles of the distribution of failure times should be made available to potential users in order for them to have as much relevant data as possible on which to make engineering judgments. Leaving information like that out of the report makes it far less valuable to municipal engineers who are charged with choosing a pipe for a specific water system from among the broad variety of materials available.

Use of Median ORP Value Excludes a Large Number of U.S. Water Systems - Jana performed the estimates presented in Table 1 of the report based upon "average" conditions they derived from an examination of an AWWA survey conducted about 15 years ago[14]. The numbers they utilized in their calculations may indeed have been average, or more likely median, values for U.S. water companies that responded to the survey, but no consideration is given to what happens when an individual utility operates at other temperatures, pressures and ORP's. For example, the 650 mV ORP employed in the calculation of HDPE pipe lifetime for an "Avg. US Utility" is actually the median of reported ORP values. This means that 50% of the utilities that responded to the survey reported pH and free chlorine concentrations corresponding to ORP values greater than 650 mV. Appendix X3 of ASTM F2263 reports that the same survey indicated that 1.8% of responding utilities reported conditions that would yield ORP values greater than 825 mV. ASTM F2263 also requires, in Section 9.1.1, that testing be performed with water having an ORP of 825 mV.[3] The U.S. EPA reported that there were 51, 988 community water systems in the U.S., serving over 292,000,000 people.[15] Approximately 70% utilize chlorine for the residual disinfectant that should be present throughout the distribution piping system. This implies that roughly 18,000 water systems have chlorinated water with an ORP greater than 650 mV. If one applies the 1.8% number to 70% of 51,988, the result implies the existence of over 600 community water systems carrying chlorinated water with an ORP above 825 mV. Even larger numbers of systems will be operating with water ORP's between 700 mV and 750 mV, between 750 mV and 775 mV and between 775 mV and 825 mV.

Table 1 of the report does provide a lifetime estimate for an "Aggressive US Utility." While the ORP of 825 mV can be viewed as "aggressive," the temperature (15°C or 59°F) and pressure (70 psig) are quite benign. Use of a low temperature and low pressure in the calculation favors a long lifetime estimate. As such, it is misleading to label this condition as "aggressive".

Use of "Average" Temperature Underestimates Effects of Seasonal Highs - Another problem with the lifetime estimates presented in Table 1 of the Jana report is that the calculations were done using one value of temperature, supposedly an average for the range of temperatures that the water in each system experiences over the course of a year of operation. However, given the strong effect that temperature has on the results of these calculations, the estimates can vary dramatically with a change of only a few degrees of temperature. Performing the test for a fixed length of time at a higher temperature will use up much more of the pipe lifetime than testing for the same length of time at a lower temperature. Further, the change in lifetime is not linear with temperature; rather the logarithm of pipe lifetime varies linearly with the reciprocal of absolute temperature. In this author's experience, better estimates of pipe life can be made with the same regression equation by utilizing Miner's Rule to account for lengths of time spent at different temperatures. Utilization of Miner's Rule with two or more temperatures for varying lengths of time chosen to reflect seasonal temperature changes will yield more realistic results. Picking a single "average" temperature to capture the effect of seasonal temperature changes that occur is highly arbitrary, and a poorly chosen value can yield very misleading results.

Report Omits Critical Information - One final observation concerning the presentation of test results in the report can be seen in Figure 9, on page 23. The plot of test results has no numerical values assigned to either the "log Stress" or the "log Test Time" axes. This omission makes it impossible for a reader of the report to attempt to extract information from which he could try to make his own projections to actual use conditions. It is as if the Jana report has been sanitized of any information that would permit readers to actually do anything with the results.

In light of the above, the verbiage in Sec. 3.4 of the Jana report, "Overall Impact of Primary Variables," conveys a false sense of security with the use of HDPE pipe that isn't justified by the results presented. While a majority of end use conditions might be within some plus or minus range of the values of temperature, pressure and ORP employed in the calculations, the distribution of operating conditions is critical. If even 5% of all water utilities are operating at the extreme high values of ORP, pressure and temperature, that could mean that hundreds of water utilities might be operating under conditions that could potentially yield unsatisfactory performance with HDPE pipe products. Readers of the report are given nothing concrete that they can use to determine what a lifetime prediction might be for their specific operating conditions.

Research Does Not Support Longer Life Expectancy For Larger Diameter, Thicker Walled HDPE Pipe - In Section 4.3 of the Jana report, an argument is made that pipe lifetime will be strongly affected by the pipe wall thickness and that overall time to rupture for HDPE pipes will dramatically increase as pipe wall thickness increases. While this idea has some common sense appeal, reality is rather different. Research studies of this issue in HDPE pipes show there to be very little increase in the time for a crack to propagate fully through the pipe wall, denoted in Section 4.3 of the report as t_p as wall thickness increases. The equation for t_p , derived by Dear & Mason[16] predicts an increase in t_p of only 2% in going from ¾ inch IPS, DR 11 pipe with a minimum wall thickness of 0.095 inches to 24 inch, DR 11 pipe with a minimum wall thickness of approximately 2.2 inches. The fracture mechanics-based Lifespan computer program, developed by Southwest Research Institute for the Gas Research Institute, yielded similar results.[17] Figure 2 is a plot from Reference 17 of "Estimated Safe Operating Life" versus pipe diameter for DR 11 pipes ranging from 2" IPS to 16" IPS. There is very little increase in pipe lifetime over this broad range of pipe diameter and wall thickness. In the text of Reference 17 the authors explain that this occurs because, "Differences in wall thickness have only a small effect on the pipe life because the crack grows more rapidly as its length increases." Clearly the claim that the lifetime predictions in Table 1 of the report are conservative because the data were obtained on small, relatively thin-walled pipe specimens, while intuitively appealing, is invalid.

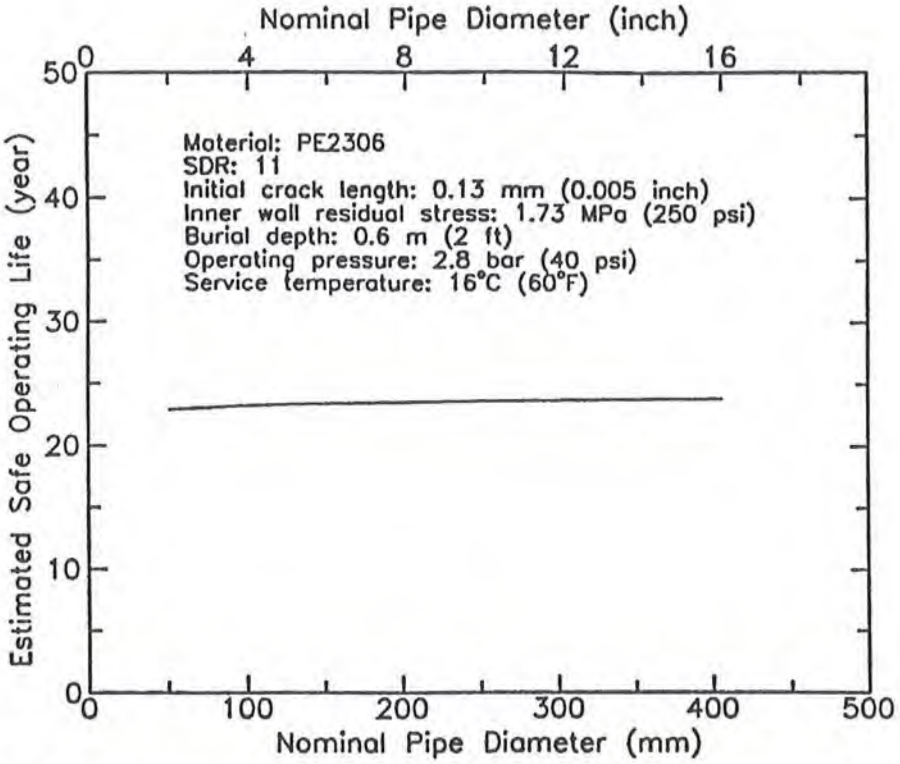

Figure 2: Estimated Life vs. Pipe Diameter of MDPE Pipe at Constant DR (Ref. 17).

In support of the idea that the pipe lifetimes will be far greater for large pipe than for small pipe, the authors of the subject Jana report offer the observation that, in the past, far more failures have been reported on service-sized (i.e. small) pipe than on larger sizes used for water mains. Based upon my experience in performing failure analyses on hundreds, if not thousands, of polyolefin pipes the real reasons that more failures are reported on small diameter services than large diameter mains is due to the fact that small, service-sized pipe is more compliant (more flexible) than large, thick-walled pipe. Because service-size pipe is more flexible, service lines that run from the corporation stop at the water main to the water meter see much greater stresses due to deformations of the service lines that aren't usually imposed upon the main. These include bending due to the contour of the service line, bending of the service line at the mechanical connections at each end, and excessive soil settlement around the connections from poor installation practices. Greater failure rates in small sized pipe, if they exist, are due to higher levels of stress in those sizes rather than to a presumed pipe wall thickness effect that doesn't exist to any significant extent.

Modern HDPE Pipe Materials With Higher PENT Test Values Are As Vulnerable To Oxidative Degradation As Earlier PE Materials - Another argument offered in the report to support the idea that HDPE pipe made from modern resins will exhibit superior performance is that these newest materials perform far better in the PENT test[18] than HDPE pipe compounds of just a few years ago.[19] However, there are clear problems with using a test like the PENT test to predict long term pipe performance, particularly for pipe that has an oxidized and embrittled surface. First, while the specimen used in the PENT test is notched, the razor blade notch in the specimen will not have as severe an effect on fracture properties as a notch created by imposing a tensile stress on a specimen with a sufficiently embrittled surface.[20] Second, a recent paper from Chevron Phillips, a polyethylene pipe resin manufacturer, has raised serious questions about using the results of the PENT test as a predictor of long term pipe performance.[21] This paper's first conclusion states, "... PENT does not accurately measure or reflect SCG [Slow Crack Growth] performance and its use should be limited in the industry as a result." The use of PENT test results to justify a prediction of long time HDPE pipe performance is inappropriate, particularly for pipe afflicted with a sufficiently deep and extensively degraded embrittled surface layer.

It has been claimed that long PENT test failure times for modern HDPE pipe resins indicate that creep cracks grow at a slower rate in such materials than in resins with shorter test failure times. However, no direct evidence of that has ever been offered to support this contention. No crack speed vs. stress intensity factor (da/dt vs. K_I) data for the newest HDPE resins has peen published, that this author is aware of. Modern HDPE resins do exhibit longer PENT test failure times and longer times to the transition from Stage I to Stage II failure in hydrostatic pressure tests of pipe. However, it is possible that this is due to extended crack incubation time (the time required for formation and breakdown of the initial craze) rather than a slower crack growth rate. If this were true, then oxidative degradation of the inside surface of an HDPE pipe to the requisite level to cause surface embrittlement would have the same effect on modern pipe as it would on pipe made from older PE compounds. In other words, if t_p is essentially the same for new and old HDPE resins, then any benefit from lengthening the crack incubation time would be negated by oxidative degradation and embrittlement of the pipe surface and modern HDPE materials would perform no better than older materials having the same resistance to oxidation (i.e. the same stabilizer package) in the pipe compound.

Stabilizer Systems, Not PENT Test Values, Control Life Expectancy - This last idea is strongly supported by a recent presentation made by representatives of the French water utility Suez Environnement (Suez).[22] The paper presents results of a four year testing program directed at evaluating the potential performance of HDPE pipe in potable water service. The test system developed by Suez exposes test pipes to accelerated aging conditions that generate Stage III failures. Summaries of the results of this program presented in Figures VII and VIII of the paper (Figures 3 and 4 below) are particularly informative. Figure VII in the Suez paper (Figure 3 below) showed that the worst performing PE80 (PE 3408 or 3608 grades) pipe in these tests performed better than the best performing modern PE100 (PE 4710 grade), even though the modern PE100 pipe compounds are the ones purported to have superior slow crack growth resistance. It also showed that there was a wide range of results between the best and worst performing pipes in each of those two groups. For both PE80 pipe and PE100 pipe, the best performer predicted 70% longer life than the worst performer.

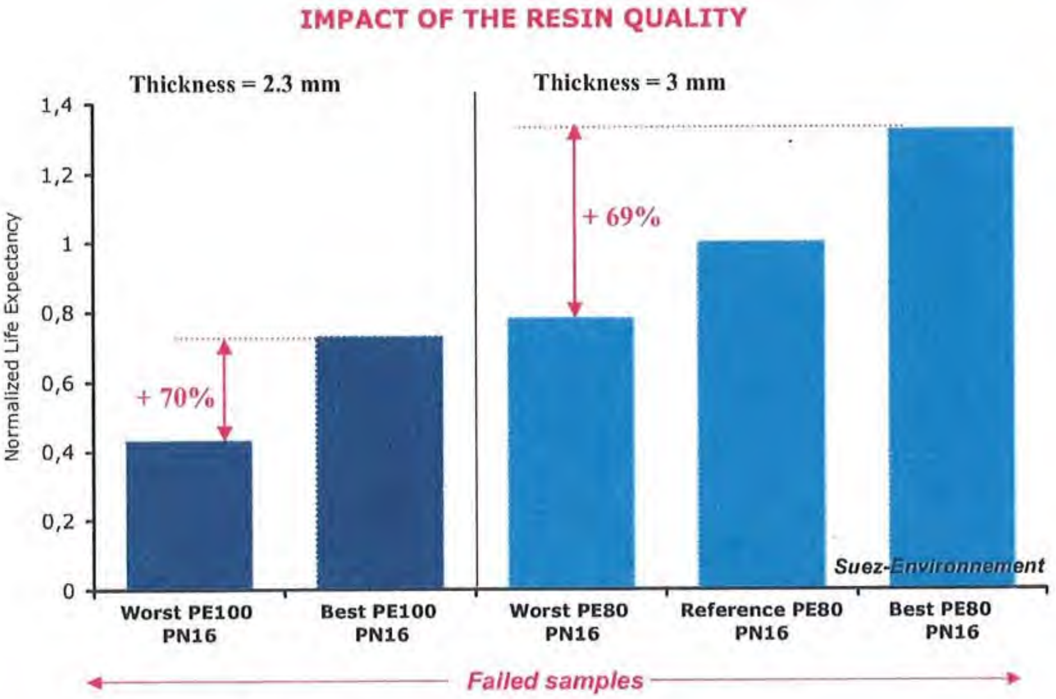

Figure VII: resin impact on the PE pipe's longevity

(40°C / 104 °F, 6 bar / 87 psi, 1 mg/L ClO_2, Nominal Pressure: PN16 = 232 psi)

Figure 3: Relative life expectancy for different commercially available HDPE pipes (from Ref. 22).

Figure VIII in the Suez paper (Figure 4 below) showed results of tests on a new developmental grade of PE100 that exceeded the performance of the "reference" PE 80 pipe by about three times, and exceeded the performance of the best commercial PE100 by about four times.

The most plausible explanation for these dramatic differences in the Stage III failure mode among pipe compounds within one type (PE80 vs. modern PE100), between the two types (allegedly superior PE100 vs. PE80) and the developmental grade of PE100 versus the commercial grades of HDPE pipe is differences in the stabilizer packages. If the difference between PE80's and PE100's in Stage II performance were due to superior (slower) crack growth rates in modern PE100's, that difference would carry over into Stage III performance. Clearly, Suez's testing did not find any improvement in life expectancy for even the best commercial PE 100 sample.

However, if the difference between PE80's and modern PE100's in Stage II behavior is due to superior resistance to formation and breakdown of the initial craze from which crack growth progresses, then the rate at which the oxidation creates the necessary embrittled surface layer for crack growth to begin controls Stage III behavior. The rate at which the brittle layer develops is a function of stabilizer package and perhaps to a small extent the molecular architecture of the specific base polyethylene resin. These results from the Suez testing program strongly support the latter mechanism.

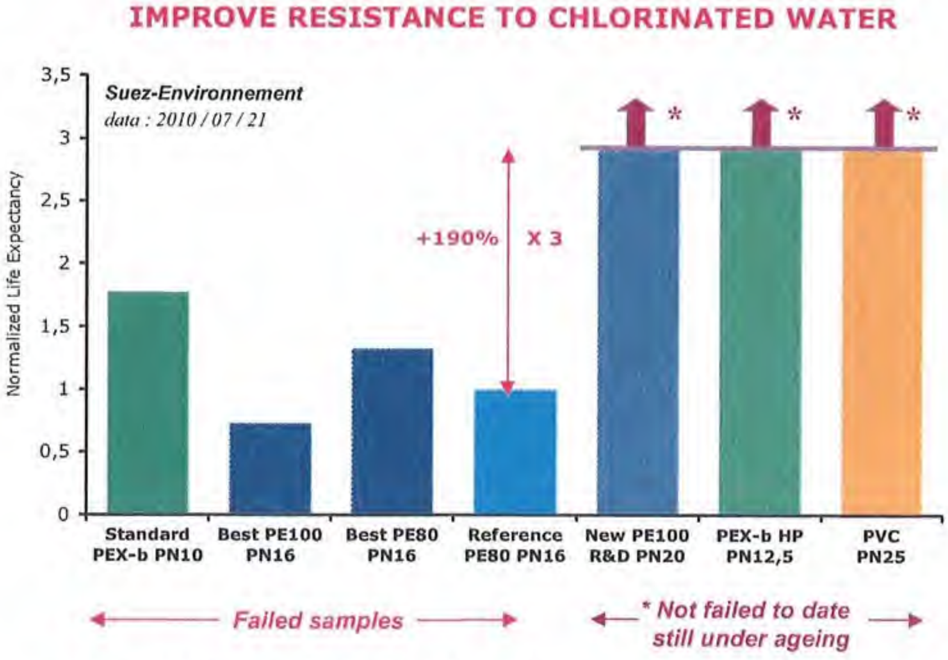

Figure VIII: products with high resistance to chlorinated water

(40°C/104 °F, 6 bar/87 psi, 1 mg/L ClO_2, Nominal Pressure PN10 = 145 psi; PN12.5 = 181 psi; PN16 = 232 psi, PN25 = 362.5 psi)

Figure 4: Estimated life for some commercial and other developmental grades of plastic piping products (from Ref. 22).

Significant Over Estimation Of Remaining Life Is The Result Of Failure To consider Depth of Degradation Effects & The Tested Pipe's Stabilizer Package - In the Jana report, the authors are dismissive of the techniques that have historically been employed to measure and quantify oxidation in polyethylene pipe. For one thing, they focus on effects at the thinnest possible layer of inner surface of the pipe wall. For example, they employ attenuated total reflectance (ATR) fourier transform infrared (FTIR) spectroscopy to look for carbonyl development on the pipe surface. However, the ATR-FTIR method obtains a spectrum from only the first few microns of material at the surface being tested[23] (25.4 microns = 0.001 inch). There is no consideration given to depth effects. Several authors have clearly shown that it is both extent and depth of oxidation that are important in the surface embrittlement process and Stage III failure.[24-26] The focus in the report on examining only a small fraction of the first 0.001 inch of the pipe surface provides misleading results. This extremely thin layer will, of course, be the first to exhibit oxidation and will initially be extremely superficial. Surface embrittlement effects and Stage III failure do not come into play until much later, when oxidation has developed to a sufficient level and deeply enough into the pipe wall to have an effect on creep rupture behavior.

This is why profiling of oxidative degradation into the pipe wall, for example by use of an FTIR microscope attachment to the basic spectrophotometer, is so important. The Jana report's claim that superficial surface oxidation, as measured by the ATR method, appears in the first approximately 10% of pipe lifetime is a correct observation. However, the implication that this means that the remaining 90% or so of pipe lifetime is taken up in (very) slow crack propagation is incorrect. The oxidation must become more highly developed and deeper into the pipe wall than the first few microns before it becomes problematic. Only then will cracks initiate in the embtittled surface that will propagate (much more rapidly than implied by Jana's analysis) through the pipe wall and result in a Stage III failure. It is the development of a brittle surface layer that is both severe enough and deep enough into the pipe wall (at least 50 - 100 microns) that takes up the greatest portion of the total time to failure; far more time that the 10% of total pipe lifetime necessary to create low level oxidation in the first few microns of pipe surface.

The report also states that infrared spectra of oxidized polyethylene should not be used to quantify the extent of oxidation.[27] However, this statement runs counter to decades of actual practice. There has even been an ASTM standard method developed that employs infrared spectroscopy to quantify oxidative degradation in polyethylene components of orthopedic implants.[28] FTIR spectroscopy as a means of quantifying oxidation in polyethylene has been widely and very successfully practiced for at least three decades. The ability to quantify the extent and depth of oxidative degradation into the wall of a polyethylene pipe is essential to understanding the extent to which that oxidation will affect long term pipe performance.

In discussing the use of oxidation induction times to evaluate the relative amount of antioxidants (AO) in polyethylene pipe, the report again focuses on a thin layer at the inner surface and ignores AO levels deeper into the pipe wall. Their observation that the OIT at the inside pipe surface reduces to a low level in a fairly short time has been made by others. However, research performed at the Studsvik laboratory in Sweden shows the importance of profiling the OIT across the full width of the pipe wall. Studsvik researchers observed that significant oxidation doesn't commence at the inner pipe surface until the AO is effectively depleted throughout the wall.[29] Relating surface OIT by itself to pipe lifetime serves no useful purpose, but to confirm that the AO content at the surface is low. The significant factor in overall pipe life is resistance of the AO throughout the pipe wall to neutralization by doing its job and extraction by flowing water. This is clearly demonstrated by testing performed by Studsvik on polyethylene pipe produced with no long-term AO package.[30] That work demonstrated that the time for Stage III failure of unstabillized PE pipe life was less than 12% of that for pipe made of the same polymer with an AO package. It implies that nearly 90% of pipe life was Regime A (surface AO depletion) & Regime B (diffusion of AO from the interior of the pipe wall to the surface until overall AO depletion to a no longer effective level) and Regime C (the crack initiation & growth part) was only 10 - 12% of total life. The Jana report attempts to argue that low AO content marks the end of Regime B, as opposed to the Studsvik conclusion that overall AO depletion marks the end of Regime B. This point of view is then used to support the contention that the crack initiation and growth regime makes up 90%+ of overall pipe life; a position totally in opposition to the Studsvik position that Regime B makes up 80% - 90% of overall pipe life.[29] It is another attempt to support the false claim that crack growth rates in modern HDPE pipe resins are vastly lower than in older resins. As explained earlier, there is no direct evidence to support this hypothesis, and claims of indirect evidence based upon results like Jana's OIT measurements are contradicted by other independent research.

Another attempt to support the hypothesis that Regimes A and B make up only a small part of overall pipe life makes reference to a study performed on a blue PE100 pipe.[31] This study reported that the there was a 95% reduction in AO (based upon OIT measurements) within the first 8% of the total pipe lifetime. There are two big problems with this statement. One is the above. The other is that the blue HDPE pipe, because it does not contain carbon black for UV exposure protection, does contain hindered amine light stabilizers (HALS) in blue compound. HALS are effective as long-term stabilizers against general oxidative degradation, but do little-to-nothing for OIT. A low surface OIT is not an accurate measure of stabilizer depletion in a compound containing HALS for that reason. The time for complete depletion of stabilizer even at the inside pipe surface is likely much longer than stated because the stabilizing effect of HALS does not show up in an OIT measurement.

Finally, it should be noted that in Reference 1, the OIT measurements were not intended as a predictive tool, but as a means of characterizing the failed pipe that was evaluated. Similarly, the bend back test was not used as a predictive tool but as one means of characterizing the failed pipe. FTIR profiling was used in the same way, but with the knowledge of years of work that demonstrate how deep and intense oxidation needs to be for surface embrittlement and premature (Stage III) failure from it to occur.

Chlorine Dioxide Exposure Testing Needs To Be Included - One final observation is offered relating to statements made in Sect. 3.1 on "Water Quality" on the use of chlorine dioxide as a water disinfectant. The Jana report estimated that less than 1% of water utilities in the US utilize chorine dioxide as a disinfectant. This claim was made based upon information in the 1996 AWWA Survey.[14] However, a more recent AWWA survey reports that 8% of water systems employ chlorine dioxide as a disinfectant.[32] This is important because it has become recognized that chlorine dioxide is much more aggressive in oxidizing polyethylene pipe than the standard hypochlorous acid/hypochlorite anion "chlorine" disinfection treatment. The report tried to dismiss concerns about the effect of chlorine dioxide in the water on HDPE pipe by stating that the number of users of chlorine dioxide was small and therefore the greater impact of chlorine dioxide versus chlorine disinfectant on HDPE pipe didn't need to be discussed. However, more recent data appears to show that the number of chlorine dioxide users is greater than was thought. This aspect of HDPE pipe performance does need to be made known to the user community, so that water company engineers can make educated decisions about what water pipe product to specify for their systems.

RECOMMENDATIONS FOR FUTURE WORK

In the light of the above discussions and based upon current literature reports it is imperative that a more realistic approach towards the lifetime prediction of PE water pipes be developed and be incorporated in the standards that pertain to HDPE water pipe. It has been established that material, environment and loading control pipe lifetime and that Stage III failure does occur to a significant extent in the field. Therefore, HDPE compounds that are to be used in the manufacture of water pipe need to be qualified for long term performance not only by the traditional method of determining a hydrostatic design basis for the material[11] but also for resistance to oxidative stability and Stage III failure by ASTM F2263. The testing approach for oxidative stability must include an evaluation of performance in aggressive operating conditions which are going to produce Stage III failures, so that design engineers can have confidence that, if they specify HDPE pipe, Stage III failures will not be a significant failure mechanism within the design life of their piping system. Specific HDPE pipe compounds should be qualified for oxidation resistance just as they are for long term strength. Water pipe standards should be modified to require that only qualified oxidation resistant HDPE compounds be used to manufacture water pipe, just as the standards currently require that only compounds with a PPI hydrostatic design basis be used to manufacture HDPE pressure pipe for all applications.

Research directed at providing lifetime predictions should take better account of seasonal temperature variations, perhaps by the application of Miner's rule. Use of PE pipe has been growing in North American piping distribution networks. When sufficiently developed, regression equations like that created from the work detailed in the Jana report should be provided to the outside research community for peer review and further evaluation. Publishing predictions based upon assumptions of non-aggressive testing conditions and inappropriate use of data may result in over optimistic predictions of PE pipe lifetime.

The use of ASTM F2263 as a test method from which lifetime predictions might be made has great potential. However, in order for those predictions to have any value to design engineers and specifying engineers of pipe for water transmission and distribution pipelines, the tests must be performed on commercially available HDPE pipe.

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