RESIDUAL QUALITY OF FIRST GENERATION PE GAS AND WATER PIPES

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ABSTRACT

Segments from 32 mm gas service pipes installed in 1975-1976 and from 40 mm water service pipes installed in 1967-1968 in Germany have been excavated and tested for residual quality. Two different HDPE resin populations discovered among the German gas pipes were also found among excavated Dutch gas pipes. Internal water pressure tests of up to 13,800 hours show that the residual quality of both HDPE gas pipe populations is still remarkably good. The times to failure in internal water pressure tests at 20, 60 and 80 °C are no lower than published regression curves. Between 1,400 and 4,300 hours at 20 °C the gas and water pipes go through an early ductile-brittle transition. This occurs however without any change in slope up to 13,800 hours, whilst published data mention a ductile-brittle transition and a knee after about 10,000 hours at 20 °C.

The "MRS value" for extended operation during an additional 50 years was predicted. For the gas pipes 5.3 MPa was calculated and for the water pipes 3.9 MPa, due to much higher operational pressures over a longer period. The data also fits to Barton & Cherry's model, which assumes a log (time) versus linear stress correlation.

No oxidation effects were noted. The residual "ambient temperature thermo-oxidative lifetime" was estimated by extrapolation of test results from exposure to water and air at 60 to 95 (100) °C. No alarming results were found.

INTRODUCTION

In Germany and the Netherlands the use of PE pipes for gas and water distribution started in the early nineteen sixties with first generation HDPE pipes, which were installed up to about 1978. A service life prediction of 50 years was made. The PE pipe materials of this generation have now reached a service life that nears the expected lifetime.

Therefore, gas and water distribution companies have asked themselves whether the original lifetime expectancy of 50 years will be met. In view of the very high cost of replacing large numbers of pipelines it is also important to assess how much longer than the anticipated 50 years the pipelines can be used without risking increased failures.

A first generation PE pipeline may fail due to: point loads, low resistance to Slow Crack Growth, a failing antioxidant system, bad joints, Rapid Crack Propagation and condensate. In this paper, only the second and third items are investigated. Positive results on the electro fusion of old first generation PE pipelines were reported earlier [1]. Gaube et al [2] and Fleischner [3] have published on internal water pressure testing of first generation Hostalen GM 5010 PE pipes. Their results are re-produced in Figure 1. The extrapolated brittle failure line at 20 °C beyond the "knee" (solid blue line) intersects with the 50 years line at 6.3 MPa (LTHS).

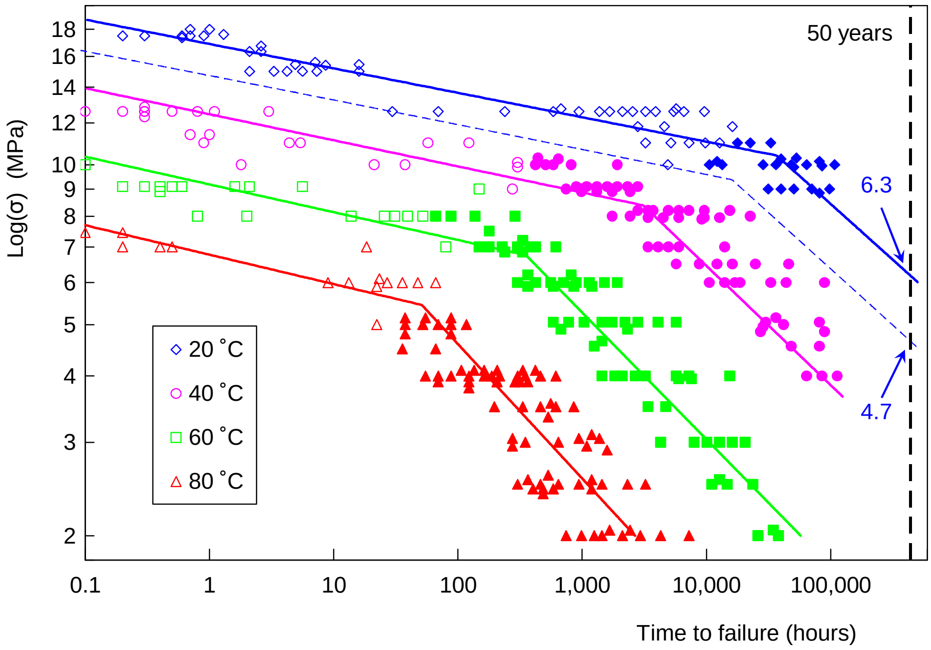

Figure 1. Internal water pressure tests on unused first generation Hostalen GM 5010 pipes. Open symbols: ductile failures. Closed symbols: brittle failures (courtesy Lyondell Basell).

That is why these pipes were sometimes denoted PE63. However, according to ISO 9080 the LPL (Lower Prediction Limit) of 4.7 MPa shall be used for MRS classification. Therefore, these pipes are "PE47".
In 1992 Scholten et al [4] have published on internal water pressure testing of excavated first generation gas pipes and found no alarming results, except when point loads were present.

MATERIALS AND METHODS

<u>Materials</u>
More than 150 one meter segments of 32 mm SDR11 gas pipes and a similar number of 40 mm water pipes (SDR11 and SDR6) were excavated in Germany. The gas pipes had been used for about 32 years at 80 or 800 mbars pressure and the SDR11 water pipes for about 40 years at a pressure of 7 bars. SDR6 water pipes had also been used, but at a pressure of 4.5 bars. All pipes were carefully inspected for the absence of point loads.

<u>Methods</u>
Ethyl branch content was measured using FTIR spectroscopy and the method of Usami et al [5]. The Cone test was performed on 32 and 40 mm pipes according to ISO 13480, the PENT test according to ASTM F1473 and internal water pressure tests according to ISO 9080. Oxidation Induction Times (OIT) were measured according to ISO 11357 but - in view of the low OIT values - at 190 °C. First it was assessed [6] that also at 190 °C reliable OIT values could be measured. The OIT at 190 °C serves as a measure of the residual thermal stability after exposures to air and water at 60, 80, 95 and 100 °C. Such exposures simulate the influence of groundwater, drinking water and air on the pipes.

RESULTS

Materials Characterisation

Using the print on the excavated pipes and DSC Fractionation (DCS/SIS) [4] it was found that three resin materials had been used. Figure 2 shows a few examples.

1. Hostalen GM 5010 gas and water pipes from the former company Hoechst,
2. Vestolen A 5140 gas pipes from the former company Hüls,
3. LDPE water pipes, all thick-walled SDR6 and used at 4.5 bars.

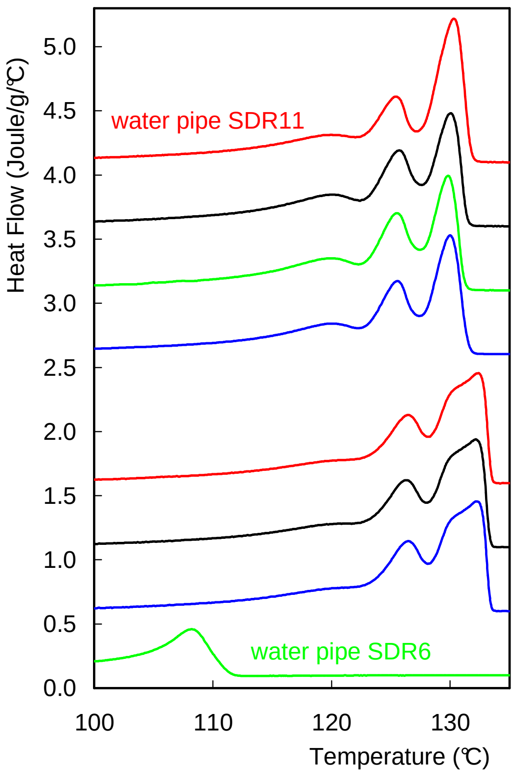

Figure 2. Examples of DSC fractionation (SIS) curves [4] of (from top to bottom): one SDR11 Hostalen water pipe, three Hostalen gas pipes, three Vestolen gas pipes and an LDPE SDR6 water pipe.

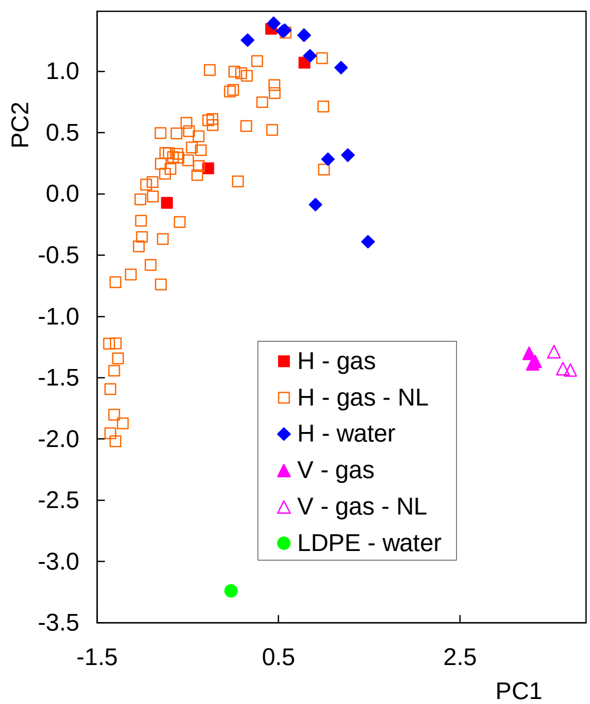

Figure 3. Score plot [7] showing Hostalen (H) and Vestolen (V) populations. Open symbols: Dutch pipes. Closed symbols: German pipes. The Hostalen gas and water pipes overlap.

Another manner of presentation is based on Principal Component Analysis [7]. Figure 3 shows a "Score Plot" of all DSC Fractionation curves, made with the software "The Unscrambler" from Camo Software AS, Norway. Results of many Dutch Hostalen and Vestolen gas pipes were added. Several populations are discerned. Only the Hostalen and Vestolen HDPE gas or water pipes were investigated further.

Table 1 shows melting enthalpies by DSC (proportional to crystallinity) and ethyl branch contents of the HDPE materials, as well as PENT and Cone test results. The Cone test results are similar to those measured by Gueugnaut et al on first generation PE pipes [8].

Table 1. Melting enthalpy by DSC, ethyl branch content by FTIR spectroscopy, Cone and PENT results of gas and water pipes.

Material	ΔH (Joule/g)	FTIR Ethyl/1000 C	Cone test (mm/day)	PENT test (hours)
Hostalen GM 5010 (g+w)	174-178	3.0-4.2	15-22	1-3 *
Vestolen A 5140 (gas)	185-186	1.5-2.1	18	1-3 *
new PE80	-	-	2.6	> 500
new PE100	-	-	1.3	> 500

* *measured at 1.5 MPa instead of the prescribed 2.4 MPa.*

<u>Identification and Content of Residual Antioxidants</u>

The concentrations of 4 types of antioxidants were assessed by Ciba AG, Basel, CH (Table 2). Other antioxidants were suspected, but not identified. The Vestolen pipe contains much more antioxidants than the Hostalen pipes.

Table 2. Concentrations of four identified antioxidants (n.f.: <0.002 ppm).

Pipe type	Irganox 1076 (ppm)	Irganox 1010 (ppm)	BHT (ppm)	Irgafos 415 (ppm)
Hostalen gas (2x)	n.f. and 180	n.f.	n.f.	70 and 159
Hostalen water (2x)	n.f	n.f	n.f	n.f
Vestolen gas (1x)	840	30	110	n.f

<u>Oxidation Induction Times</u>

Table 3 shows the OIT values as measured at two temperatures. There is a constant ratio between the OIT at 210 and the OIT at 190 °C, so either temperature may be used. Because of the low values at 210 °C, the test temperature was changed to 190 °C. Kramer et al [10] have performed OIT measurements down to even 150 °C. The higher content of antioxidants in the Vestolen pipe explains its higher OIT values.

For the water pipes the OIT at the inner pipe surface was always about 3 to 5 times as low as elsewhere in the pipe wall. For the gas pipes, the OIT at the external pipe surface was about 20 % lower than elsewhere in the pipe wall.

Table 3. OIT results of as-received gas and water pipes at 190 and 210 °C. Samples taken from the middle of the pipe wall.

Pipe type	OIT at 210 °C (min.)	OIT at 190 °C (min.)	Ratio
Hostalen gas	10.6	48.5	4.6
Hostalen water	10.7	44.7	4.2
Vestolen gas	48.5	234	4.8

<u>Internal Pipe Stresses</u>

The residual pipe stress was determined according to Janson [9]. The results are presented and compared to the values for new PE80 (MDPE) and PE100 pipes in Table 4.

Table 4. Internal compressive stresses according to Janson [9] in excavated and new 32 and 40 mm pipes.

Diameter 32mm Pipe type	Compressive Stress (MPa)	Diameter 40 mm Pipe type	Compressive Stress (MPa)
Hostalen gas	3.0 - 3.4	Hostalen water	3.0 - 4.6
Vestolen gas	3.5		
new PE80	2.4	new PE80	6.3
new PE100	3.7	new PE100	5.3

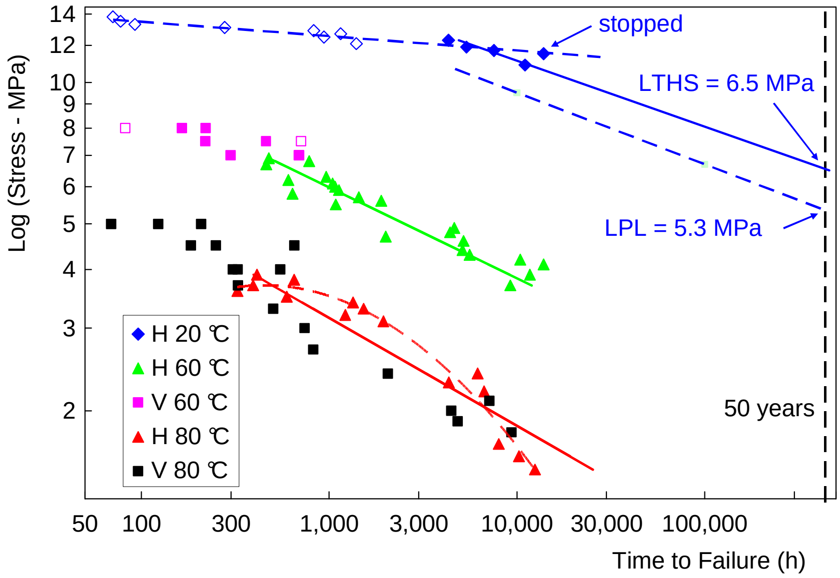

Figure 4. Internal water pressure results of excavated Hostalen (H) and Vestolen (V) gas pipes and the four parameter model (ISO 9080) on the Hostalen pipes. For the Vestolen pipes no data at 20 °C is available. The Hostalen pipes show a downward curvature (dotted line) at 80 °C. Open symbols: ductile failures.

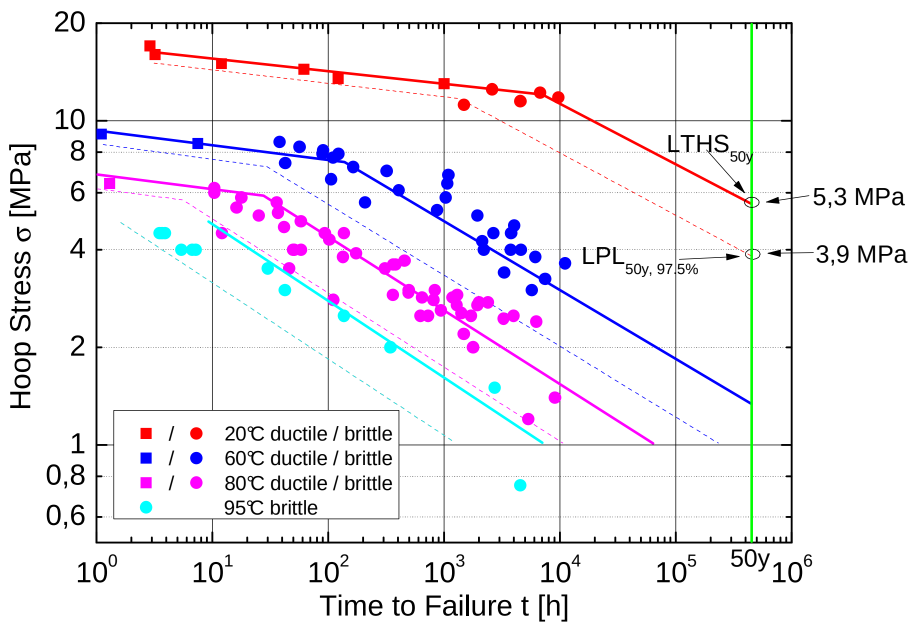

Figure 5. Internal water pressure results on a double logarithmic scale of excavated Hostalen water pipes and application of the three parameter model according to ISO 9080. Square symbols: ductile failures.

Internal Water Pressure Tests

Figure 4 shows the results of the internal water pressure tests on the excavated Hostalen and Vestolen gas pipes. At 80 °C the dotted line through the Hostalen pipes is used to guide the eye and illustrate a downward curvature. This necessitates using the four parameter model according to ISO 9080 for calculating the LPL at 20 °C. At 20 °C the dotted line of the ductile points also describes the brittle points well, up to 13,800 hours. Figure 5 shows the results for the excavated 40 mm Hostalen water pipes. In this case the curves at different temperatures are more parallel, which allows use of the three parameter model according to ISO 9080.

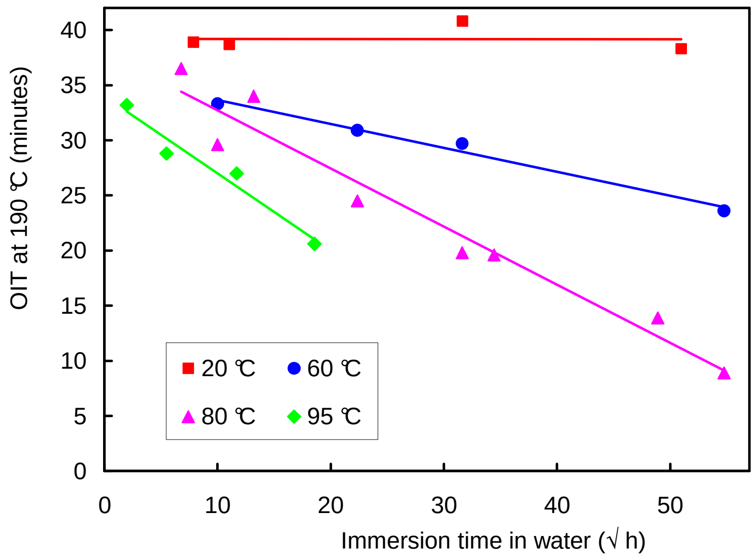

Figure 6. OIT at 190 °C of samples from the middle of the wall of the excavated Hostalen water pipes as a function of immersion time in water at different temperatures. At 20 °C there is no change up to about 2,500 hours.

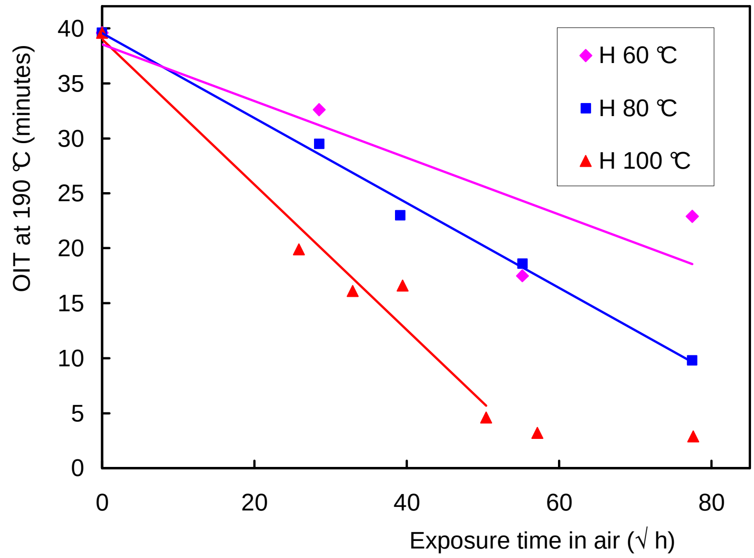

Figure 7. OIT at 190 °C of samples from the external surface of excavated Hostalen gas pipes as a function of exposure time in air at different temperatures. After ±3380 hours at 100 °C the OIT no longer decreases. There is much scatter at 60 °C. Up to 6000 hours (√ time = 77.4) the OIT at 100 °C of the external surface of Vestolen gas pipes decreases from 224 to 57 minutes (off-scale).

OIT after Immersion in Hot Water

Figure 6 gives an example of how the OIT value (at 190 °C) of excavated 40 mm Hostalen water pipes depends on the immersion time in water at different temperatures.

The curves (only of samples from the middle of the pipe wall) are linear as a function of the square root of the immersion time. This suggests a diffusion process. For 32 mm excavated Hostalen gas pipes a plot similar to Figure 6 was made (not shown).

OIT after Exposure to Hot Air

The excavated Hostalen and Vestolen gas pipes have also been exposed to high temperatures in air. The resulting decreases in OIT are shown in Figure 7.

DISCUSSION

Internal Stresses

The excavated first generation pipes still contain considerable internal stresses, although they are compressive in nature. Frank et al [11] found 2.0 to 3.8 MPa for old (mainly) second generation MDPE pipes. In comparison to an LPL of 5.3 and 3.9 MPa such internal stresses are quite influential and should be considered in lifetime predictions.
The internal stresses in the excavated 32 mm gas pipes are lower than those in the excavated 40 mm water pipes and similar to those found in new 32 mm pipes. New 40 mm pipes contain higher residual stresses than new 32 mm pipes. Possibly, 40 mm pipes show a slower stress relaxation than 32 mm pipes, due to the effect of wall thickness.

Internal Water Pressure Tests

Table 5 shows the calculations of the LTHS and the LPL using different models.

Table 5. Prediction of the long-term strength (LTHS and LPL) during additional 50 years of use of excavated first generation HDPE gas and water pipes according to the three or four parameter model in ISO 9080 and according to Barton and Cherry [12] (B&C). MOP: Maximum Operational Pressure.

Pipe type	Model	LTHS (MPa)	LPL (MPa)	Safety factor	MOP (bar) at SDR11
Hostalen unused [2,3]	3 param. 9080	6.3	4.7		
Hostalen gas pipe	4 param. 9080	6.5	5.3	2.0	5.3
Vestolen gas pipe		similar to Hostalen gas pipes			
Hostalen water pipe	3 param. 9080	5.3	3.9	1.25	6.2
Hostalen gas pipe	3 param. B&C	8.8	8.2	-	-
Hostalen water pipe	B&C	8.5-9.0	7.5 – 8.5	-	-

The LTHS of the Hostalen gas pipes is similar to the value published for unused pipes. No decrease was noted after 32 years of use at the aforementioned low gas pressures. The LPL of the excavated pipes is even higher than published earlier, indicating reduced scatter. This could be due to testing equipment and measurements becoming more accurate. For the Vestolen gas pipes the results at 60 and 80 °C are similar to the results of the Hostalen gas pipes (Figure 4), but no LPL calculation is possible.

For the Hostalen water pipes reductions in the LTHS and LPL are noted, so part of the pipe quality seems to have been used up. This is explained by three effects:

1. The water pipes have been used 8 years longer than the gas pipes
2. They were used at a much higher pressure (7 bars) than the gas pipes
3. The water pipes were produced 8 years before the gas pipes. In this time period resin and pipe production will have been improved.

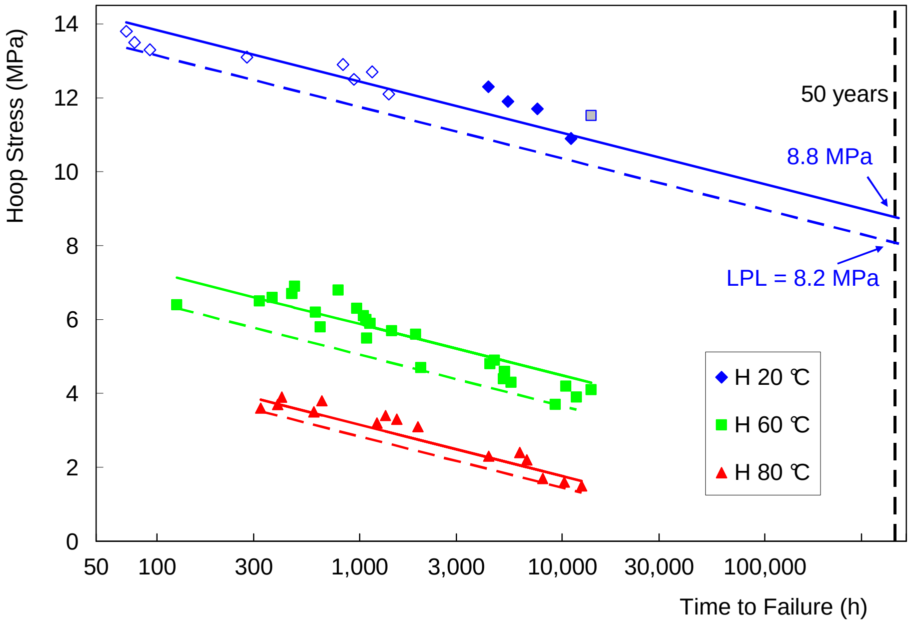

Figure 8. The Hostalen data in Figure 4 plotted on a semi-logarithmic scale according to the model of Barton & Cherry. Open symbols: ductile failures. Grey-filled symbol at 20 °C: un-failed.

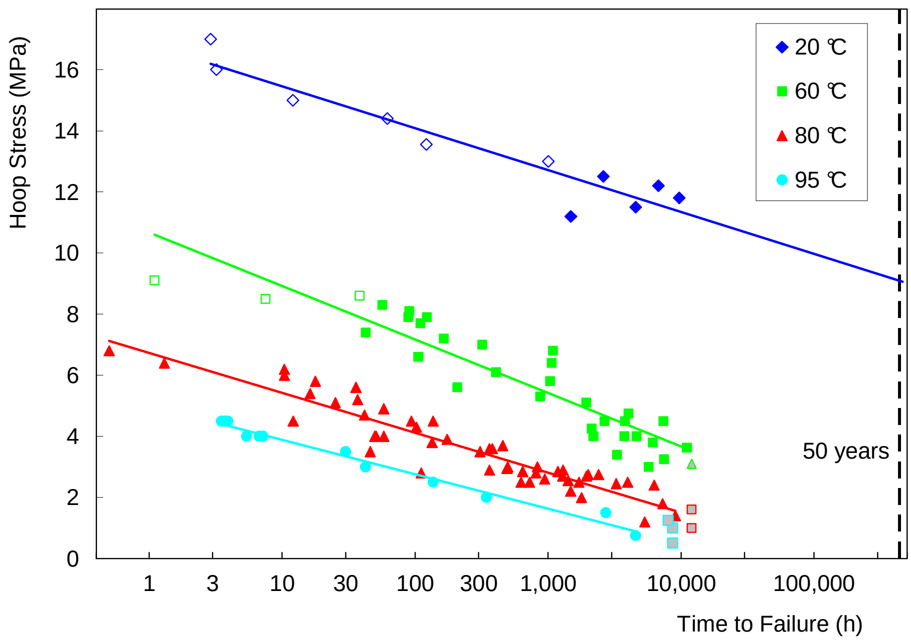

Figure 9. The same data as in Figure 5 plotted on a semi-logarithmic scale according to the model of Barton & Cherry. Open symbols: ductile failures. Grey-filled symbols around 10,000 hours: un-failed.

Barton & Cherry's Model for Internal Water Pressure Tests

The downward curvature of the Hostalen data at 80 °C in Figure 4 triggered the use of an alternative model published by Barton and Cherry [12] (B&C). These authors used the same data set as in Figure 1, with good results. In the B&C model the vertical axis is not on a logarithmic but on a linear stress scale. Due to this, the knee between ductile and brittle branch is lost. Ductile and brittle data points are described by the same straight line.

This behaviour is confirmed in Figure 8 and Figure 9. Most lines are also parallel, except for the 60 °C line of the water pipes. Because in the B&C model a knee is no longer apparent, the predicted LPL value at 50 years is much higher than when using ISO 9080. The results of the B&C model were added to Table 5.

The B&C model is worth considering further, because Visser [13] recently found the knee for PVC pipes is also lost when using this model.

Lifetime of the Antioxidant System

Based on the extrapolated lines in Figure 6 the water immersion time needed to reach OIT=0 at 60, 80 and 95 °C was calculated. Such calculations were also made for excavated Hostalen gas pipes. The results for the water immersions are presented in Figure 10.

The results for the oven tests in air (Figure 7) are presented in Figure 11. There is a relatively large scatter in the line for the Hostalen gas pipes.

The residual lifetime of the antioxidant system in the gas and water pipes seems adequate for the coming years, but the prediction for longer times is somewhat insecure for the Hostalen gas pipes exposed to air (Figure 11).

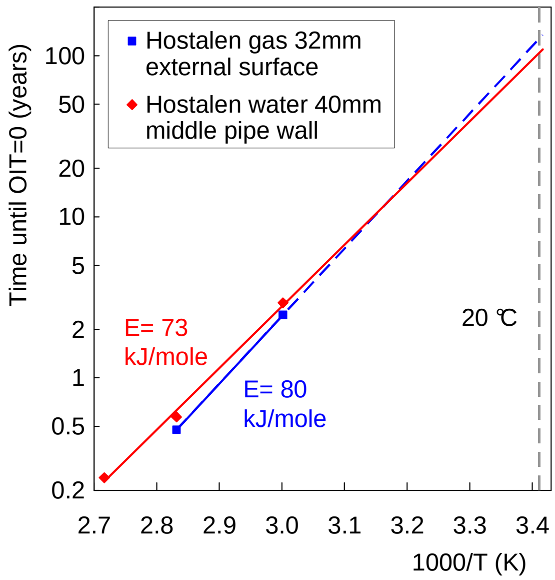

Figure 10. Arrhenius plots of the time until OIT=0 determined after immersion in hot water at 60, 80 and 95 °C of Hostalen gas and water pipes and extrapolation to 20 °C.

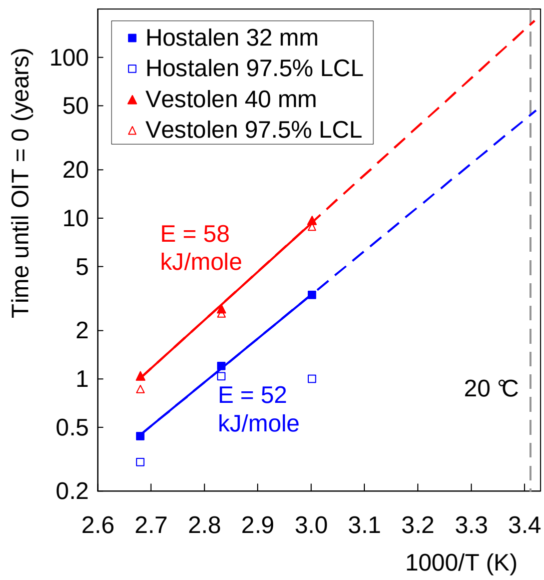

Figure 11. Arrhenius plots of the time until OIT=0 determined in air at 60, 80 and 100 °C of the external surface of Hostalen and Vestolen gas pipes.

CONCLUSIONS AND RECOMMENDATIONS

1. The mechanical properties of the excavated first generation HDPE gas and water pipes are still remarkably good. The residual "MRS" for an additional 50 years of use of the gas pipes is 5.3 MPa and 3.9 MPa for the HDPE water pipes.
2. The extrapolated "lifetime of the antioxidant system" in the pipes at 20 °C is high enough to expect no problems in the near future. Since the mechanical integrity is still rather good, it is worthwhile considering additional testing to enable more accurate predictions.
3. Whilst published data on unused first generation pipes show a ductile-brittle transition at around 10,000 hours of testing at 20 °C, the excavated gas pipes go through this transition between 1,400 and 4,300 hours and the excavated water pipes after 1,500 hours. Still, for all excavated pipes, no "knee" is observed at 20 °C up to 13,800 hours for the gas pipes and 10,000 hours for the water pipes. This phenomenon remains unexplained. Further investigation is recommended.
4. The semi-logarithmic model of Barton & Cherry gives the same good description of the internal water pressure data as the double-logarithmic models in ISO 9080. It is recommended to investigate the usefulness of the B&C model further.
5. After 32 and 40 years of use, internal compressive stresses of 3.0 to 4.6 MPa are still present. Stresses of such magnitude must have a large influence on the results of lifetime prediction models. Further investigation of this is recommended.

ACKNOWLEDGEMENTS

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