PREDICTING THE LIFETIME OF PE50 GAS PIPES UNDER POINT LOADING

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KEYWORDS *PE50, first generation, PE pipe, point load, lifetime, prediction*

ABSTRACT

The residual quality of first generation PE50 gas pipes, installed in Netherland between 1961 and 1979, is still remarkably good. The only premature failures of a few PE50 pipes were exclusively caused by point loads. When under point loading, they started failing in practice after 8 to 26 years, in a brittle manner.
The effect of point loads was modeled in order to help grid-owners to prioritize replacements.
Many Point Load Tests (PLTs) were performed using 8 mm indentation and a new Dehyton PL detergent on excavated, defect-free, 110 mm PE50 gas pipes. The influence of temperature (40, 60 and 80 °C), pressure and SDR (standard dimension ratio) was measured and later modeled using a multi-variate statistical model. The squared correlation coefficient (R^2) was found to be favorably high: 0.940. For all three variables, the statistical probability (P_{stat}) of there being no correlation is favorably low (for all three variables <0.033), and lower than the requirement (<0.05). All three variables therefore have a separate effect on lifetime.
The PLT model shows that a lower gas pressure reduces the effect of a point load and that thin-walled PE50 pipes fail sooner than thick-walled pipes, probably because in a thin-walled pipe a growing crack needs to travel a shorter distance through the wall until a leak is formed.
The acceleration factor in the PLT with Dehyton PL detergent with respect to water is 16. With this factor, the PLT model predicts a lifetime for PE50 pipes at 3 and 4 bars and 10 °C of 5 to 35 years, which is remarkably close to practice, demonstrating the value of the PLT model.
When, for the sake of argument, the LPL in ISO 9080 for PE50 pipes without point loads is extrapolated a failure time of about 4,300 *years at 4 bars and 10 °C is calculated.*
The time to failure in the PLT for PE80 pipes is 9 to 10 times longer than for PE50 pipes.

INTRODUCTION

PE50 (first-generation PE) pipes were first used in Netherland in 1961 and a few years earlier in Germany [1]. The PE50 pipes used in both countries for water and gas distribution pipelines were produced from the same two commercial resins produced by the former companies Hoechst and Huels.
Installation of these first-generation pipes stopped in both countries in 1979, when they were followed up by second-generation PE80 HDPE pipes. The period in which PE50 pipes were used in Netherland and Germany is therefore relatively well defined.
In a previous publication relating to the residual quality of old PE50 pipelines [1] it was concluded that, as long as the PE50 pipes are not exposed to any point loads, they last, at typical pressures of between 2 and 4 bars, much longer than the intended 50 years. This was assessed by internal water pressure tests in accordance with ISO 1167 and calculated in accordance with ISO 9080, on carefully inspected, defect-free excavated pipes.
For these pipes, a remaining MRS value of 5.3 MPa was proven. This can be seen in Figure 1. Consequently, in the absence of any point loads, old PE50 gas and water pipes do not pose a problem in terms of the residual lifetime at 2 to 4 bars pressure or even somewhat higher.

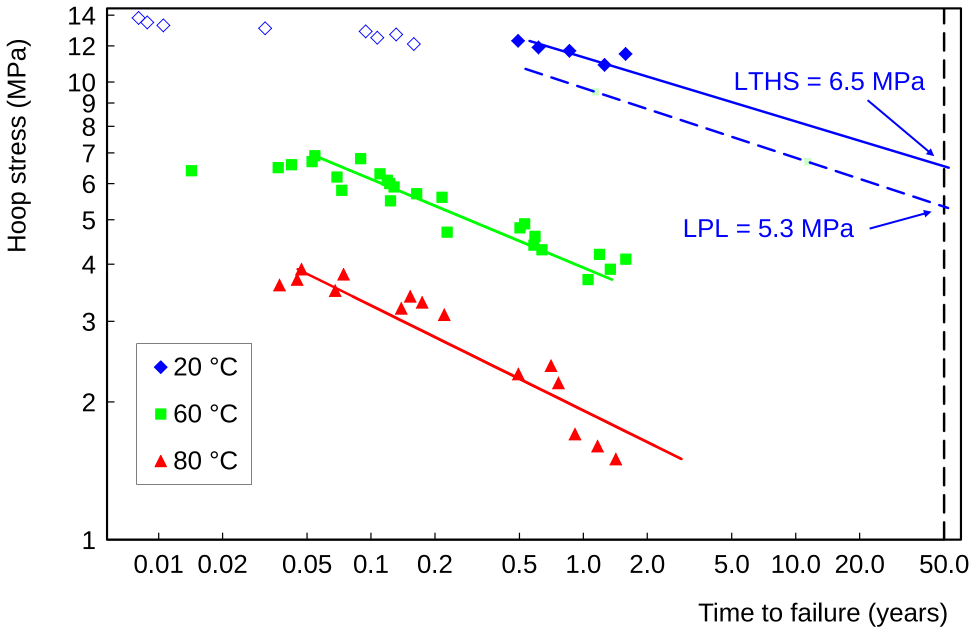

Figure 1. Internal Water Pressure tests evaluated according to ISO 9080 on excavated German PE50 gas pipes, after 32 years of use. Reproduced from [1]. *Open symbols: ductile failures, closed symbols: brittle failures. The Lower Probability Limit (LPL) proves the MRS class was still above 5 MPa.*

This conclusion also follows from another project [2] that is running in the lab of the authors since 2004. During a period of 12 years about 200 excavated PE50 pipes were gathered and tested using the PENT test. Again, excavated PE50 pipe segments that showed any signs of point loading were carefully removed from the study.
Also in this project no negative influence of the operation time was found.
This is not surprising. Figure 1 is valid for the situation without point loads. If the LPL at 20 °C is extrapolated to hoop stresses linked to 4 bar pressure, a time to failure of about 4,300 years is calculated. This seems rather long.

However, the presence of point loads may change the situation drastically. The first complaints about failed PE50 gas pipes were noted in Netherland in 1987. Investigations showed that these premature failures were always due to point loads. This finding was first described in a publication as far back as 1992 [3].

Occasional point load failures in PE50 gas pipelines continue to occur but in low numbers. The failure statistics for PE gas pipes in Netherland still remain similar to values found in other countries. Moreover, gas leaks caused by the slit-like, relatively small brittle failures due to point loads are not very large (Figure 2).
For the purpose of comparison with the point load model set up in this publication, it was calculated that the time to failure of Dutch PE50 gas pipes that started failing due to point loading varied between 8 (1987 minus 1979) and 26 years (1987 minus 1961) [4].

Figure 3 explains why a point load acting on the external surface of the pipe not only leads to additional compression stresses at the outside surface but also to additional tensile stresses on the internal pipe surface. These additional tensile forces align more or less with the hoop stress (tangential tensile stress) caused by the internal pressure and reduce the time to failure considerably, as will be shown.

Figure 2. Brittle failure on the inner surface of an excavated PE50 gas pipe due to a point load. The failure occurred in practice. The crack on the inside of the pipe bore is 75 mm long but the crack on the external surface is only 1 – 2 mm (not shown). The axial pipe direction is horizontal.

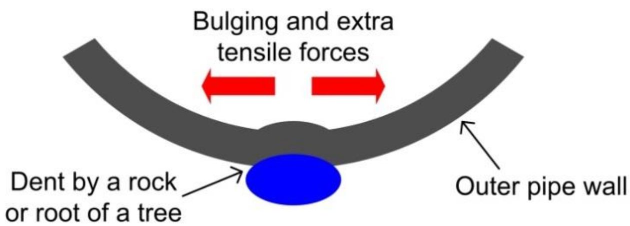

Figure 3. A point load acting externally on a PE pipe leads to additional tensile stresses on the inside of the pipe (schematic). These additional tensile stresses lead to premature failure, with respect to the situation without point loads.

Point Load Tests

ISO 1167 does not cover this loading condition. The purpose of the present paper is to predict, using the Point Load Test (PLT) on pipe segments, how long and in which conditions PE50 pipes may be used when point loads are present.

Goal

The work described in this publication focuses not only on old PE50 pipelines but also on the variables that govern the time to failure of these point-loaded pipes. This knowledge will also be valuable for future point load tests on PE100 RC pipes in order to determine whether these pipes can be used in installations without sand beds, in other words in circumstances where it is certain that there will be point loading.

EXPERIMENTAL METHODS AND MATERIALS

Figure 4 shows the equipment used for the PLT and Figure 5 gives a view of the point loading device surrounding the tested pipe. Point load equipment built by Sciteq A/S, Denmark was used.
A detergent reduces the time to failure in slow crack growth tests on PE materials. In this study, Arkopal N100 was finally completely abandoned because it degrades rather quickly at 80 °C, as is already known for a very long time [9,10]. It was replaced with two much more stable but also more aggressive detergents.
Some initial tests were performed using Disponil but Dehyton PL is currently the best choice because it shows the least degradation at 80 °C [5]. As the results in the present publication will confirm the time to failure in both detergents is similar.
The detergents Disponil LDBS 25 and Dehyton PL were purchased from BTC Specialty Chemical Distribution Unit, Waterloo, Belgium (BASF).

PE50 pipes were taken from the old gas grids in Netherland. The segments to be tested were first carefully examined and those containing any defects due to point loads or otherwise were rejected. Only 110 mm pipes were tested, but the wall thicknesses (SDR) varied.
This publication defines SDR as the measured external diameter divided by the measured wall thickness. These values may be different from (usually lower than) the official SDR classes, because pipe manufacturers made the pipe walls slightly thicker than necessary.

Figure 4. Execution of the PLT. The PE pipe segment is hydrostatically tested with a 2% detergent solution pumped through the inside and an additional point load on the external surface in the middle.

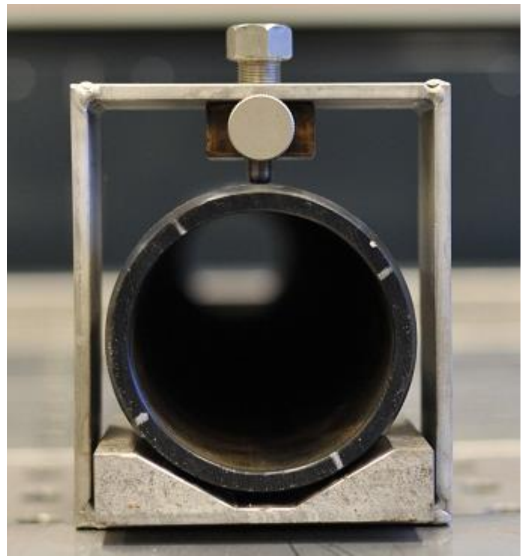

Figure 5. The point loading tool at the top (diameter 10 mm with round top) and the support at the bottom. A 110 mm PE pipe is placed in between.

RESULTS

The first PLTs served to assess the effect of the indentation depth. An indentation of between 4 and 10 mm made by the point load has no influence on the results. This was already published previously [6]. The PLTs described in this publication were therefore all performed with the same indentation of 8 mm.

To set up the model, many point load tests were performed at various internal pressures, temperatures and SDR values.

Figure 6 shows the effect of temperature and hoop stress (apart from the stress caused by the point load) for PE50 pipes. The lower the hoop stress (depending on the testing pressure inside the pipe) and the testing temperature, the longer the time to failure.

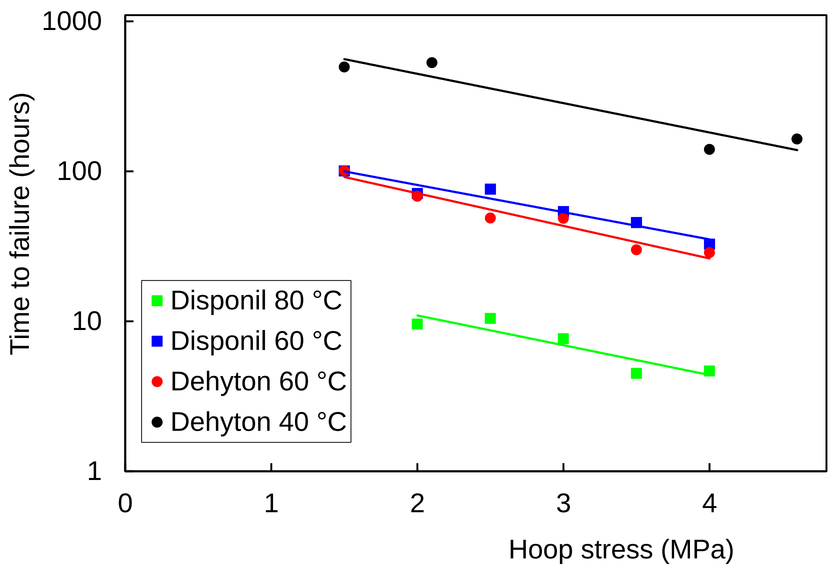

Figure 6. Influence of the hoop stress (calculated from the internal pressure) and the testing temperature using two very similar detergents, at 8 mm indentation of the point load.

Two different detergents were used. Disponil was used for the initial measurements at 80 and 60 °C in Figure 6. Later, information was received [5] that another detergent with almost the same acceleration factor is more stable in the long run at 80 °C. Confirmation that this accelerating factor is almost the same can be seen in the two lines obtained at 60 °C. The results at 40 °C were obtained using Dehyton PL only.

Figure 7 shows the measured times to failure at 60 °C of PE50 pipes as a function of the internal pressure for three different wall thicknesses. There is a lot of scatter in the values for the SDR22 pipes because small thickness variations have a relatively large influence in these thin walls, in percentage terms.

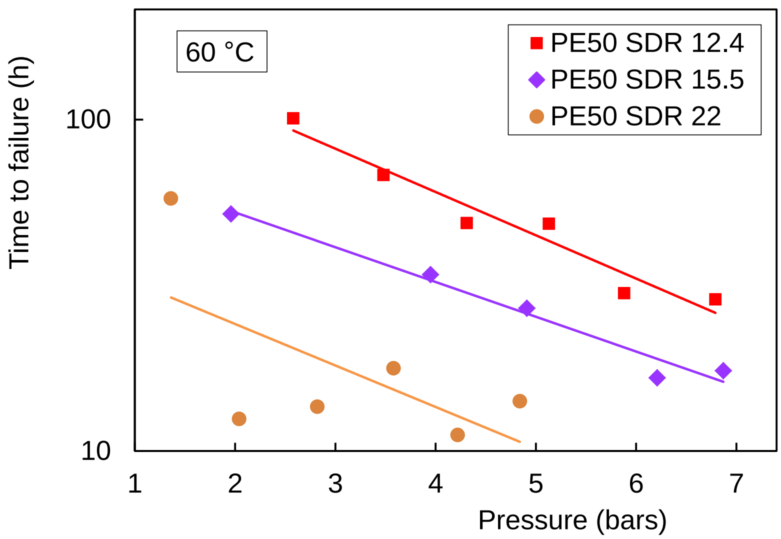

Figure 7. Failure times for 110 mm PE50 pipes with three SDR values in the PLT at 60 °C plotted as a function of the internal pressure. When the SDR increases (the wall thickness decreases), the time to failure decreases.

Tests on PE80 HDPE and PE100 pipes

Figure 8 shows the results for SDR10.6 PE80 HDPE pipes tested using the PLT. It is best to compare these results with PE50 pipes with a similar SDR, in this case the SDR12.4 PE50 pipes (red data points). It appears that the times to failure for the PE80 HDPE pipes are about 9 to 10 times as long as for the PE50 pipes.

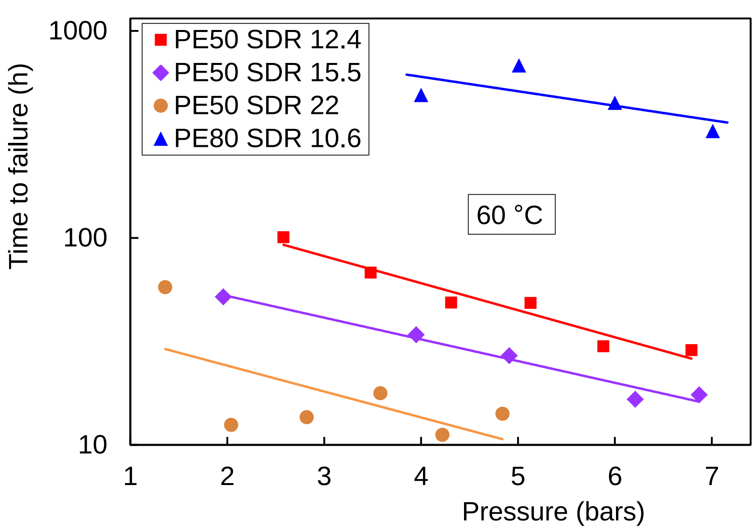

Figure 8. Addition of the results from the PLT on PE80 HDPE pipes at 60 °C to Figure 7.

Another comparison between different PE generations was made using the PLT at 80 °C. Figure 9 shows the results of point load tests on first-, second- and third-generation HDPE pipes tested at 4 MPa hoop stress. The increase in the time to failure in the sequence PE50, PE80 and PE100 is quite large.
However, it is emphasized that PE80 MDPE pipes may behave differently in the PLT than PE80 HDPE pipes. PE80 MDPE pipes have not yet been investigated by the authors.

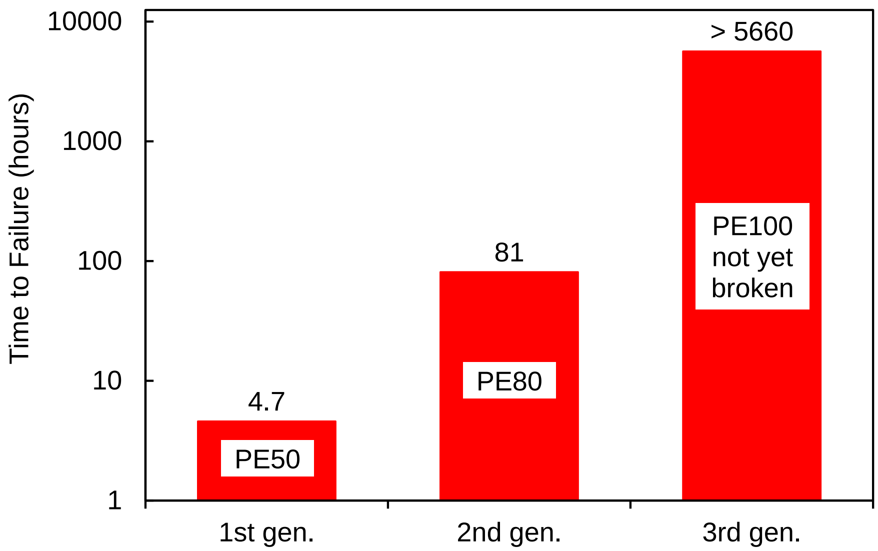

Figure 9. Failure times in the PLTs on three generations of HDPE pipes at 4.0 MPa hoop stress at 8 mm indentation and at 80 °C. The PE50 pipe is SDR12.4, the PE80 HDPE pipe is SDR11. The SDR11 PE100 pipe has not yet failed.

Shortening the duration of the PLT

It has been discussed for some years that the turbulence of the 2% detergent solution inside the tested pipe segment plays a role. It is undesirable for a stagnant layer to develop on the inner pipe surface due to laminar flow inside the pipe. This might prevent the continuous refreshment of the detergent solution acting on the stressed pipe. A turbulent flow is considered to be preferable.
A check was therefore conducted to determine whether a more turbulent flow provided by a lance that directs the detergent solution exactly to the location of the tensile stresses on the inner pipe surface will result in shorter times to failure. Figure 10 shows that this is indeed the case.

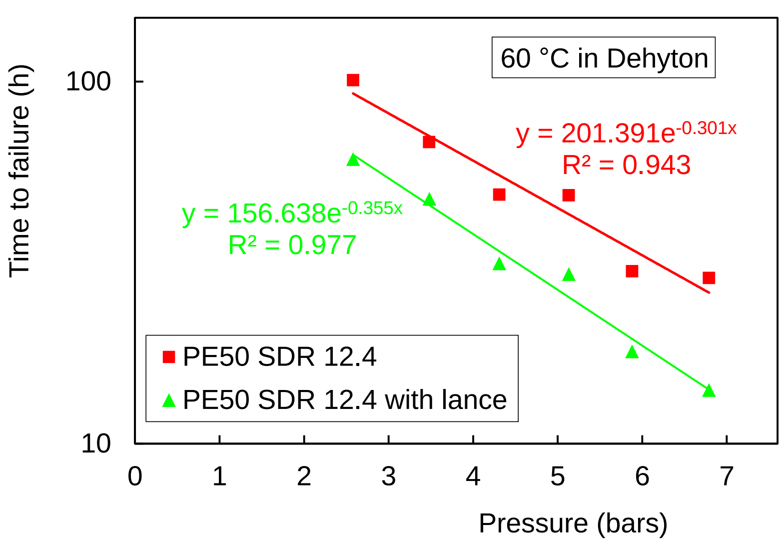

Figure 10. A reduction of the time to failure by about 40% when the turbulence of the detergent solution inside the tested pipe segment is increased. Measured on SDR12.4 PE50 pipe segments at 60 °C in 2% Dehyton PL in water.

DISCUSSION

The influence of temperature (40, 60 and 80 °C), pressure and SDR as shown in Figure 6 and Figure 7 was modeled using SigmaPlot, software for multivariate statistics [7]. Equation (1) was set up:

$$^{10}\text{Log}\ t_f = -\ a_0 + a_1 * (1000/T) - a_2 * \text{SDR} - a_3 * P \qquad (1)$$

where:
t_f = failure time (h), T = temperature (K) and P = pressure (bar).
a_0 through to a_3 follow from the best fit and are all positive.

Table 1. The values of a0 to a3 as found from the best fit in the model.

Parameter	a0	a1	a2	a3
	-10.042	4.359	-0.0647	-0.121

From the value of a1 the activation energy (temperature dependence) of the failure process may be calculated, when the factor of 2.305 for the conversion from ^{10}log to the natural logarithm is used. The value of the activation energy is 83.5 kJoule/mole. This is close to the activation energy for another slow crack growth test, the PENT, which was determined as 85 – 95 kJoule/mole [8].

Table 1 shows the values of the parameters a0 through to a3 that were found from the best fit of the model to the data.
The squared correlation coefficient (R^2) was found to be favorably high: 0.940. For each of the three variables, the statistical probability P_{stat} of there being no correlation (that the Null Hypothesis is true) is also important. It is usually required that P_{stat} is lower than 0.05. In other words this means that there should be less than 5% chance that there is no correlation. Obviously, this also means that for each of the three variables the chance there is a correlation indeed is more than 95 %.
In each case, P_{stat} is favorably low: < 0.001 for the influence of 1000/T, < 0.001 for the influence of pressure and 0.033 for the influence of SDR. All three P_{stat} values are therefore lower than the requirement (< 0.05). Therefore, all three variables have a separate and statistically significant effect on the lifetime in the PLT.

Gas grid owners who have old PE50 pipelines in which point loads are active can now be advised to give priority to replacing thin-walled pipes. Moreover, it is clearly advantageous – if the required minimum gas flow at the extremities of the gas grid allows – to lower the gas pressure. The negative effect of the same point load is much smaller at lower gas pressures.
The remaining question is: Do the model predictions based on the PLT results at elevated temperatures with detergent also produce credible lifetimes at actual soil temperatures in the absence of a detergent?

Comparison with practice

To make the required quantitative predictions the accelerating factor caused by a solution of 2% Dehyton PL in water needs to be known. In the point load test, this detergent leads to an acceleration of the failure rate by a factor of 16 by comparison with point load tests on PE50 pipes in water. The relevant and desired failure mechanism, brittle behavior, is unaffected.
The average failure times at elevated temperatures and in the presence of 2% Dehyton PL can now be used to predict the average failure time without detergent at, for instance, 10 and 14 °C. The results are given in Table 2.

Table 2. Predictions based on the model in equation (1) of the lifetime of PE50 pipes under point loading. For comparison: failure times from practice for PE50 pipes under point loading range from 8 to 26 years.

Temperature (°C)	Measured SDR	SDR class	Pressure (bar)	Predicted average lifetime (y)
10	12.4	13.6	2.0	35.2
10	17.6	17.6	2.0	16.9
10	22.0	26.0	2.0	9.1
10	12.4	13.6	3.0	26.6
10	17.6	17.6	3.0	12.8
10	22.0	26.0	3.0	6.9
10	12.4	13.6	4.0	20.1
10	17.6	17.6	4.0	9.7
10	22.0	26.0	4.0	5.2
14	12.4	13.6	4.0	11.9
14	17.6	17.6	4.0	5.7
14	22.0	26.0	4.0	3.1

The values in Table 2 (3 to 35 years) are in the same order of magnitude as the failure times of PE50 pipes that have failed within 50 years - in other words, prematurely - in practice. The failure times for these pipes were between 8 and 26 years, as calculated in the Introduction. This is encouraging because this is one of the first times that a good match has been found between predictions based on lab results and lifetimes noted in practice.
It is also interesting to note that an increase in the soil temperature from 10 to 14 °C at 4 bars almost halves the predicted lifetime.

The results in Figure 8 show that PE80 pipes have a time to failure which is about 9 to 10 times as long as the time to failure of PE50 pipes, although only a limited number of tests have been performed with PE80 HDPE pipes. Still, when estimating the behavior of PE80 pipes, as is performed below, it is assumed that the three variables such as the SDR, internal pressure and temperature behave in the same manner as for PE50 pipes.

The lowest predicted time to failure in Table 2 is 5.7 years for SDR 17.6 pipes at 14 °C soil temperature. To stay on the safe side when estimating the average time to failure at this temperature, the value of 5.7 years for the PE50 pipes is multiplied by 9, to arrive at the lowest predicted average lifetime for SDR17.6 PE80 HDPE pipes of about 51 years. This result for PE80 HDPE pipes is relevant for pipeline owners.
However, it is emphasized that PE80 MDPE pipes could behave differently in the PLT than PE80 HDPE pipes.

At present, in 2016, 41 years have passed since the first introduction of yellow MDPE PE80 gas pipes and 37 years since the introduction of black HDPE PE80 gas pipes. At gas pressures of 4 bars or lower, no failures in these grids have yet been observed.

Future work
Now that the average lifetime of PE50 pipes under point loading can be estimated rather accurately, it is useful to assess if even more reliable predictions can be made.
To be able to do so the scatter in the data should be taken into consideration. This scatter must therefore be calculated and described better by using the Lower Prediction Limit (97.5 % lower confidence limit) to determine the minimum time in operation with point loads before failure occurs. It will be useful for owners of pipelines made of PE80 HDPE to know when the first failures due to point loads may be expected with 97.5% certainty. This will require additional PLTs on PE80 HDPE pipes.

In the future, more point load tests will be performed on modern materials, PE100 and PE100 RC pipes, for a project sponsored by DVGW in Germany [11]. The expected failure times for such high quality pipes are quite long, as Figure 9 for a PE100 pipe indicates. Additional acceleration of the PLT will therefore be required for these pipes and this can be achieved by increasing the detergent turbulence. An even larger acceleration factor can probably be achieved by performing point load tests at 90 rather than 80 °C.

PE100 RC pipes will perform even better than the PE100 pipes. PE100 RC pipes are intended for installation without sand bedding at operating pressures of 8 to 10 bars. The gas distribution sector, especially in Germany but also in Netherland, has opted to use these PE100 RC pipes and has expressed confidence in this new resin material. Reliable requirements for PE100 RC pipes in the PLT will however be necessary.

CONCLUSIONS

1. A model was set up based on the PLT at 40, 60 and 80 °C to describe the influence of SDR, internal pressure and temperature, and to estimate lifetime at lower temperatures.
2. There is semi-quantitative agreement between the calculated average lifetime for point-loaded PE50 pipes in field conditions (3-35 years) and lifetimes encountered in practice (8-26 years) when there are point loads. This is a major step forward compared with the extrapolated time to failure of 4,300 years based on the LPL in internal water pressure tests in the absence of a point load.
3. The SDR value (diameter divided by the wall thickness) has a marked effect on the lifetime of PE50 pipes threatened by point loads. Thin pipes fail sooner at the same point load than thick-walled pipes. Owners of old PE50 gas grids are therefore advised, when considering the replacement of PE50 pipelines subject to point loads, to replace thin-walled pipes first.
4. It is suspected that the effect of SDR on the point load resistance can be explained by the assumption that a crack that grows slowly needs more time to reach a critical size for final failure to occur when the pipe wall is thicker.
5. To test PE100 RC materials, the PLT as it is performed now requires further optimization involving an increase in the turbulence inside the tested pipes and testing at 90 rather than at 80 °C.

ACKNOWLEDGMENTS

The financial support from Netbeheer Nederland in The Hague, Netherland is gratefully acknowledged.

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