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Life-Time of Polyethylene Pipes Under Pressure and Exposure to High Temperatures

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1 Experimental techniques

In all about 270 pipes have been pressure tested in both water and air at temperatures between 20 and 105 °C. The longest tests have been running for nearly ten years (83 000 h). The material which has been studied is a medium density polyethylene (type: DGDS-0909 manufacturer: Neste Polyeten AB). The dimensions of the pipe are 32 mm × 2 mm. The material is characterized in [1, 2].

2 Long term hydrostatic testing

Before presenting the individual test results a more general discussion of the degradation mechanisms is given for plastic pipes in hot water. In general, water pipes are subjected to two main types of degradation mechanisms: a chemical and a mechanical. The chemical degradation is caused not only by the temperature but also by the environment. The mechanical degradation is caused by the applied load: in this case the internal excess pressure. The interaction of the two degradation mechanisms is affected by the temperature and loading time. In principle the failure curve for a material can be divided into three stages (I: mechanically, II: mechanical-chemically and III: chemically induced fracture) [3, 4].

The results of the pressure testing of PE-MD, with either water or air as the external environment, are shown in Figs. 1 and 2. The results show that at both 95 and 80 °C air is a more aggressive environment than water. In air at 95 °C Stage III (the chemical knee) occurs after 5000 h. With water as the external environment at 95 °C Stage II (the mechanical knee) occurs after approximately 10000 h. No Stage III has been observed in water after more than 39 000 h. At 80 °C in water Stage III occurred after 30000 h. This result is better than the corresponding result from tests in air, when Stage III occurred after 16 500 h. At 70 °C in an external environment of water Stage III occurred after 50000 h. This is also the life-time which is expected for tests in air at 70 °C, which to date have been running for more than 45 000 h. At 60 °C in water an indication of a Stage II after approximately 75 000 h can be seen.

The results show that it is necessary to take the external environment into consideration when extrapolating results from pressure testing of hot-water pipes.

3 Extrapolations of life-times

In order to obtain a more complete assessment of the extrapolation of life-times an overall Arrhenius relationship has been plotted in Fig. 3. GM 5010 (manufacturer: Hoechst) has been chosen as the standard PE-HD material in this article [5, 6]. The time to reach Stage II is shown in Fig. 3. A similar relationship, but displaces towards longer times, is obtained if the time to failure at a stress level of 3 N/mm^2 is used. It should be pointed out that these relationships for PE-HD are based upon a large statistical population, comprising a large number of experimental results with a relatively large spread [6].

The extrapolation of the life of PE-MD in air is presented in more detail in Fig. 4. This extrapolation includes test results at 105, 95 and 80 °C. This extrapolation is presented in Fig. 3 giving a predicted life at 60 °C of about 109 000 h (12.5 years) and about 35 years at 50 °C. A life of 50 years is predicted at a continuous temperature of 47 °C.

The situation is more complicated for static pressure testing in water. In Fig. 3 the shaded area shows that the time to Stage III is asymptotically approaching the corresponding Stage III curve in air

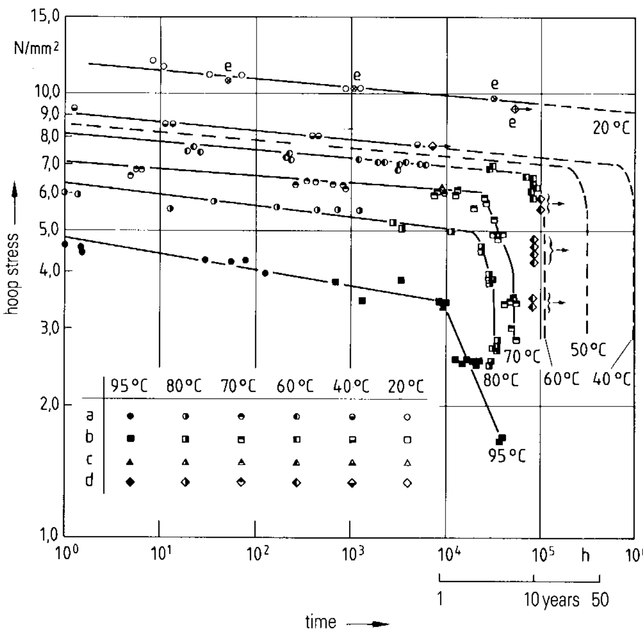

Fig. 1. Extrapolated life-times of PE-MD using test results from pressure testing in water at 70 and 60 °C (internal medium water)
a: ductile mode, b: brittle mode, c: mixed mode, d: under test, e: test series from Neste at 20 °C, test medium water

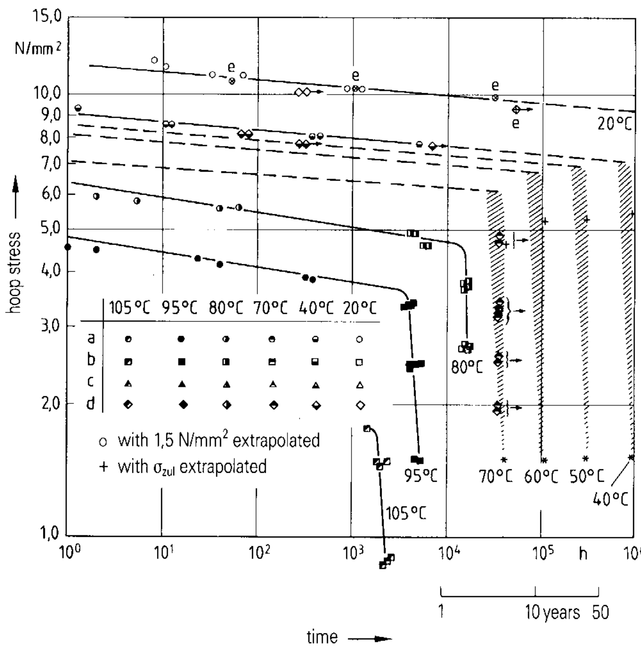

Fig. 2. Extrapolated life-times of PE-MD using test results from pressure testing in air, see Tables 2 and Eqn. 4 (internal medium water)
a to e: as in Fig. 1

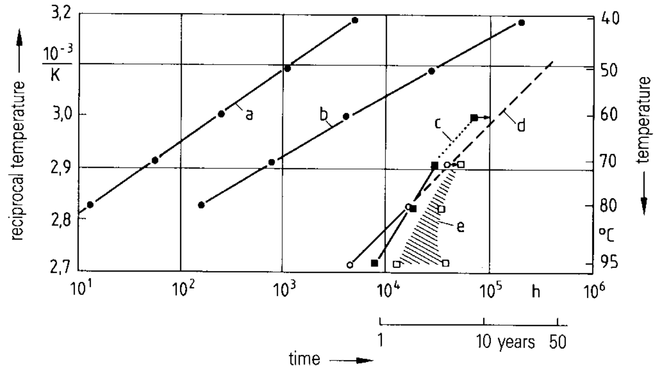

Fig. 3. Arrhenius plot for PE-HD and PE-MD
a: PE-HD, time to reach Stage II, b: PE-HD, time to failure at σ = 3 N/mm², c: PE-MD, time to reach Stage II in water, d: PE-MD, time to reach Stage III in air, e: PE-MD, time to reach Stage III in water (stresses: 95 °C, 2.5 to 1.7 N/mm²; 80 °C, 2.8 to 2.5 N/mm²; 70 °C, 3.5 to 2.8 N/mm²)

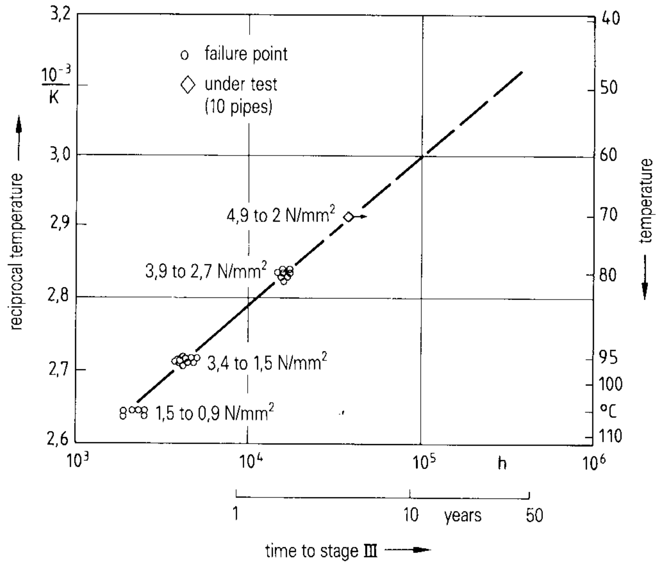

Fig. 4. Arrhenius relationship for PE-MD, the curve has been derived by regression analysis of Stage III failures (regression equation: $1/T = 2.0689 \cdot 10^{-4} \log t_f + 1.9602 \cdot 10^{-3}$, correlation coefficient: 0.9918)

at temperatures below 70°C. it is quite clear that the time to Stage III in water at temperatures higher than 70°C, is longer than it is in air. The largest effect is observed at higher temperatures. This could possibly be related to the fact that the oxygen concentration in the water at high temperatures is so low that the chemical degradation proceeds slower at higher than at lower temperatures.

If the explanation of the different results in air and water is only dependent upon the availability of oxygen, Stage III in water should approach the corresponding air curve asymptotically at lower temperatures. However, several other parameters are changed simultaneously when the temperature is reduced. The material becomes less ductile, which can affect the crack propagation and sensitivity to defects. It is thus not impossible that the shaded area in Fig. 3 will intercept the Stage III curve in air in the same way as was the case for the Stage II. It is most probable, however, that the life (Stage III) at lower temperatures, 70 to 60 °C, is the same in water and in air.

Further it can be noted that for prediction of the life (Stage III) of PE-MD pressure testing in water at higher temperatures is of little value. This is also true for many other materials such as cross-linked polyethylene and other polyethylene qualities [3]. It is therefore unfortunate that in several standards and suggested standards, such as ASTM 2837 and ISO 9080.2 [7], water is the recommended environment for pressure testing. The choice has historic reasons: previously worse pressure testing results have been obtained for example for PE-HD in water than in air [6]. Such material is available commercially today, which means that pressure testing in water could be relevant, but it must be complemented by pressure testing in air.

The results in Fig. 3 show that the time to Stage II for PE-MD in water is much longer than for PE-HD. However, the results at 95 and 80°C cannot be used to extrapolate the time to Stage II at lower temperatures. If the time to Stage II is extrapolated to 60°C from the results obtained at 95, 80 and 70°C then Stage II should occur after about 50000 h. To date a Stage II has been observed at 60°C first after about 75000 h. The conclusion is that the time to Stage II at 95 and 80°C in water cannot be used for extrapolation. This, because the results at 95 and 80°C are "too good". The reason for the good results for Stage II at 95 and 80°C is that water at these temperatures is a less critical environment than at lower temperatures (oxygen solubility).

For dimensioning PE-MD with regard to pressure, information about Stage II is, however, also necessary in order to determine the permissible dimensioning stress. We have chosen to carry out this extrapolation partly based on the pressure tests in air and partly on those in water. Since we consider the effect of water at 95 and 80°C to be erroneous, the results from these tests have not been used. However, we consider that the results in water at 70 and 60°C are representative, and thus these have been included.

With regard to the pressure testing in air, a regression analysis has been performed on all the failures which have occurred in Stage III at 105, 95 and 80°C, since a stress dependence can be observed for Stage III. The results are shown in Table 1. The coefficient of correlation at 105 and 95°C is somewhat low, and at 80°C the fit is very poor. The reason for this is that the slope of the Stage III curve at 80°C is very steep. The slope in Eqn. 3 (see Table 1) is in fact slightly positive, which means that the life is longer at higher stresses. Therefore, it is necessary to obtain complementary failure points at 80°C in particular at low stresses. Even at 95 and 105°C further failure points should be obtained.

Table 1. Regression analysis on Stage III curves for PE-MD from hydrostatic pressure testing in air

Temperature °C	Eqn.	Regression analysis	Coefficient of correlation	Remarks
105	1	$\log t_f = -0{,}227 \log \sigma_f + 3{,}351$	0.658	6 points (1.48 to 0.87 N/mm²)
95	2	$\log t_f = -0{,}256 \log \sigma_f + 3{,}748$	0.636	10 points (3.42 to 1.49 N/mm²)
80	3	$\log t_f = 0{,}014 \log \sigma_f + 4{,}209$	0.006	8 points (3.89 to 2.67 N/mm²)

t_f = time to failure (h), σ_f = hoop stress at failure (N/mm²)

Table 2. Arrhenius relationships for PE-MD at different hoop stresses based on the data in Table 1, see also Fig. 5

σ N/mm²	Based on the data in Table 1	Arrhenius regression	Coefficient of correlation	Time to failure 70 °C h	Time to failure 50 °C h	50 years life °C	Acceleration factors 105 to 95 °C	Acceleration factors 105 to 80 °C	Acceleration factors 105 to 50 °C
1.0	105, 95, 80 °C	$1/T = 2.188 \cdot 10^{-4} \log t_v + 1.907 \cdot 10^{-3}$	0.996	40400	270000	45.3	2.13	7.19	114
1.5	105, 95, 80 °C	$1/T = 2.067 \cdot 10^{-4} \log t_v + 1.959 \cdot 10^{-3}$	0.998	42300	316000	47.0	2.23	8.07	151
3.8	95, 80 °C	$1/T = 1.878 \cdot 10^{-4} \log t_v + 2.041 \cdot 10^{-3}$	-	45300	414000	49.5	–	–	–

Using Eqns. 1 to 3 in Table 1 the predicted failure time can be cal- lated at different stresses. This has been done for the stress levels), 1.5 and 3.8 N/mm^2. These data have been plotted in Fig. 5. ısed on the data an Arrhenius relationship can be established, see ble 2. As can be seen from Table 2 and Fig. 5 better extrapolated lues are obtained if higher stresses are used. This is due to the pre- ›us relationship of the slope of the Stage III curve at 80 °C. The ›advantage of this extrapolation method is that such low stress lev- ; are obtained, because of the high testing temperature. A life ex- ıpolated at σ = 1 to 2 N/mm^2 is quite uninteresting in the temper- ıre range 30 to 50 °C.

An alternative method to extrapolate the life, considered better, is select a specific dimensioning stress for each temperature, and en to establish the Arrhenius relationship from these. The follow- g has been assumed: at every temperature level, 105, 95, 80, 70 and °C, Stage I has been extrapolated linearly to the calculated Stage I. The time to Stage III at different temperatures has been calculat- . by using all Stage III failures at 105, 95 and 80 °C to establish an rhenius relationship (Fig. 4). The stress attained from the extrapo- :ion of Stage I to the time of Stage III at every temperature has en divided by a factor of 1.3, see below. A detailed description of is approach is given in Table 3.

Using the Eqns. 1 to 3 in Table 1, the failure times at 105 °C (1.5 /mm^2), 95 °C (2.7 N/mm^s) and 80 °C (3.6 N/mm^2) can be calculat- l. The stress-time pairs are 2004 h, 4340 h and 16474 h respectively. ısed on these results the following Arrhenius relationship is obtained

$$T = 2.042 \cdot 10^{-4} \log t_v + 1.973 \cdot 10^{-3}, \qquad (4)$$

th t_v = time to failure at σ_{zul} (see Table 3) and temperature T in K; e correlation factor is 0.999. A summarial presentation of the extra- ›lated lifes based on the pressure testing data in air at 105, 95 and °C is shown in Fig. 2. It shows the spread in the extrapolated re- lts depending upon which extrapolation method is used. The slopes all the creep rupture curves after the knee for the temperatures of), 60, 50 and 40°C have been taken to be the same as that for 95°C. hen testing at 70°C in air is complete the slope of the Stage III ırve at lower temperatures can be established with better confi- :nce. The results in Fig. 2 show that for a dimensioning stress of N/mm^2 the following life-times are obtained:

)°C 3 to 4.5 years
)°C 8 to 12 years
)°C 22 to 35[1] years (36 years)[2]
'°C 31 to 50[1] years
;°C 39 to 60[1] years (63 years)[2]
)°C 66 to 105[1] years (110 years)[2]

Analysis shows that extrapolation according to Table 2 using σ = 5 N/mm^2 results in a conservative extrapolation, in particular if ıe considers the results for 70 °C. As can be see from Fig. 2, the two ›ecimens at 5 N/mm^2 have already been running for more than ;000 h. It has therefore been considered that extrapolation accord- g to Eqn. 4 results in better agreement with experimental data from :essure testing in air. In this case a 50 year life for σ_{zul} = 5 N/mm^2 obtained at 47 °C.

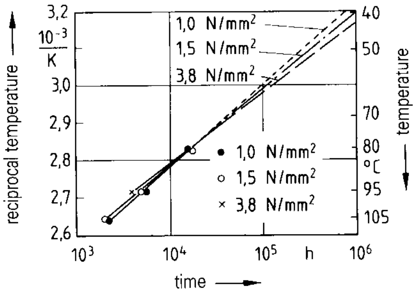

Fig. 5. Arrhenius plot for PE-MD pressure tested in air, the relationship has been determined for different stresses, see Table 2

The results from pressure testing in water can also be used to determine the Stage II to be expected at lower temperatures. In this case only the results at 70 and 60 °C can be used, as discussed previously. In order to determine the time to Stage II at 70 °C regression analysis has been used with all the failures which occurred at 70 °C in water at σ = 4.84 to 5.93 N/mm^2, and the same for Stage I. This analysis predicts that Stage II will occur after 24000 h. If one also assumes that Stage II occurs after 75000 h at 60 °C, then an extrapolation of Stage II as illustrated in Fig. 1 is obtained. It should be pointed out that this extrapolation is preliminary; it is based on only two temperatures. Further there is currently only an indication that Stage II occurs at 60 °C. The extrapolation can, however, be considered to be conservative. The slope for Stage II assumed in Fig. 1 for temperatures below 70 °C has been taken to be the same as that for 70 °C. The following life at σ = 5 N/mm^2 is calculated:

70 °C 3.9 years
60 °C 12 years[3] (15 years)[4]
50 °C 35 years[3] (47 years)[4]
45 °C 60 years[3] (88 years)[4]
40 °C 105 years[3] (170 years)[4]

If the extrapolated life-times, using data from pressure testing in water, have exceeded the Stage III values, using data from pressure testing in air, the latter have been used. For polyethylene pipes dimensioned for a stress of σ_{zul} = 5 N/mm^2 a safety factor of 1.3 has normally been applied. If one takes this into account, it is our opinion that PE-MD at a dimensioning stress of 5 N/mm^2 will have a life of 50 years at 45 °C at the lowest. Continued evaluation together with further test data, primarily from 60 °C, will probably raise this temperature. It must be considered to be most unlikely that the temperature level of 45 °C, predicted for a 50 year life at a dimensioning stress of σ_{zul} = 5 N/mm^2 is too high.

Preliminary calculations have been carried out for PE-MD using ASTM 2837 and ISO 9080.2 [7]. Using test data up to only 10^4 h with water as the external testing environment leads to inaccurate extrapolations. It is therefore very important to use test data from the most critical test environment. In this case test data with air as the external testing environment should be used.

able 3. Calculation of the dimensioning stress σ_{zul} at different temperatures for PE-MD

Temperature °C	Stage III h	σ' at Stage III	$\sigma_{zul} = \frac{\sigma'}{1.3}$ N/mm^2	Remarks
105	2050	1.9	1.5	Stage I unknown, assumed σ' = 1.9 N/mm^2
95	4550	3.5	2.7	σ' from regression analysis of Stage I failures in air and water
80	16500	4.7	3.6	
70	41200	6.0	4.6	σ' from regression analysis of Stage I failures in water
60	109000	6.6	5.1	
50	307000	6.8	5.2	σ' by interpolation
40	923000	7.0	5.4	σ' by preliminary regression analysis
20	10400000	8.7	6.7	

according to Fig. 4
according to Eqn. 4

3 according to Fig. 4
4 extrapolated value for Stage II in Fig. 1 (σ = 5 N/mm^2)

4 Temperature cycling

Extrapolations described so far have been carried out for different specific temperatures. In practical applications the temperature will vary considerably. By use of so-called acceleration factors [4] the life of PE-MD can be calculated for any given temperature durability. In order to check these calculations of life in practice a temperature cycling test was run for PE-MD. The specimen was first held at 95 °C for 7 days and then at 80 °C for 28 days, alternately. In all, four pipes were started at $\sigma = 2.5$ N/mm^2 and four at $\sigma = 1.5$ N/mm^2. Theoretical calculations based on acceleration factors from Table 2 give a predicted failure time of 10500 to 11300 h (13 to 14 cycles). The experimental result was 10000 to 12400 h (12 to 15 cycles) (Fig. 6). The results have shown that the isothermal creep rupture curves can be used to predict the length of life for PE-MD under various non-isothermal conditions. With the performed experimental results very reliable life predictions can be made for PE-MD under any given temperature durability.

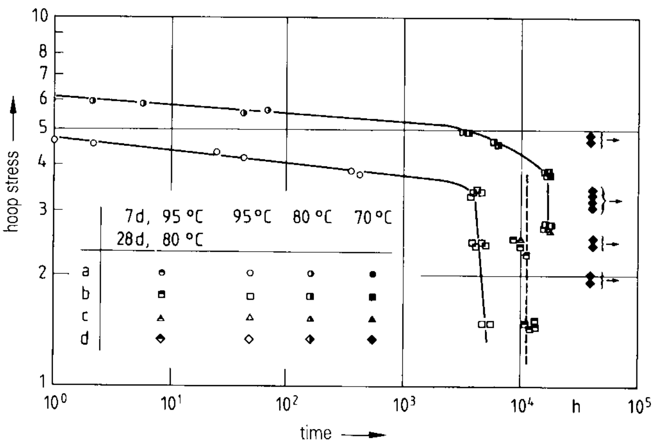

Fig. 6. Hydrostatic pressure testing of PE-MD in air under isothermal and nonisothermal conditions, the predicted life-time for the temperature cycling is drawn as dashed line (test conditions: repeated stress 7d, 95°C; 28d, 80°C; continuous stress 95, 80 and 70°C)
a: ductile mode, b: brittle mode, c: mixed mode, d: under test

5 Summary

Ten years of evaluation of the medium density polyethylene grade, PE-MD, has proven that a 50 years life at 5 N/mm^2 at 50 °C is possible to reach. Based on test data available today a 50 years life at 5 N/mm^2 and 47 °C can be predicted. Further test data will probably raise this temperature level. The evaluation of the PE-MD-material has shown the importance of the external environment for the extrapolation of life-times.

It should be noted that the use of this quality is not limited to temperatures below 50 °C. Short periods of time up to 70 to 80 °C can be tolerated, if only the temperature for the most part is lower (< 50 to 40 °C).

Extensive evaluation of the same PE-MD type have also been carried out on bended, welded and notched pipes. Tests on larger diameter pipes (110 × 10 mm) and tests with different chemicals as the internal testing environment have also been performed as well as pressure cycling of pipes. The results of these investigations will later be published.

The good performance of the new material has shown that PE-MD material, with similar performance, can be expected to be of great interest for several applications with short-term temperature loads up to 80 °C and long-term durabilities at temperatures lower than 50 °C.

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