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Since 1976 Studsvik Energy has been studying more than 12 different PB formulations. The aim of the work has been to study the long term properties of PB-pipes and to determine their life-times at temperatures between 60–95 °C. A total of more than 1100 PB-pipes have been started. The longest tests have been running for more than 8 years. In the article the PB-grade 4137 from Shell has been studied. Different extrapolation methods, including the use of a computer programme based on SEM ISO/DP 9080.2, are presented. Based on the present results on a development grade of PB-4137 a life-time of more than 50 years is estimated at a temperature level of 68–72 °C for stress levels of 5 to 2 MPa. Complementary tests on a commercial PB-4137 indicates that a 50 years life-time is expected at a temperature of 74–78 °C.

1 Experimental techniques

The testing of PB-pipes has been concentrated to hydrostatic pressure testing [1] with both air and water as the external environment at temperatures between 20 and 120 °C.

The results presented in this article have mainly been based on a development grade (PB-A) and a comparable commercial grade (PB-B) from the same manufacturer (product type: PB-4137, manufacturer: Shell Chemie). The tested pipes had a diameter of 22 mm and 15 mm (wall thickness 3,0 and 2,5 mm) for PB-A respectively PB-B.

2 Long term hydrostatic testing

In [1] and [2] an extensive 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 mechanical, II mechanical/chemical and III chemical).

PB-pipes normally have failure curves comprising all three stages. Fig. 1 shows the results for PB-A. The time to the kneepoint between Stage I and II at 110 °C is about 300 h. The corresponding time between Stage II and III is about 10000 h. Regarding the following extrapolation of the life-time for PB-pipes the discussions will be limited to Stage III. Fig. 1 also shows the effect of the external testing environment on the time to Stage II and III at 95 °C. At 4 N/mm² the life-time in water is 1.7 times the corresponding life-time in air. At 2 N/mm² the life-time in air is about 41000 h. In water no failures have occurred after testing for more than 57000 h (6.5 years).

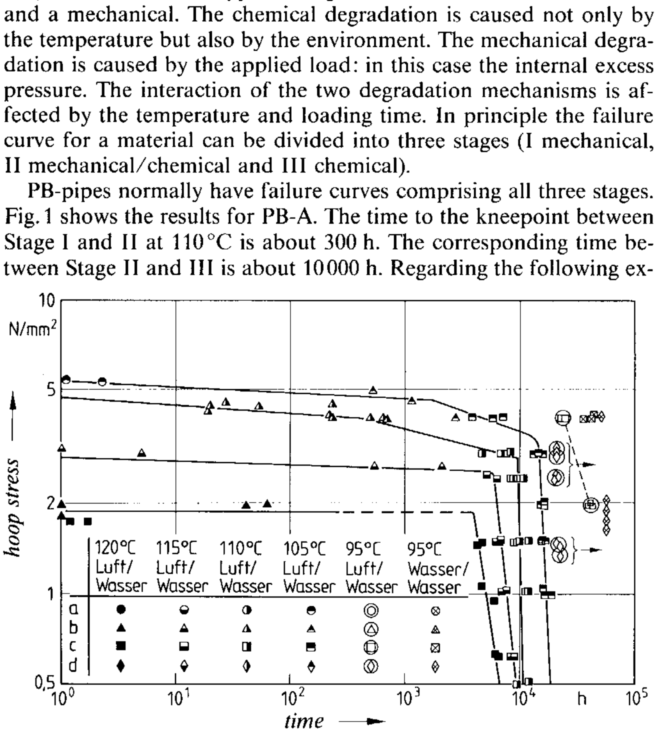

Fig. 1. Hydrostatic pressure testing of PB-A at different temperatures using air as the external environment, at 95 °C both air and water have been used as external environment
a: ductile mode, b: mixed mode, c: brittle mode, d: under test
Luft = air
Wasser = water

3 Life-time prediction

In order to extrapolate Stage III at lower temperatures, hydrostatic pressure testing in air of PB-A has been performed at 120, 115, 110, 105 and 95 °C (see Fig. 1). Regression analysis has been performed on all the failures which have occurred in Stage III. Tests on PB-A have been performed using both commercial brass fittings and plastic fittings made of PVDF. The reason for the study was to investigate the chemical effect of brass fittings for the life-time of PB-A. Although the difference in results was marginal for PB-A it was chosen to use only the results for the brass fittings in the final analysis. The reason for this is to use a homogeneous data lot.

The slope of the Stage III curves for PB-A (Fig. 1) are not as steep as those for cross-linked polyethylene (PE-X) [1, 2]. There is a stress dependence at all temperatures for the Stage III curves for PB-A. The slopes of the Stage III curves increase in the order 120, 115, 105 and 110 °C. This finding is probably a result of material scatter.

Using the results in Fig. 1 the predicted failure time can be calculated at different stresses. This has been done for the stress levels 1.0, 1.5 and 2 N/mm² (Fig. 2). The analysis for $\sigma = 2$ N/mm² based on data from 120, 115, 110 and 105 °C, gives an extrapolated life-time at 95 °C and 2 N/mm² of 40200 h. This result is only 3% lower than the experimental result at 95 °C and 2 N/mm² (average 41320 h, see Fig. 1). The Arrhenius relationships in Fig. 2 are presented in more detail in Table 1. In Table 1 an Arrhenius relationship including the three failure points at 2 N/mm² and 95 °C has also been carried out (method 1 a). In this case an even better agreement is achieved compared to the experimental failure points at 95 °C. The results show that a life-time of 50 years at $\sigma = 2$ N/mm² is obtained at a temperature of at least 72 °C. The corresponding temperature for $\sigma = 1.5$ and 1 N/mm² are 71 and 68 °C respectively. Better extrapolation values are obtained if higher stresses are used. This is a consequence of the different slopes of the Stage III curves at different temperatures. Another disadvantage with the used extrapolation method is that such low stress levels are obtained, because of the high testing temperature. A life-time extrapolated at $\sigma = 1$ to 2 N/mm² is relatively uninteresting in the temperature range 60 to 95 °C.

A second method to extrapolate the life-time is described in [3]. A specific dimensioning stress at each temperature is selected and then the Arrhenius relationship from these established. This method is quite extensive. The results of this method for PB-A is summarized in Table 1.

A third method for extrapolation is to use a multiple linear regression of Stage III. This could be done in several ways. The results presented here have been calculated with a computer programme based on ISO-SEM 9080.2 [4]. A complete evaluation according to ISO-method I or II is impossible because the number of failure points is not enough. The ISO-method does not separate Stage I, II and III. The ISO-method only describes one knee-point at every temperature. We have instead been using only the Stage III failures for PB-A in Fig. 1 and applied models QI and RI for these. The model RI is rejected by the ISO-method due to negative constants. If model RI is to be used positive slopes of the Stage III curve will be obtained for temperatures lower than 100 °C. As can be seen in Fig. 3 model QI correlates very good with the results at 105 °C. At 110 °C the correlation for $\sigma = 1$ to 3 N/mm² is good. At 115 and 120 °C the fits between the QI model and the individual regression analyses are not so good.

Table 1. Comparison between different extrapolation methods for Stage III of PB-A

Method[1)]	Stress N/mm²	Time to failure 95 °C h	85 °C h	60 °C h	Life-time 50 years at °C	Acceleration factors 110 to 95 °C	110 to 85 °C	110 to 60 °C
1	1.0	37000	88000	978000	68	3.39	8.09	89.7
2	1.0	44500	112000	1520000	72	3.85	9.73	132
3	1.0	39000	95800	1150000	69	3.51	8.63	104
3a	1.0	42700	111000	1540000	72	3.81	9.91	138
1	1.5	39000	101000	1420000	71	3.82	9.95	140
2	1.5	40600	103000	1390000	71	3.85	9.76	132
3	1.5	36300	89100	1060000	69	3.51	8.65	103
3a	1.5	39600	103000	1420000	71	3.81	9.90	137
1	2.0	40200	112000	1870000	72	4.18	11.6	194
1a	2.0	41000	115000	2000000	73	4.23	11.9	204
2	2.0	38000	96200	1300000	70	3.85	9.73	132
3	2.0	34500	84500	1000000	68	3.51	8.60	102
3a	2.0	37500	97100	1340000	70	3.78	9.80	135
2	3.0	34700	87800	1190000	69	3.85	9.73	132
3	3.0	32100	78600	928000	67	3.50	8.56	101
3a	3.0	34800	89900	1230000	69	3.77	9.75	133
2	4.0	32500	82300	1120000	69	–	–	–
3	4.0	30600	74600	878000	67	–	–	–
3a	4.0	33000	85100	1160000	69	–	–	–
2	5.0	–	75100	1020000	68	–	–	–
3	5.0	–	69300	811000	66	–	–	–
3a	5.0	–	81600	1110000	68	–	–	–

1 Explanations see text

As can be seen in Table 1 the multiple linear regression (method 3) is quite conservative. The extrapolated life-time at 2 N/mm² and 95 °C is more than 16 % lower than the real failure points. In order to improve the extrapolation the three failure points at 2 N/mm² and 95 °C have been included in a multiple linear regression in the same way as for method 1a in Table 1. The results of this new method is denoted (3a in Table 1). In this case better agreement is achieved with the experimental failure points at 95 °C but the method is still conservative.

In order to show a complete extrapolated creep rupture curve for PB-A failure points are needed within Stage I and II at different temperatures. The available data points for PB-A are not enough for a multiple linear regression. Fig. 4 shows a schematic complete creep rupture curve for PB. The Stage I and II results refer to a large statistical regression analysis performed by Shell [5] on several PB-grades. For Stage III the results have been extrapolated according to methods 3 and 3a.

Table 1 shows that for all hoop stresses, except $\sigma = 1$ N/mm², the multiple linear regression model (method 3) gives the most conservative values. It is notable that all three methods (methods 1, 2, 3) give a lower extrapolated value at 95 °C and $\sigma = 2$ N/mm² compared to experimental data. The average failure time is 41300 h, see Fig. 4. This result indicates that after completion of the testing of PB-A at 95 °C the extrapolated temperature for 50 years life-time will probably be raised. An indication of this can be obtained by looking at methods 1 a and 3 a where experimental data have been incorporated in the analysis.

In Table 1 the different acceleration factors [1] have also been calculated. Except for $\sigma = 2$ N/mm² the acceleration factors for the three different methods are quite similar. In Table 2 the acceleration factor of Stage III for PB-A is compared with cross-linked polyethylene (PE-X), polyethylene-medium density (PE-MD) [3] and with that recommended according to the SEM-method [4]. To summarize you can state that the calculated acceleration factors for the three polyolefine pipes are very similar. However, there is a small increase in the acceleration factor in the sequence: PE-MD, PB and PE-X. Be-

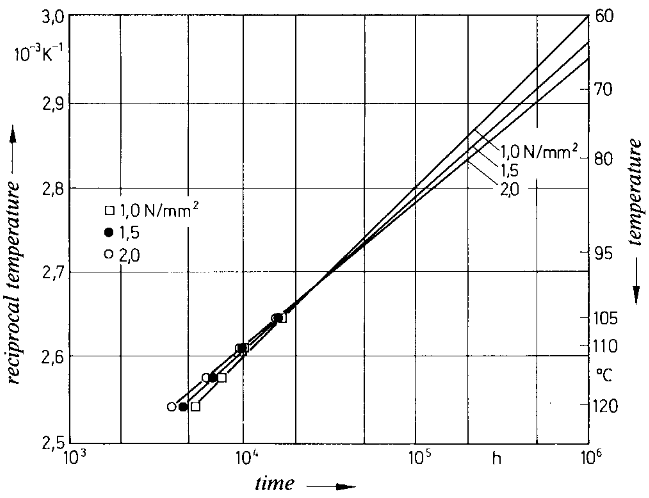

Fig. 2. Arrhenius relationship for PB-A, the curves have been derived by regression analysis of failures at 1, 1.5 and 2 N/mm²

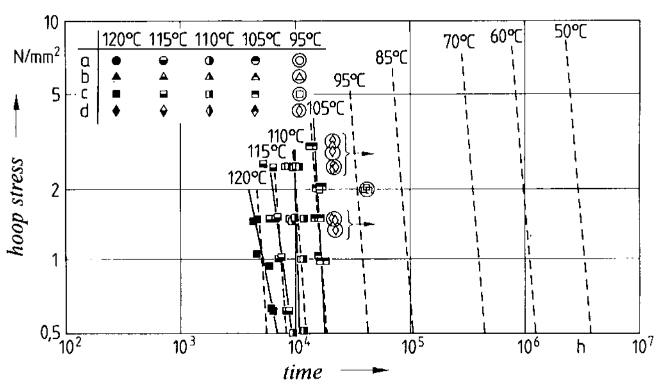

Fig. 3. Stage III failures of PB-A at 120, 115, 110, 105 and 95 °C using air as the external environment; the dotted lines show the results with multiple linear regression according to ISO-SEM 9080.2 [4], model QI; the continued lines represent the individual regression analysis for every testing temperature
a: ductile mode, b: mixed mode, c: brittle mode, d: under test

Table 2. Acceleration factors for crosslinked polyethylene (PE-X), polybutylene (PB) and polyethylene of medium density (PE-MD) [3], and values according to SEM 9080.2 [4]

Temperature range °C	Acceleration factor (Stage III)				
	PE-X[1]	PB[2]	PE-MD[1]	SEM	SEM'[3]
105 to 94.9	2.5	2.5	2.2	3	1
105 to 79.9	11	9.8	8.2	16	9
105 to 69.9	31	30	21	50	28
105 to 59.9	96	81	56	–[4]	50

1 Values investigated at Studsvik [1, 3]
2 PB-A according to Table 1, method 2
3 Results according to SEM for temperature intervals 105 to 95.1 °C, 105 to 80.1 °C, 105 to 70.1 °C, 105 to 60.1 °C
4 Acceleration factors according to SEM are limited to a maximum of 50

fore comparing the results with the SEM-method the following should be taken into consideration: the SEM-method is constructed for a certain temperature interval. This means that the acceleration factor can change very drastically for a very small change in the temperature interval. For example if the temperature interval in Table 2 was 105 to 95.1 °C (ΔT 9.9 °C) the acceleration factor would be 1, see SEM' in Table 2. But all temperature intervals between 10 and 15 °C give an acceleration factor of 3. Depending on how you chose your testing temperatures the extrapolated life-times of the SEM-method could vary by a factor of 1 to 3! Table 2 shows that if an optimistic use of SEM is applied this results in much higher acceleration factors than the ones found for PE-MD, PB and PE-X. But if a more conservative extrapolation, according to SEM in Table 2 are used, good agreement is achieved in comparison with the experimental results. In conclusion we believe that the "step by step" method proposed by SEM may lead to erroneous results regarding lifetime predictions. Instead the proposed multiple linear regression in the ISO-SEM can be applied to Stage III failures and allows direct calculation of acceleration factors for any given temperature interval.

The results in Table 2 show that very similar acceleration factors are achieved regardless of the type of polyolefine pipes. To demonstrate that this is not always the case, studies on experimental grades of polyolefine pipes have shown that higher as well as lower acceleration factors can be obtained.

The different extrapolated life-times for different polyolefine pipes are illustrated by the following examples:

PE-X	62 to 70 °C
PB	67 to 69 °C
PE-MD	47 to 50 °C.

The extrapolated temperatures are valid for a 50 years continuous exposure at a hoop stress of 3 MPa.

The temperature level for PE-X and PB-A is about the same. PE-MD [3] has a temperature level of about 20 °C below PE-X and PB. With new experimental grades using better antioxidant systems much higher temperatures can be obtained [1, 6].

It should be pointed out that some temperature levels refer to a continuous exposure. In practical installations the average temperature is much lower than these values, which signifies a longer lifetime than 50 years. Short temperature peaks of 95 to 110 °C are tolerated, if the temperature lies below 70 to 60 °C during the major part of use.

In order to compare the development grade PB-A with a commercially extruded PB-B, complementary testing has been performed. The results at 110 °C indicate an increase in life-time (Stage III) with a factor of more than 1.5 for the new grade PB-B. Using the acceleration factors in Table 1 a 50 years life-time at 74 to 78 °C can be estimated.

4 Temperature and pressure cycling

In practical installations both the pressure and the temperature varies. The question is, how does this cycle affect the life-times of PB-pipes? At 110 °C the test shows that no effect on the time to Stage III can be found for PB-A under dynamic pressure testing (3 cycles/h). At 95 °C the test is still running with testing times of more than 13 000 h.

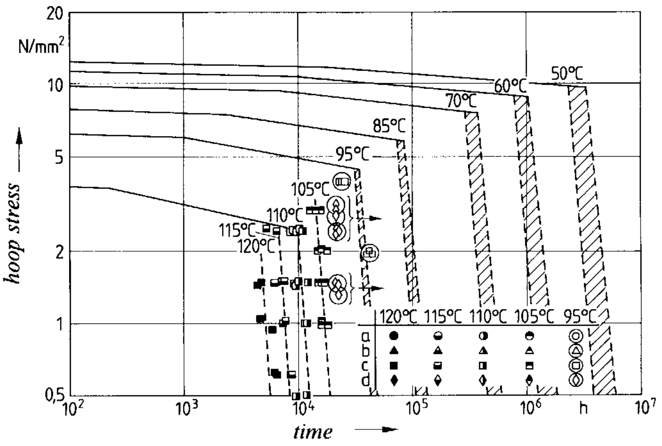

Fig. 4. Stage III failures of PB-A at 120, 115, 110, 105 and 95 °C using air as the external environment; the shaded areas from 95 °C to 50 °C show the results with multiple linear regression according to methods 3 and 3a in Table 1. The continued lines represent the Stage I and II curves for PB pipes according to Shell.
a: ductile mode, b: mixed mode, c: brittle mode, d: under test

In order to check the use of the calculated acceleration factors for PB-A under non-isothermal conditions two sets of experiments have been started, one with a temperature cycling between 110 °C (7 days) and 95 °C (14 days), the other with a cycling between 105 °C (7 days) and 90 °C (14 days), each testing set under pressure of = 2.5 and 1.5 N/mm². These experiments run since more than 11 300 and 12 800 h. One can expect a life-time of more than 19 000 and 32 000 h according to the calculation method described in [3].

5 Other tests performed

Evaluations of PB-A have also been carried out on bended and notched pipes as well as tests with different chemicals. Extensive studies using fractography and chemical analyses have been performed in order to explain the fracture mechanism. These results will later be published.

6 Summary

Three different extrapolation methods give conservative results. The three methods give in most cases the same acceleration factors for PB. The acceleration factors for different polyolefine pipes are very similar. Depending on how the SEM ISO/DP 9080.2 method is applied much too high acceleration factors can be obtained compared to experimental results. This could result in too optimistic life-time predictions.

Literature:

1 *Ifwarson, M.; Eriksson, P.:* Zwölf Jahre Erfahrung bei der Untersuchung von vernetztem PE. Kunststoffe 76 (1986) 3, S. 245–248
2 *Ifwarson, M.; Eriksson P.:* Experience from 12 Years Evaluation of Crosslinked Polyethylene. Plastics Pipes VI (1985). The Plastic and Rubber Institute, S. 40A.1–40A.11
3 *Ifwarson, M.:* Gebrauchsdauer von Polyethylenrohren unter Temperatur- und Druckbelastung. Kunststoffe 79 (1989) 6, S. 525–529
4 ISO Standard Extrapolation Method. Draft Proposal ISO/DP 9080.2.ISO/TC 138 N1081, 1987-01-08
5 Burst Hoop Stress Performance of Pipe Materials. Firmenschrift, Shell Polybutylene 1989
6 *Kramer, D.; Koppelmann, I.:* Alterungsverhalten von Heißwasserrohren aus Polybuten-1 und vernetztem Polyethylen. Kunststoffe 73 (1983) 11, S. 714–716

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