WHICH FACTORS CONTROL THE LIFETIME OF PLASTIC PIPES AND HOW THE LIFETIME CAN BE EXTRAPOLATED

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The lifetime of plastic pipes has been studied at Bodycote Polymer AB (formerly Studsvik Polymer AB) for more than 27 years. This paper presents some of the factors found to control the lifetime of plastic pipes. How to extrapolate the lifetime of plastic pipes will be presented and discussed. A question will also be raised with regards to the test method used in order to determine the lifetime for multi-layer pipes based on an aluminium layer.

INTRODUCTION

Bodycote Polymer AB is an independent research and testing company in Sweden. The company is probably better known as Studsvik Polymer AB. Studsvik Polymer AB changed name to Bodycote Polymer AB in January 2000 when Bodycote plc. became the new owner. Bodycote plc. has its headquarters in the UK, with Bodycote Polymer AB belonging to the Materials Testing Group.

Plastic pipes have been studied at Bodycote Polymer AB (formerly Studsvik Polymer AB) since 1973 [1-14]. The work has mainly been concentrated on the long-term behaviour of plastic pipes for use in gas, cold- and hot water and industrial process applications.

The lifetime of a plastic pipe (the creep rupture curve) can be divided into three stages: Stage I, II and III depending on the mode of failure, see Figure 1. The lifetime of a plastic pipe is controlled by: <u>material</u>, <u>environmental</u> and <u>loading</u> factors.

The use of plastic pipes for pressure applications depends strongly on the possibility of establishing the allowable hoop stress (or design stress), which a pipe should withstand without failure. Due to the lack of international standards for calculating the allowable hoop stress, numerous studies and proposals were initiated in the mid-1970s. This work resulted in the Technical Report ISO/TR 9080:1992(E). ISO/TR 9080 describes a Standard Extrapolation Method (SEM) for obtaining the expected hoop stress, which a pipe can withstand using a certain probability level at defined times and temperatures. Later on a new draft version, ISO/DIS 9080:1999(E), was issued.

The use of multi-layer pipes comprising of an aluminium layer sandwiched between two plastic layers has expanded considerably within different plumbing applications in Europe. The test procedures developed for ensuring long lifetime of these multi-layer pipes have usually followed the corresponding test methods for ordinary hot water plastic pipes such as PEX, PP and PB. The most common test procedure used to establish the allowable hoop stress (or design stress) is the Standard Extrapolation Method (SEM). This means that extensive pressure testing has been performed for many multi-layer pipes.

THE PROBLEM WITH PLASTIC PIPES

The basic difference between pressurised plastic and metal pipes operating at close to ambient temperature is that the plastic pipes are being used very close to their melting temperatures. Plastic pipes have many advantages compared with metal pipes such as no corrosion, low weight, low material cost, low installation costs and greater flexibility. Plastic pipes can also be delivered in long lengths avoiding fittings and welds. The major disadvantage with plastic pipes is their inferior temperature resistance compared with metal pipes. Since plastic pipes are used at relatively high temperatures, the pipes will be subjected to creep. This is the reason why it is so important to perform long-term creep rupture testing on plastic pipes.

In Figure 1 a schematic creep rupture curve is presented. The creep rupture curve can be divided into three stages, Stage I, Stage II and Stage III. During Stage I the pipe is mainly subjected to mechanical overload. In this portion of the curve the failure is almost always ductile (plastic instability). Sometimes brittle failures may occur at Stage I level due to the presence of different defects in the material. The slope of the curve increases during Stage II. The first "knee" which is observed has sometimes been called the "mechanical knee". Transition or brittle failures are the most common types in Stage II. Stage III is characterized by the fact that the failure time is virtually independent of the hoop stress. The second "knee" is known as the "chemical knee" and indicates the chemical life of the material under loaded conditions. In Stage III failures are almost exclusively brittle.

For all plastic pipes Stage I is important to determine. For gas pipes Stage II is also an interesting stage to study. For hot water pipes Stage III is probably the most important stage.

In general, the lifetime (Stages I, II and III) is a function of material, environmental and loading factors, see Figure 2. The main factors may further be divided into a number of sub-factors, see Figure 3. The number of different sub-factors affecting the lifetime is large. In order to be able to predict a certain lifetime, it is necessary to develop a test programme for the specific application including all the critical sub-factors. Of particular interest are Stages II and III because these stages control the lifetime of a plastic pipe in practice.

A very important material factor to consider is the manufacturing process since even the best resin will give a poor pipe if a bad manufacturing process is used. It is therefore very important that lifetime testing is performed on the final component for the specific application. The internal and external production controls are very important. Problems, which may occur during pipe extrusion, are described in references [15-18].

An example of an environmental factor, which has been intensively discussed in recent years, is chlorinated water and its effects on the lifetime of plastic pipes. In 1992 Bodycote Polymer AB (formerly Studsvik Polymer AB) initiated a project to study the influence of chlorine, added as a sterilant to potable water, on the performance of plastic pipes [19]. Over the last seven years, Bodycote has completed a number of projects for clients to investigate the influence of chlorine in potable water on pipes produced from polyolefins such as Polybutylene-1 (PB), Polyethylene (PE), Cross-linked Polyethylene (PEX), Polypropylene (PP) and multi-layer pipes. A considerable amount of data has been generated which demonstrates without doubt that small quantities of chlorine exhibit a strong oxidising effect on polyolefin pipes resulting in a significant reduction of the expected lifetime. The conclusions today are that it is probably not only the antioxidant system that is important for chlorine resistance. The chlorinated water initiates so called "chemically induced notches" in the pipe wall. The crack propagation of these notches is then controlled by the slow crack growth behaviour of the material.

As can be seen in Figure 3 the temperature is defined as a loading factor. Normally for metallic materials the temperature is defined as an environmental factor but for polymer materials the temperature has such a strong effect and gives such limitations, compared to metallic materials, that we have defined the temperature as a loading factor. The effect of the temperature on polymer materials is vital. The lifetime in service, which is the time to Stage II and Stage III, decreases when the temperature is increased. This has been used in a number of accelerated extrapolation methods in order to predict the lifetime at lower temperatures.

EXPERIMENTAL PROCEDURES

The question is which testing method should be chosen in order to determine the lifetime for plastic pipes. Before that question will be answered a short description of the pressure test equipment used at Bodycote Polymer AB will be presented.

The equipment for hydrostatic pressure testing has been designed and built by Bodycote Polymer AB (formerly Studsvik Polymer AB), see Figure 4. The pressure is generated using compressed nitrogen. The nitrogen is led through an electronic pressure regulator. From the pressure regulator a specific pressure is now achieved. The specific pressure goes into a float valve. In the float valve the pressurised medium is changed from gas to water. Out from the float valve pressurised water is now in connection with the pipe. The pipe can then be exposed to water or air at elevated temperatures. When the pipe fails the water will flow out from the pipe and the float will drop, actuating a photocell to record the failure time and isolating the pipe specimen from the pressurised nitrogen system.

The reason why hydrostatic pressure testing is an excellent test method is because it considers the following factors:

- **Material factors**
  Complete control over both the material and the manufacturing process.

- **Environmental factors**
  Within the test procedure a simulation of the real environments on the inside as well as the outside can be performed. Different types of commercial fittings can also be used.

- **Loading factors**
  Complete control over both temperature and pressure. The pipe can be subjected to notches, scratches or include welds. The pipe can also be bended. With small adjustment pressure- and temperature cycling can be performed [22].

EXTRAPOLATION METHODS TO PREDICT THE LIFETIME

The assessment of the reliability of plastic pipes in service for use in pressurised applications is strongly dependent upon the method used for estimating the lifetime and ensuring safe operation for 50 years or more. Usually, the question is what is the expected lifetime for a certain pipe material subjected to given service conditions, i.e. a given combination of temperature and stress. Since long-term testing is very costly and time consuming there is obviously a need for accurate and well accepted (standardised) accelerated testing methods, allowing extrapolation of the lifetime to actual service conditions. Two commonly used methods for lifetime predictions are the Arrhenius method [20] and Miner's rule [21, 22]. Whereas the Arrhenius method considers only the temperature, Miner's rule can be used to estimate the time to failure at various temperatures and stresses. The Standard Extrapolation Method (SEM) according to ISO/TR 9080 [23], is another method, which is frequently used today to meet this demand.

Based on the experiences from Bodycote Polymer AB (formerly Studsvik Polymer AB) the SEM, ISO/TR 9080:1992(E), is the most promising extrapolation method to describe the creep rupture performance for most pipe materials. One great advantage of the SEM compared to other methods is that it offers a mathematical (multiple linear regression analysis) as well as a statistical treatment of the experimental data obtained from hydrostatic pressure testing. The data obtained from a SEM evaluation are also needed to support the calculations according to Miner's rule. The SEM is further used for classification of pipe materials, e.g. MRS 10 (Minimum Required Strength).

Two models (equations) are included in the SEM, ISO/TR 9080:1992(E), referred to as Models Q and R. The equation of Model R for calculation of the time to failure (t_{fi}) contains four unknown regression coefficients (A, B, C, D) and two independent variables, temperature (T_i) and hoop stress (σ_i), see equation I:

$$t_{fi}(T_i, \sigma_i) = \log(t_{fi}) = -A - (B/T_i) \log(\sigma_i) + C/T_i + D \log(\sigma_i) \qquad Eq. (I)$$

Model Q of ISO/TR 9080 is obtained if the regression coefficient D is set to zero.

During 1999 a new draft version of ISO 9080 called ISO/DIS 9080:1999(E) [24] was presented. The ISO/DIS 9080:1999(E) standard has the same approach as ISO/TR 9080. The differences between these two methods are:

- 30 observations are required according to ISO/DIS 9080 compared with 25 according to ISO/TR 9080.
- In ISO/DIS 9080 deletion of failure points below 1 000 h at temperatures equal or below 40°C is allowed in order to exclude the so-called elbow effect that can appear for some pipe materials. This elbow usually has a negative effect on the extrapolated value at 20°C.
- Different extrapolation factors, k_e factors. The highest k_e factor is 100 in the ISO/DIS 9080 document compared with 50 in the ISO/TR 9080 document.
- The LCL (lower confidence limit) according to ISO/TR 9080 is denoted LPL (lower predicted limit) in ISO/DIS 9080.
- The four unknown regression coefficients are denoted C(1), C(2), C(3) and C(4) corresponding to A, C, D and B in the ISO/TR 9080 document, see equation II.
- Different approaches for the knee detection analyses.

$$log(t_{fi}) = C(1) + C(2)/T_i + C(3)\ log(\sigma_i) + C(4)\ log(\sigma_i)/T_i \qquad Eq.\ (II)$$

The 3-parameter model of ISO/DIS 9080 is obtained if the regression coefficient C(3) is set to zero.

Another major difference between these two documents is the so-called Figure 2 evaluation described in the ISO/DIS 9080:1999(E) document. The Figure 2 evaluation allows evaluation of a pipe material, which shows a knee only at the highest temperature. In Figure 5 an example of a PE pipe material is presented. This pipe material has been pressure tested at 20, 60 and 80°C. As can be seen in Figure 5 the material shows a knee at 80°C but not at 60°C. Before the ISO/DIS 9080:1999(E) document existed an evaluation of a material as shown in Figure 5 could not be performed until a knee was detected at 60°C. This was of course very time consuming and costly for the producers. With the new Figure 2 evaluation described in ISO/DIS 9080:1999(E) it is possible to evaluate a material even though it only shows a knee at the highest temperature.

When all the data has been generated, as shown in Figure 5, the data is evaluated by using a computer program developed for ISO/DIS 9080:1999(E). The computer program will indicate a knee at 80°C. The evaluation will then be performed by using only one type of failure mode i.e. Stage I failures as shown in Figure 6. The time to the knee point in this case, will be the maximum extrapolation time limit at 80°C.

The ISO/DIS 9080:1999(E) standard has now been used for about two years and several evaluations have been performed according to the Figure 2 evaluation. During this time Bodycote Polymer AB has analysed more than 15 materials in this way. A comparison has been made between the Figure 2 evaluation and an evaluation where the highest temperature, e.g. 80°C, has been excluded. The comparison shows that the LPL (lower prediction limit) as well as the LTHS values increase when the Figure 2 evaluation is used. In some cases the LPL value increased as much as 8% and the corresponding value for LTHS was about 6 %. Based on this experience it is suggested that when performing a Figure 2 evaluation a comparison should be made with the evaluation where the highest temperature e.g 80°C is excluded. This suggestion is based on the fact that a material can get a too high classification i.e. MRS (Minimum Required Strength) value by using the Figure 2 evaluation.

HOW TO DETERMINE THE LIFETIME OF MULTI-LAYER PIPES

Hydrostatic pressure testing is a very good test method for most plastic pipes. However, cases exist where Bodycote Polymer AB believes that hydrostatic pressure testing is not the most suitable test method. One such case is pressure testing of multi-layer pipes for use in potable hot water systems.

The use of multi-layer pipes has expanded considerably within different plumbing applications world-wide. The test procedures to determine the long-term performance of the multi-layer pipes have usually followed the corresponding test methods for ordinary hot water plastic pipes such as PEX, PP and PB. Hydrostatic pressure testing is an excellent test method to use for multi-layer pipes if they are going to be used in applications where there is no exchange of water, which would lead to a higher concentration of oxygen on the inside of the pipe. Examples of such applications are floor heating, radiator heating and district heating systems. The problem occurs when multi-layer pipes are used in potable hot water systems, where fresh water, containing oxygen, is continuously added to the system.

When multi-layer pipes are hydrostatically pressure tested the level of oxygen on the inside of the pipes will become almost zero, see Figure 7. The reason for this is that the oxygen cannot diffuse into the pipe through the aluminium layer. The consequence is that the pipe will last for a very long time since the degradation mechanism for hot water pipes is extraction of antioxidants from the inside followed by oxidation. With no oxygen present on the inside a too optimistic prediction of the lifetime may be obtained for the multi-layer pipes used in potable hot water systems. Therefore pressure testing of multi-layer pipes should be performed in a circulation loop with an exchange of water, see Figure 8. If the test is performed in such a circulation loop, fresh water containing oxygen will continuously flow through the pipe and hence the test will be more representative of the real situation.

CONCLUSIONS

- The lifetime of a plastic pipe (the creep rupture curve) can be divided into three stages, Stage I,II and III.

- The lifetime of a plastic pipe is affected by: material, environmental and loading factors. Within each main factor a large number of sub-factors can be found.

- How the different factors affect the different Stages are of vital importance to ensure safe long-term use of plastic pipes. For this reason most of the long-term testing programmes for plastic pipes have to be specified for the specific application.

- Hydrostatic pressure testing is an excellent test method because it considers the Material factors, Environmental factors, and Loading factors.

- According to Bodycote Polymer AB (formerly Studsvik Polymer AB) ISO/TR 9080:1992(E) is the best standard method available for extrapolation of lifetimes for plastic pipes.

- When evaluations are performed according to the draft version ISO/DIS 9080:1999(E) and Figure 2 it is suggested that a comparison should be made with the evaluation where the highest temperature is excluded.

- It is recommended that pressure testing on multi-layer pipes used in potable hot water systems should be carried out in a circulation loop in order not to get a too optimistic lifetime prediction.

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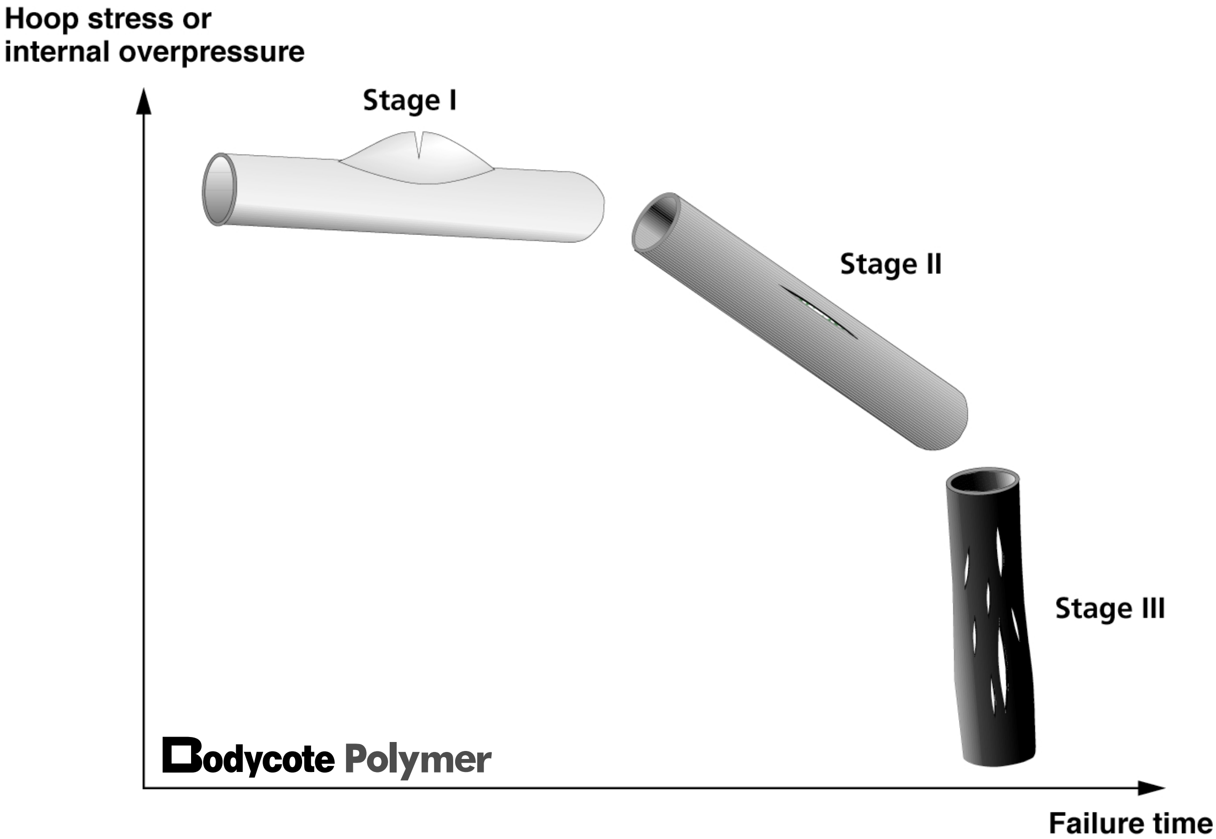

Figure 1 Schematic creep rupture curve for plastic pipes (at higher temperatures).

Lifetime=f(material factors,
environmental factors,
loading factors)

Figure 2 The main factors affecting the lifetime of plastic pipes

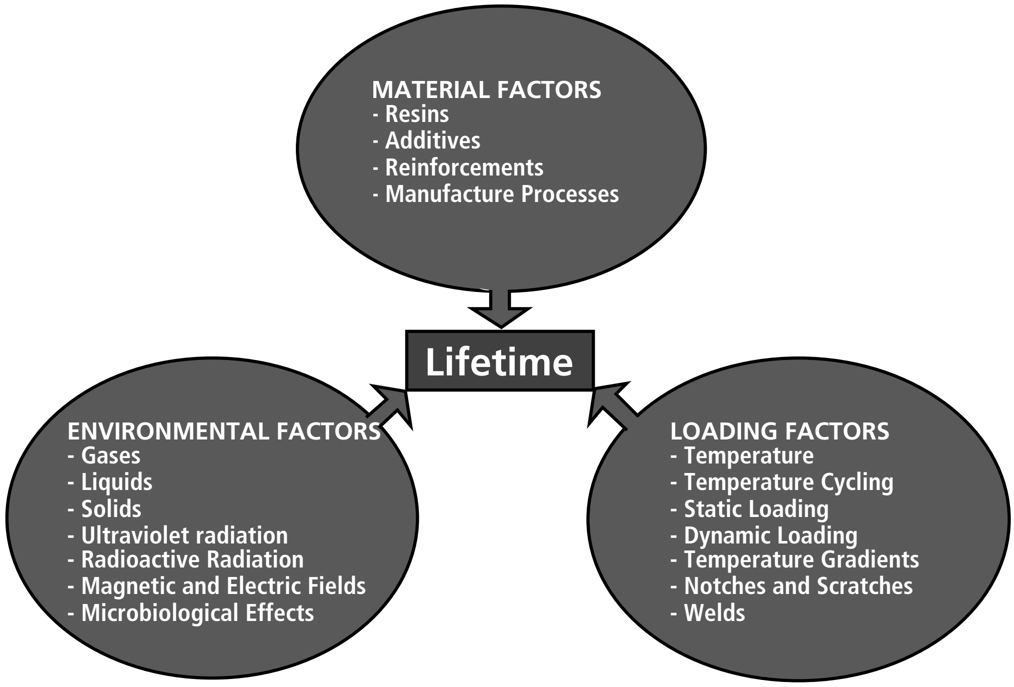

Figure 3 Examples of different factors affecting the lifetime of plastic pipes.

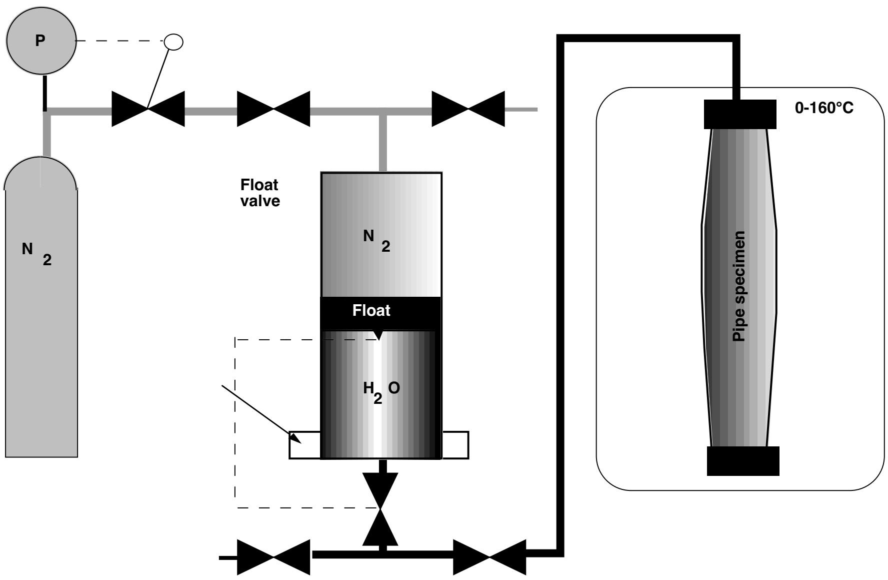

Figure 4 Schematic picture of the hydrostatic pressure test equipment used at Bodycote Polymer AB (formerly Studsvik Polymer AB).

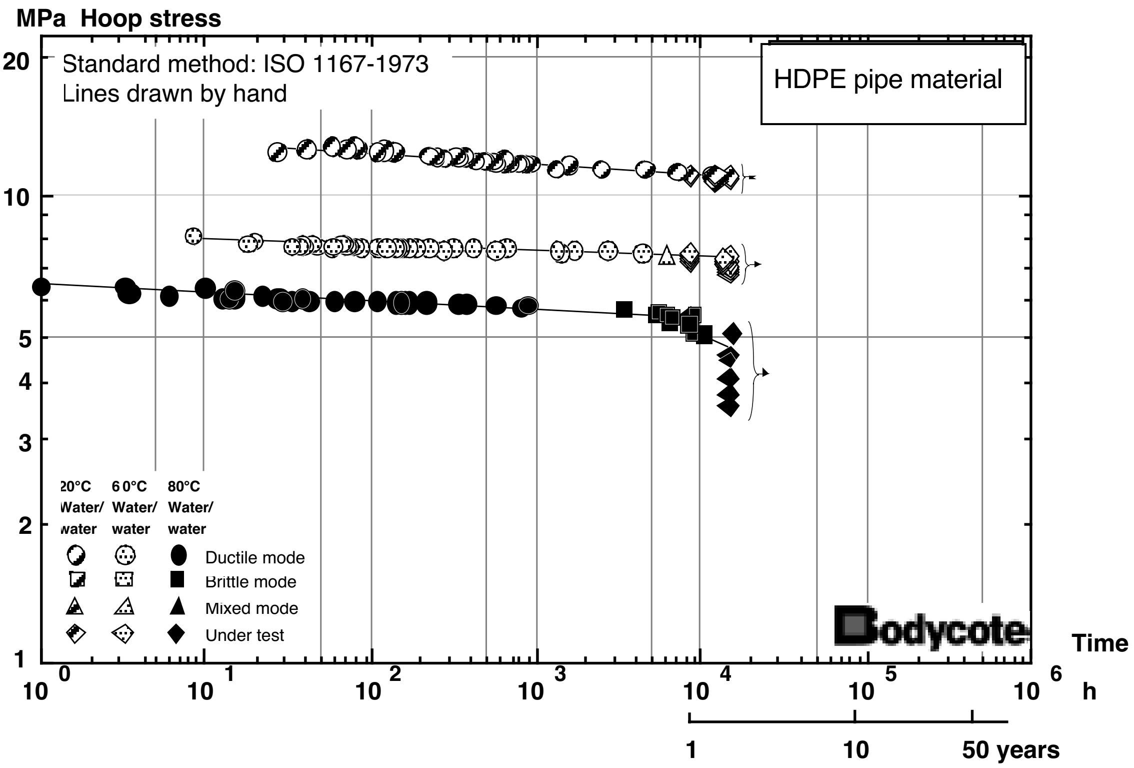

Figure 5 Creep rupture diagram of a HDPE pipe material tested at 20, 60 and 80°C.

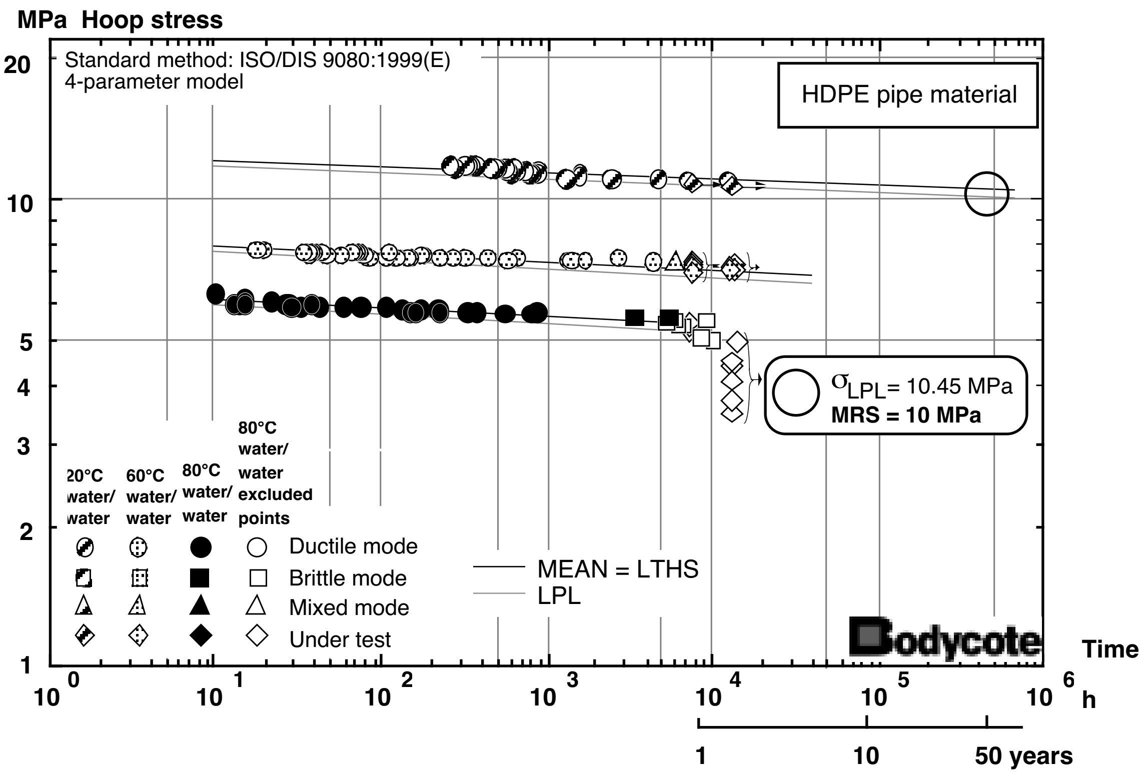

Figure 6 SEM evaluation according to Figure 2 in the ISO/DIS 9080:1999(E) document.

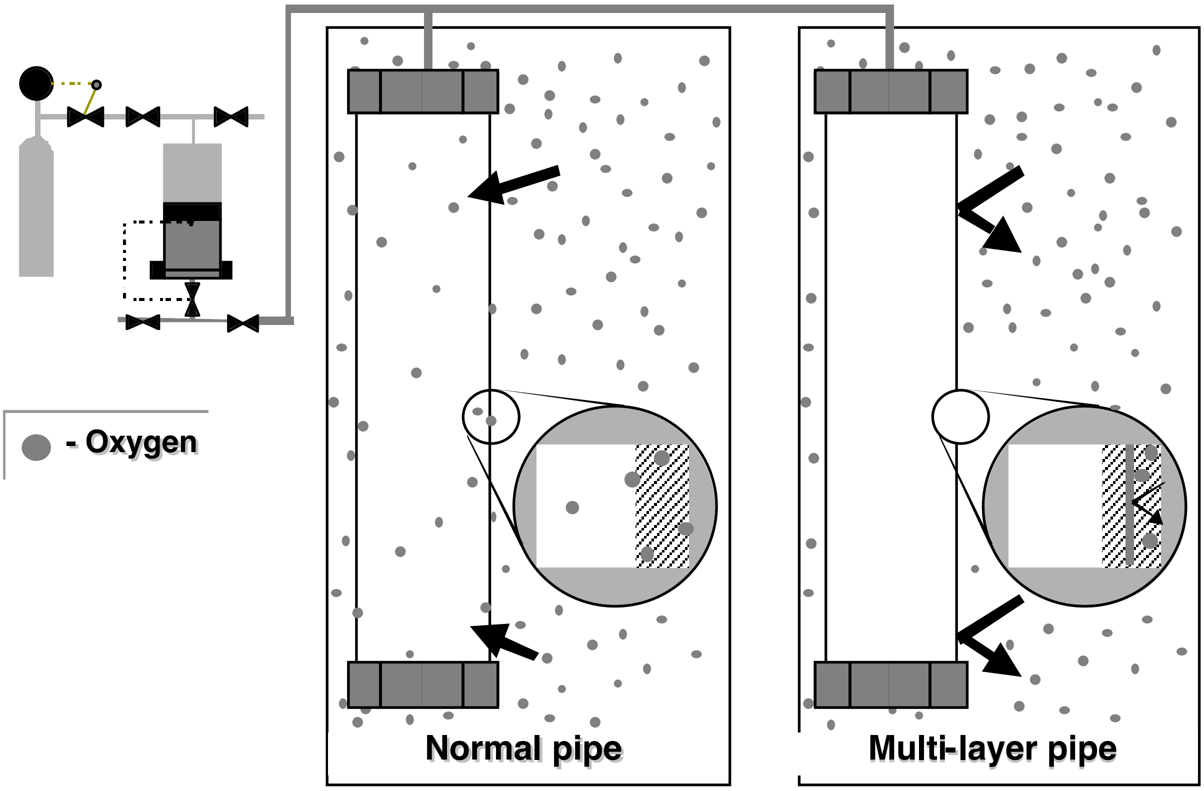

Figure 7 Schematic picture of the oxygen diffusion during hydrostatic pressure testing between a normal plastic pipe and a multi-layer pipe.

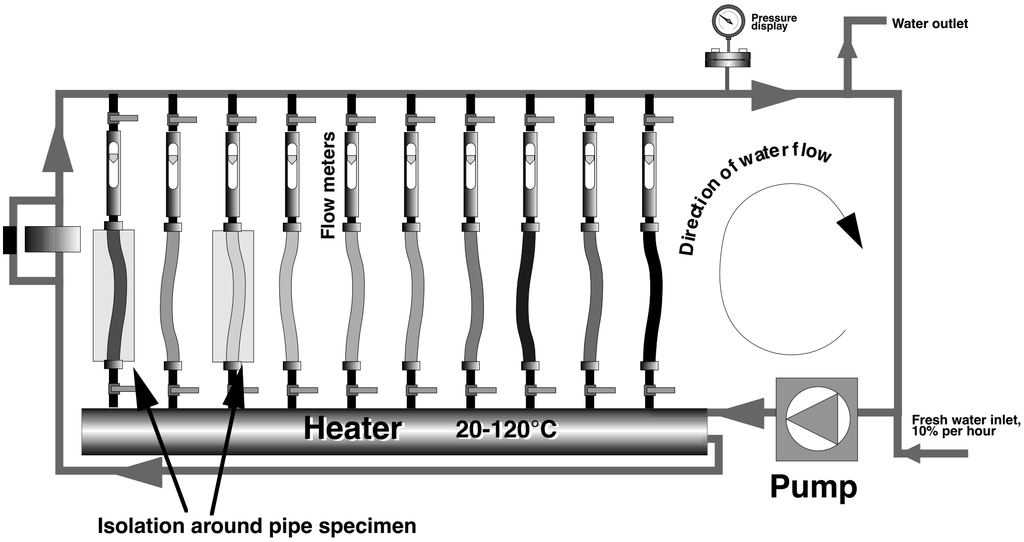

Figure 8 Schematic picture of the circulation loop used at Bodycote Polymer AB (formerly Studsvik Polymer AB)