PRESSURE PIPELINE MADE OF HDPE – DETERMINATION OF REMAINING LIFETIME AFTER 47 YEARS OF OPERATION IN LAKE OSSIACH (CARINTHIA, AUSTRIA)

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ABSTRACT

In order to protect the Austrian lakes effectively against the discharge of effluent, a 13 km long pressure pipeline made of high density polyethylene was laid on the bottom of Lake Ossiach back in 1971. The DN355 to DN200 pipes were produced from a first generation HDPE-compound. The classification would have been close to “PE63”. [1].
This pipeline serves to collect waste water and to pump an average volume of about 1.1 Mill. m³/year with a maximum pressure of 4 bar to a nearby sewage treatment plant. The maximum temperature of the lake water is 15°C.
In the design phase in 1970 the planned lifetime for such a pipeline was set to 50 years. While this pipeline is still in operation to the satisfaction of all stakeholders, it now reaches the end of the planned operating time. As part of a general risk assessment of pressure pipelines in the Austrian lakes, studies were carried out to determine the residual life of a sample that had been installed in 1971 to allow the operator to decide whether a rehabilitation of the pipeline needs to be considered or whether a longer operation time can be justified. The studies are based on the empirical relationships for temperature dependent reactions, discovered by the Swedish physicist Arrhenius in the 19th century. The Arrhenius law allows for accelerated testing at elevated temperatures and extrapolation to expected lifetimes at ambient temperatures.
A sample of a DN 355 SDR 17 pipe had been taken from the pipeline and analysed with respect to slow crack growth resistance, as well as thermal ageing properties. With the Arrhenius approach, it could be concluded that with respect to both stress crack resistance as well as thermal aging, the pipe made out of Ziegler HDPE could be operated for at least another 50 years, doubling the lifetime of the original plan [2]. The outcome of these investigations confirms like former investigations on other pipes

KEYWORDS

Polyethylene, pressure pipe for waste water, long term application (47 years), remaining life time, life time prediction

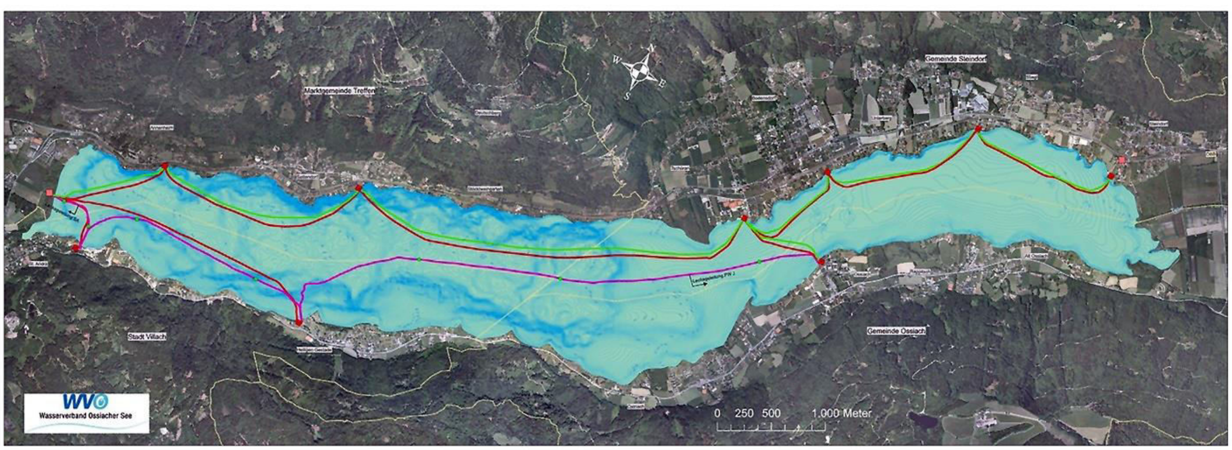
INTRODUCTION

The water quality of Lake Ossiach deteriorated drastically in the years from 1964 to 1967 through the discharge of – at best – mechanically treated effluent, so that it soon became clear that the household sewage originating from the town of Feldkirchen and the communities situated on Lake Ossiach had to be kept away from the lake. After examining various possible solutions, it was decided to discharge the sewage from the communities on the bank of the lake to a wastewater treatment plant to the west of Lake Ossiach or to the treatment plant planned for the town of Villach [1].
Because most of the households on Lake Ossiach are naturally situated at about the same height (above sea level), the only way to transport the sewage to the west end of the lake was with a system of pumping stations and pressure pipes. Laying the pipes on land would not only have necessitated approval from all the affected landowners, it would also have taken a long time to complete. The civil engineers therefore suggested laying fused plastic pipes on the bottom of Lake Ossiach. Before then, this procedure had only been applied for drinking water pipelines.

Name of pipe section (from – to)	Year built	Length [m]	Max. depth [m]	Diameter. [mm]	SDR
Steindorf - Stiegl	1971	1.455	10	200	17
Stiegl - Bodensdorf	1971	1.572	11	200	17
Bodensdorf - Tschöran	1971	1.100	9	200	17
Tschöran - Sattendorf	1971	3.860	49	355	17
Sattendorf - Annenheim	1971	1.999	46	355	17
Annenheim – collecting shaft	1971	1.123	33	355	17
Lido – collecting shaft	1971	690	16	355	17
Ossiach – Bodensdorf	1971	865	10	200	17

Table 1: Data of the pressure pipes in the lake

The pressure pipes in the lake connect nine main pumping stations in the main residential areas with the outlet at the western end of Lake Ossiach. The pumped



effluent
Fig. 1: Pressure pipes in Lake Ossiach (in green: laid in1971)

flows from the outlet chamber in a standard gravity sewer to the wastewater treatment plant in Villach. After having been treated according to the state of the art it is discharged into the river Drau. The pumping stations and pressure pipes with a total length of around 13 km were built in 1970 and went into operation in 1971 [Table 1]. The sewerage systems on land were completed by 1976 and have, since then, been expanded and retrofitted as required [Fig. 1]. Overall, around 27.7 km of pressure pipes have been laid in Lake Ossiach to date.

TECHNICAL IMPLEMENTATION

The material selected for the pipes was high-density polyethylene (Ziegler polyethylene), which at that time was a fairly new product. When the pipelines were installed, a few basic reports existed on the expected service life of pipes made of this material [2]. Long-term tests at different pressures and temperatures made it possible, based on the Arrhenius principle [3], to extrapolate to correspondingly longer operating times at lower temperatures. In the evaluation, it was possible to draw up a so-called creep diagram for the respective polyethylene material [Fig. 2]. This was based on a calculated life expectancy under service conditions of 50 years.

Since the material is lighter than water, the pipes float even when they are completely filled with water. In order to keep them on the bottom of the lake, they must be held down with ballast weights. These concrete elements were designed so that the pipes can be made to float again by filling them with air. In the first expansion stage (1970), the pipes were transported by rail in 50 m long sections and unloaded at night along the lines (when there was no rail traffic). They were fused on land, provided with the weights and floated into the lake. After they had been correctly positioned by motorboats, the pipes were lowered to the bottom of the lake by filling them with water. This was only possible thanks to the flexibility of the HDPE pipes.

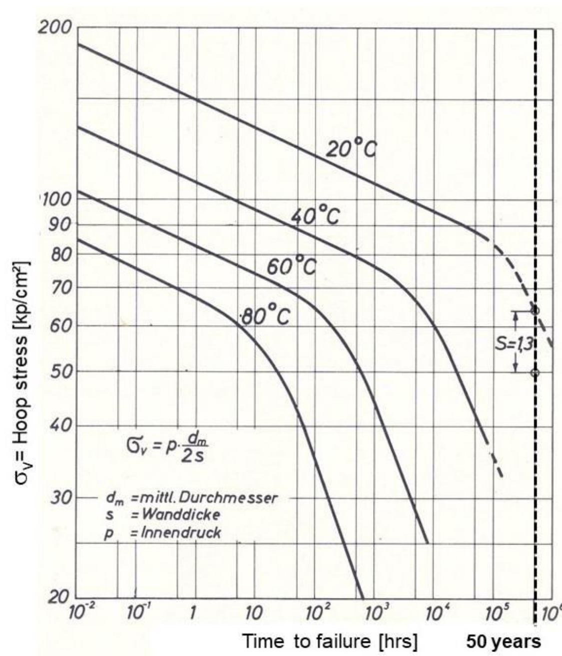


Fig. 2: Creep curves Hostalen GM5010 (1st generation)

In a second expansion stage (1978, building of a double pipeline), pipes up to 300 m long were produced on site with a mobile extrusion line and put into position in the lake.

OPERATING SAFETY AND REPAIRS

When in operation, the pipes are not subjected to particularly heavy stresses because, through the pumps, only the pressure to overcome the friction losses must be applied. Greater stress occurs if there is a need to raise and lower the pipes and when they are subjected to pressure tests. In order to avoid aging of the pipes through pressure testing, the tightness of the pipes is constantly monitored by comparing the volume measurements at the pumping stations with those at the outlet chamber. Until now, there have not been any major pipe fractures that could have led to failure of the pipes, although there have been cases of minor damage to pipes particularly in the landing area through laying them on sharp rocks or with wall ducts in the concrete.

As the sewage water is turbid, the leakages of the pipes became apparent in the very clear water in the lake. When the pumps are switched off failures could be detected through a constant small outflow at the outlets.
Repairs were easily carried out by replacing the faulty parts. In the region of the outlet chamber, the shaft structure and around 300 m of the concrete sewer had been renewed after around 35 years of operation because of pronounced microbial induced concrete corrosion. The pumping stations also had to be overhauled, with the electrical and electronic components being renewed. The submersible effluent pumps are maintained regularly and there has not yet been any need to replace the pumps that were bought in 1970. The system has proved to be very reliable and conveys around **1.1 million m³** of effluent a year.

RISK APPRAISAL

Because the pipelines will very soon reach their calculated lifetime of 50 years, the question was raised about any possible risk they might pose, especially in conjunction with the heavy tourist activity on the lake.
According to the community regulations of the EU, the special method of laying sewage pipes in lakes necessitates enhanced attention. This involves in particular the EU bathing water directive (RL 2006/7/EG). A further requirement is that the respective authorities take precautionary measures for detection and repair. A recent study [4] dealt in detail with a survey carried out on the condition of pressure pipes made (predominantly) of polyethylene in Austrian lakes – thus including the sewage pipes laid in 1971 in Lake Ossiach. Whether the new construction and renovation projects for the polyethylene pipes planned in the (near) future are really linked to their service life or whether other factors play a role was a matter of discussion during the investigations, although an estimate of the residual lifetime of the laid pipes was not undertaken.
Relevant studies have now been carried out by Hessel Ingenieurtechnik, an engineering firm and testing laboratory based in Roetgen, Germany. The results are reported in [4].

PREPARATION FOR THE TESTS ON RESIDUAL SERVICE LIFE

The relevant test specimens (black pipe with butt weld seam and stub flange, outer diameter 355 mm and 22.5 mm wall thickness) were removed in the proximity of Bodensdorf [Fig. 3]. The effluent was assumed to have a maximum temperature of 15 °C. Because of the service conditions (conservative assumption), a design pressure of 3.4 N/mm² was applied.
From a previous project report [6], it was found that the material used to manufacture the pipes in 1971 was *Hostalen* GM5010 from the then Farbwerke Hoechst AG in Frankfurt am Main. A density of 0.957 g/cm² and a melt flow rate (MFR) of 0.27 g/10 min at 190 °C and 5 kg were measured on samples from the specimen. These figures correspond to the data published at that time for this product. To evaluate the service life of the PE pipes, two failure mechanisms must be examined: 1st creep strength and 2nd thermal aging. Creep strength is a function of temperature and load and is limited by the virtually stress-independent failure mechanism of thermal aging. The start of thermal aging is mainly dependent on the temperature, flow velocity, oxygen content, and stabilization of the pressure pipe compound. Both failure mechanisms – fracture in the range of the creep strength and fracture through thermal aging – occur independently of one another. Fig. 4 shows a schematic representation of the areas of the creep curve.

Fig. 3: Test sample

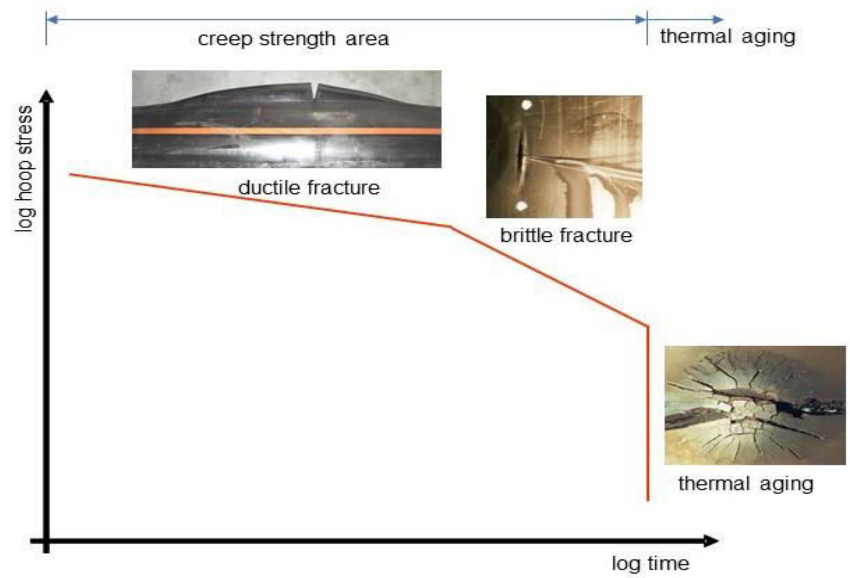


Fig. 4: Schematic representation of the three sections of the creep curve

RESIDUAL SERVICE LIFE WITH REGARD TO CREEP STRENGTH

Regarding the creep strength, slow crack growth was recognized as a defining factor for the potential failure of the pipes. Ductile failure of the pipes is regarded as unrealistic due to the low service stress within the examined part of the pipe's service life. To determine the residual service life through slow crack growth, the MAC concept (Modified Arrhenius Concept) was used [7]. The basic idea of the MAC concept is the simultaneous changing of testing stress and testing temperature of the specimens while observing the temperature-dependent resistance behavior. The advantage of the MAC concept is the arbitrary selection of a starting stress σ (testing stress at elevated temperature T) and target stress (e.g. design pressure at service temperature or real operating stress, here 3.4 N/mm²). On the condition that the activation energy for the low-deformation creep fracture (second branch) is invariant to the test stress, the variable test stresses between the starting stress and the target stress can be calculated according to the function $\log \sigma \sim 1/T$. In the test, the times to failure were measured in the full notch creep test (FNCT) in line with DIN EN 12814-3 Appendix A.1 [8] in the service medium (effluent) and deionized water. The specimen bars with a square cross section and circumferential notch were removed from the inner layer of the pipe in longitudinal direction. The results of the stress crack test are shown in Fig. 5. The correlation coefficient of the FNCT tests is above 0.999. This thus confirms the theoretical requirements of the MAC concept.

The extrapolated minimum time to fracture in the FNCT at 15°C is > 50 years (tensile stress 3.4 N/mm²; effluent)**.**

RESIDUAL SERVICE LIFE WITH REGARD TO THERMAL AGING

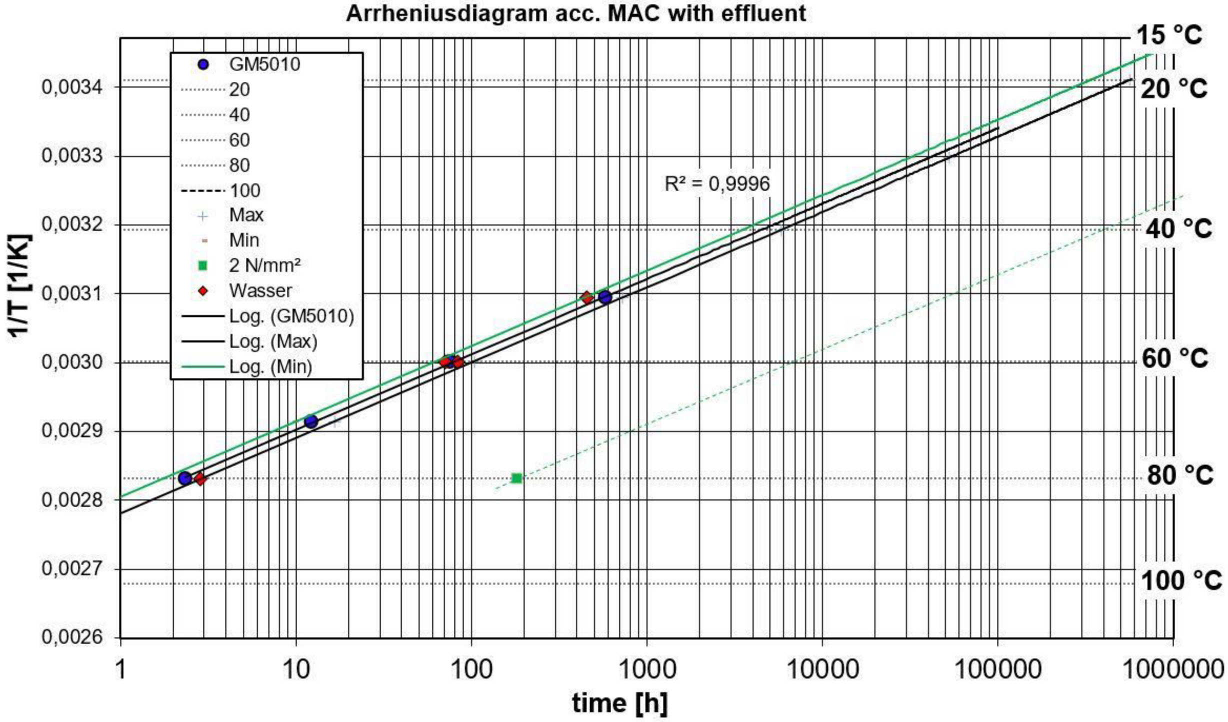


Fig. 5: Arrhenius diagram (MAC) for Hostalen GM5010 in contact with effluent (blue dots) and deionized water (red dots)

High-density polyethylene is, like many other polymers, very stable to thermal aging. However, in long-term contact with oxygen or under high-energy radiation (UV content of the sunlight spectrum), the polymer chains are destroyed and free radicals are formed. This accelerates degradation, which becomes visible as embrittlement of the parts. Materials used to produce pipes are generally colored black and thus have effective protection against weathering. For long-term applications, polyethylene is provided with additional protection in the form of stabilizers. The material used in these tests also contained such additives. Over the course of the service life, a slow depletion of these additives occurs because of migration or reaction with radicals, although the phenomenon of thermal aging does not occur immediately after they have been fully depleted. There is a certain "incubation time".
These interrelationships, too, occur as a function of service temperature T_E and testing temperature T_P in line with the Arrhenius principle. The basis of this principle is that chemical reactions (e.g. aging) or physical processes must overcome an energy barrier during their development – the so-called "activation energy". The correlation between the absolute temperature T, the activation energy E_A and the velocity constant C_v is given as

$$C_v = const \cdot exp(-\frac{E_A}{R\,T})$$

where R is the general gas constant. At a given temperature difference $\Delta T = T_P - T_E$, the so-called "extrapolation factor" can be calculated using:

$$k_e = exp\left[E_A \cdot \frac{T_P - T_E}{R}\right]$$

Between the failure time at test temperature t_P and the present life expectation at a service temperature t_E, the following equation is developed:

$$t_E = k_e \cdot t_P$$

The calculation of the activation energy is carried out in line with Westphal [10] according to the following equation:

$$E_A = 1{,}91471 \cdot 10^{-2} \frac{log\ \ (t_1/\ t_2)}{\frac{1}{T_1} - \frac{1}{T_2}} \frac{kJ}{mol}$$

E_A	Activation energy [kJ/mol]
t_1, t_2	Fracture time at temperature T_1, T_2
T_1, T_2	Absolute temperature [K]

For predicting the service life, it is important to know this activation energy, which can be applied for the thermal aging of HDPE. To carry out a conservative examination, the lowest value found in literature of 88.9 kJ/mol [9] was used here. In order to be able to apply this approach for service life prediction through thermal aging, it was first necessary to establish the present condition of the test specimen. For this, polymer-physical measurements (oxidation induction time OIT, viscosity number "Intrinsic Viscosity IV" and GPC analysis) were performed. Although the original additives to the pipe material in this study can no longer be definitively identified, the OIT value of more than 14 min at 210 °C, measured on a specimen within the pipe wall, leads to the conclusion that the originally used stabilizer has not yet been fully depleted and, consequently, thermal aging of the pipes has not yet begun. It was therefore a question here of determining, through accelerated tests, the time until thermal aging would begin and, with this figure, using the Arrhenius principle to estimate the residual lifetime at the

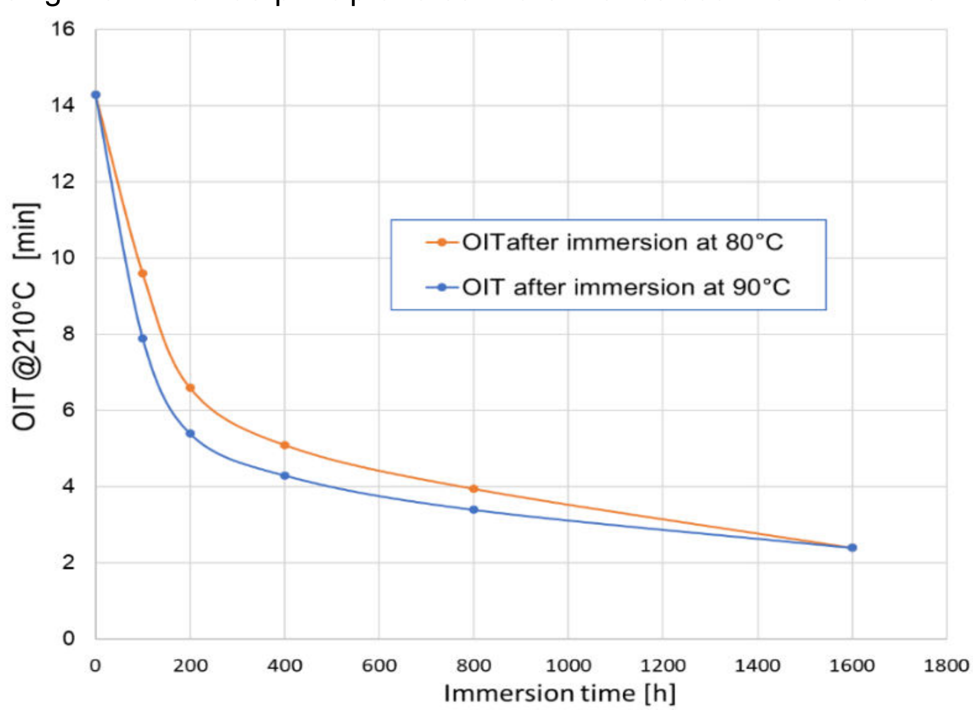


Fig. 6: Stabilizer depletion in immersion tests at 80 and 90°C

service temperature.
For this, thermal aging tests were carried out on small plaques cut out of the pipe wall of the test specimen. They were immersed in a water bath saturated with air at 90 °C and 80 °C with turbulent flow. Then, after defined time intervals, specimens were removed and the above-mentioned measurements were made. To be able to draw up a final report fairly quickly, the tests were initially evaluated up to an immersion time of 3,260 h. The OIT values in relation to the immersion time clearly indicate depletion of the stabilizer [Fig. 6].

It can be assumed that the stabilizer is fully depleted after around 300 to 400 h under both immersion conditions. However, the viscosity number IV as a measure of the mean molecular weight of the test specimen of the starting sample and the removed specimens does not, up to the evaluation of the tests after 3,260 h [Fig. 7], show any sign of molecular decomposition and thus of thermal aging.

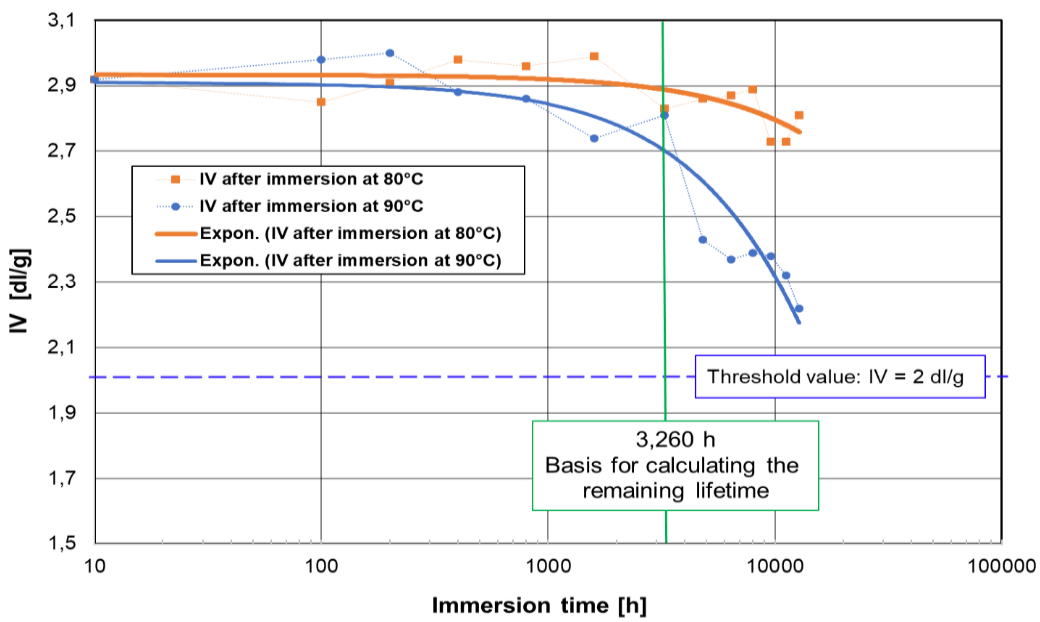
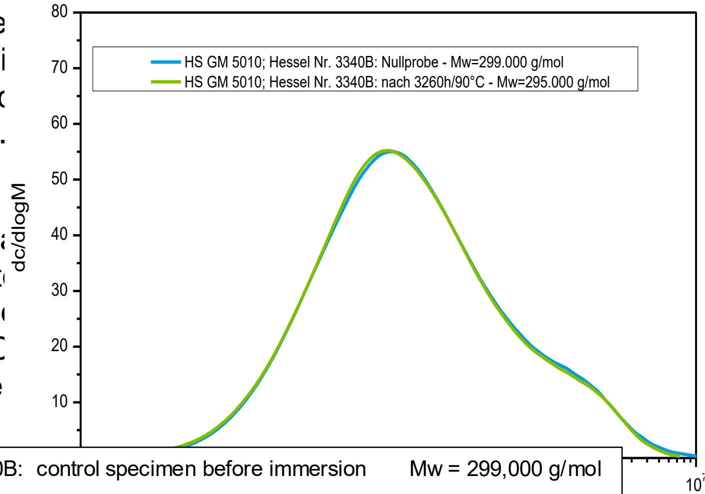


Fig. 7: Change in the mean viscosity expressed as Intrinsic Viscosity IV vs. immersion time

In addition, a GPC measurement was carried out on the specimen before and after immersion at 80 °C and 90 °C. This measuring method provides information on the molecular mass distribution of a polymer sample. In the case of the weight-average molecular weight Mw determined with this, the molecular mass data are weighted with the mass percentage of the respective fraction, as a result of which higher-molecular weight fractions having a greater influence. The weight-average molecular weight reacts sensitively to polymer degradation. The measuring accuracy – the same, and thi measurement IV to the extent that the add any significant polymer degradation [Figs.



80°C

The te e since been continued up at 90 °C, it is now possible to determine a When the specimens are also subjecte thermal aging is seen. Now, degradati evident in the GPC diagram for the 90 °C test report, however, a residual service conservative

Plaque from pipe wall; Hessel-ID 3340B: control specimen before immersion Mw = 299,000 g/mol
Plaque from pipe wall; Hessel-ID 3340B: after 12,800h / 80°C immersion Mw = 294,000 g/mol
Plaque from pipe wall; Hessel No. 3340B: after 12,800h / 90°C immersion Mw = 195,000 g/mol

ap ha made on the basis of the Arrhenius principle with an activation energy of 88.9 kJ/mol.

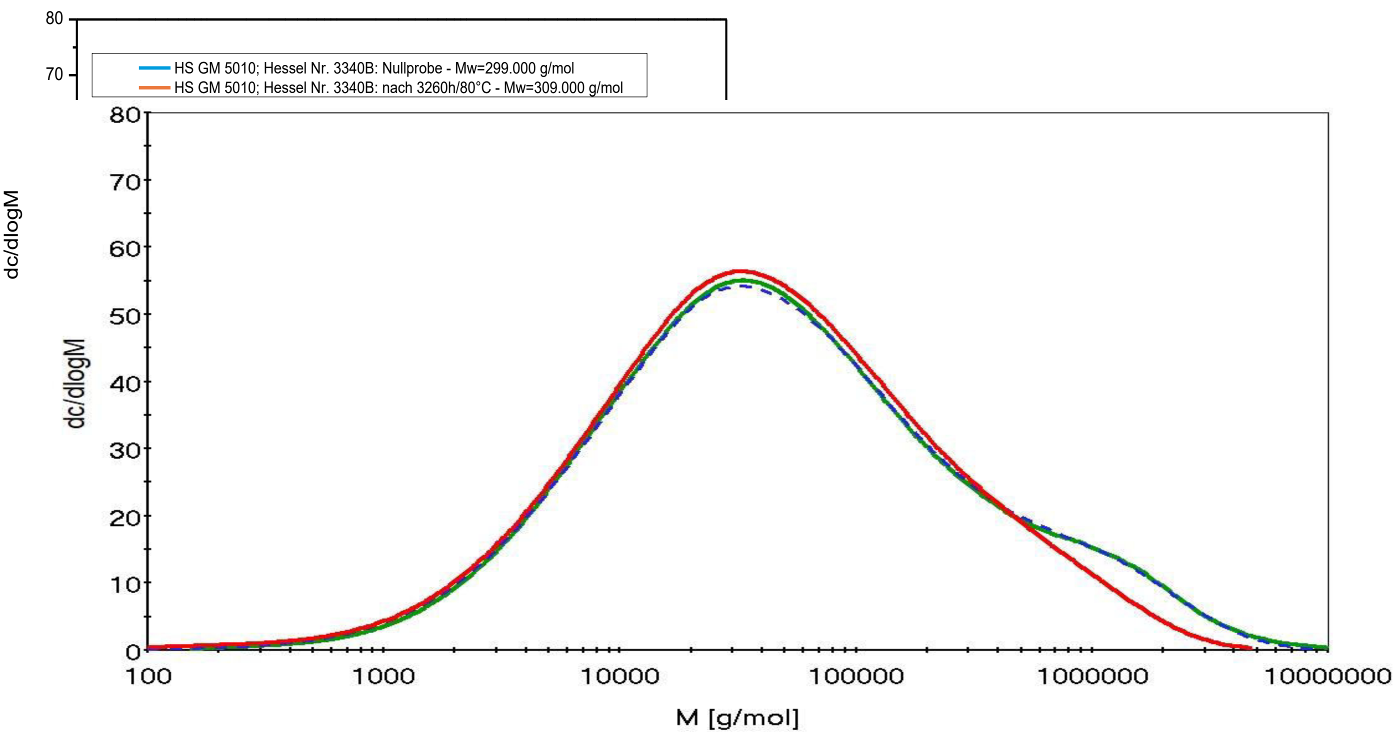
The calculated time to failure of this sample at intermittent temperature is 178 years!

SUMMARY OF THE RESULTS

The stress cracking and thermal aging tests allow to calculate, based on the aforementioned assumptions, a **minimum remaining lifetime of the tested specimen of 50 years, thereby doubling the originally expected lifetime.**

It must nevertheless be considered that, with these tests, excessive local stresses, e.g. on the concrete hoop supports, were not taken into account.

The tests confirm in an impressive manner the validity of the service life forecasts made in the 1960s based on the creep tests done at that time, predicting a minimum service



life of 50 years.

The material used then is defined as the "1st generation" of HDPE pipe materials. Present-day materials (PE100, PE100-RC) not only have a higher design pressure, they also have many times the resistance to slow crack growth. Significant progress has also been made regarding the additives used to protect against thermal aging.

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