Investigation of the Technical Service Life of Cured-In-Place Sewer Pipe Liners

Results from Literature Review, Interview Campaign and Data Analysis

Report of the SEMA Berlin 3 Project

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Summary

This research report addresses the current uncertainties regarding the technical service life and aging behavior of the most common sewer rehabilitation method, Cured-in-Place Pipe (CIPP) lining. The goal of this study is to develop a robust data foundation for a CIPP liner survival curve for use in aging models. The methodological approach includes (i) a literature review, (ii) interviews with sewer rehabilitation experts, and (iii) an analysis of data from Berliner Wasserbetriebe to create an updated and suitable data basis for the calibration of survival curves. The literature review and expert interviews predominantly estimate the service life of CIPP liners to exceed 50 years. However, the study also reveals that this lifespan is influenced by numerous factors and that there is a lack of reliable data. Further investigations of long-used CIPP liners are therefore essential. The installation process, particularly the curing phase, has been identified as the primary factor contributing to defects and deficiencies in CIPP liners. Standardizing damage assessment and condition evaluation for liner-specific defects, as well as establishing non-destructive inspection methods, is necessary to improve the understanding of aging behavior in the future. Recommendations include improving data collection during the operation, installation, and removal of CIPP liners, enhancing quality assurance during installation, investigating the impact of damage on service life, and promoting knowledge exchange among operators.

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1. Introduction & Motivation

The sewer network plays a critical role in the daily transportation of wastewater and rainwater from urban areas to pumping stations, treatment plants, and discharge points. Like all infrastructure, sewer pipes have a finite technical service life. When a sewer is damaged and requires rehabilitation, it can either be replaced through an open trench method or trenchless underground tunneling. While renewal is sometimes the only feasible technical solution, trenchless renovation methods often provide a viable and less invasive alternative.

A survey conducted by the German Association for Water, Wastewater, and Waste (DWA) by Berger et al. (2020) revealed a steady decline in sewer system renewals over the past 20 years, alongside a rise in renovation methods since 2013. Among these methods, the use of cured-in-place pipe (CIPP) liners has become the most prevalent. This technique involves inserting a flexible liner, made of a carrier material impregnated with reactive resin, into the damaged sewer via manholes. Once positioned, the liner is cured to form a new plastic pipe within the existing sewer. Compared to the open trench method, installing CIPP liners avoids prolonged roadworks, road closures, and disruptions to local residents. The streamlined process also significantly reduces construction time and costs.

CIPP liner installation has been implemented at the municipal level in Germany since the mid-1980s, with the first applications in Hamburg in 1983 and Berlin in 1986. Initially introduced as an alternative to costly sewer renewals, this innovative method has evolved into a well-established rehabilitation solution due to its proven effectiveness and economic benefits. Completing a sewer rehabilitation in just one day using CIPP lining has dramatically improved efficiency in urban environments. Today, for most German cities, relying solely on traditional open-trench renewals to meet the required rehabilitation lengths specified in sewer network strategies would be impossible. The high costs, extensive construction timelines, and associated disruptions make trenchless methods like CIPP an essential tool for modern sewer management.

Despite the general trend toward increasing renovations, there is still no well-founded evidence regarding the technical service life of CIPP liners, as no single liner has yet reached the end of its lifespan. This makes it more urgent to develop an understanding of the ageing behavior of the growing number of liners in sewer networks, as they too will eventually require rehabilitation. The widespread current use of new materials and techniques in CIPP lining for sewer networks, whose ageing behavior has not yet been comprehensively studied, further necessitates thorough investigation to minimize future financial risks associated with sewer network maintenance for coming generations.

As demonstrated by the SEMA-Berlin 2[1] project (KWB, 2020), the ageing behavior of sewer networks can, with sufficient data, be modeled with high accuracy in the SEMAplus model. This represents the most advanced method currently available for simulating future condition developments. The ageing modeling is primarily based on calibrated survival curves for material cohorts, represented in the form of Gompertz distributions (Riechel, 2021). Using these survival curves, the probability of a specific condition for a sewer segment can be calculated at any point in its service life with cohort-specific precision. Determining the survival curves for each cohort requires precise calibration values, ideally derived from condition data spanning the entire service life.

Figure 1 illustrates the survival curves for pipe liners in Berlin's sewer network, calibrated in 2019 as part of the SEMA-Berlin 2 project based on condition data from Berlin's CIPP liners and additional assumptions. These survival curves are incorporated into the SEMAplus strategy simulator, which Berliner Wasserbetriebe has used since 2020 for strategic rehabilitation planning

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[1] Since 2016, Berliner Wasserbetriebe, in collaboration with Kompetenzzentrum Wasser Berlin gGmbH, has been developing simulators in several SEMA projects (SEMA Berlin 1 to 3) to model the ageing of the sewer network and individual sewer segments, known as SEMAplus simulators.

to calculate required rehabilitation lengths and methods, forming the basis for their investment planning. Simulations of sewer network development in Berlin have shown that the ageing behavior of CIPP liners is one of several critical factors in shaping the sewer rehabilitation strategy. This creates a direct link between survival curves and investment planning, making accurate calibration of survival curves for CIPP liners all the more important.
According to regulations, the use of ageing models for sewer network maintenance planning is mentioned only as an option and does not further specify the technical implementation of such models (DWA-M 143-14). The use of survival curves to simulate ageing behavior is merely one of many mathematical approaches.

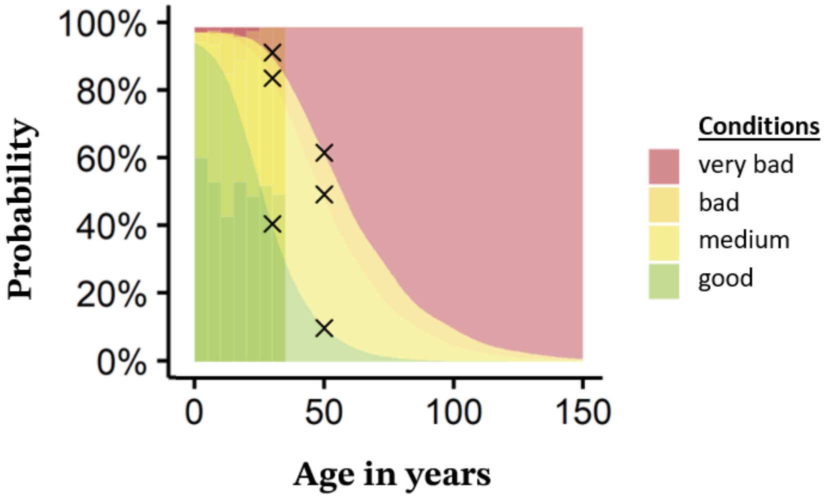

Figure 1: Assumed survival curves for modeling the aging behavior of Berlin liners; calibrated based on marked points from previous assumptions of the SEMA Berlin project

In this report, "technical service life" is defined, as per DWA-A 143-3, as the period during which a CIPP liner must ensure safe sewer operation without incurring repair costs. Properly installed CIPP liners are designed to achieve a technical service life of 50 years under building inspectorate approvals. This figure originates from suitability certificates, which use this timeframe as a benchmark (RSV-M 1.1). However, due to a lack of empirical data, the DWA worksheet DWA-A 143-3 defines an "economically appropriate service life" of 50 years, which forms the basis for general assessments. Currently, no sewer liner in Germany has reached an age of 50 years. Furthermore, the evolution of materials and installation methods over recent decades means that a 30-year-old CIPP liner is only partially comparable to a 5-year-old one, necessitating careful evaluation of damage transferability.

In summary, there is considerable uncertainty in assessing the reliability of the assumed 50-year service life for CIPP liners outlined in structural approvals and regulations due to:

- The definition of technical service life in regulations being based on expert estimates without comprehensive data;
- The lack of long-term data on the ageing behavior of liners; and
- Technological advancements that likely influence the ageing characteristics of liners.

This uncertainty highlights the need for a deeper investigation into the ageing behavior, technical service life, and condition development of pipe liners, which is the focus of this report.

Building on the findings of a 2017 literature review (Wicke, 2017) and a data evaluation of the Berlin sewer network (Riechel, 2021) conducted by Kompetenzzentrum Wasser Berlin (KWB), this report incorporates a new literature review, an interview campaign, and an updated 2023 data analysis by Berliner Wasserbetriebe. The study emphasizes the technical service life of pipe liners and the key factors affecting it, including relevant damage mechanisms and possible preventive measures. The report is structured around three main investigative methods:

1. A comprehensive literature review on the current state of research, extending the work of Wicke (2017)
2. An evaluation of a wide-ranging interview campaign
3. A data analysis of CIPP liners that have been operational for extended periods.

Additional insights from technical discussions conducted by Berliner Wasserbetriebe with other operators and experts from the DWA working group ES 8.63[2] (see Chapter 6) further enrich these findings.

The subsequent sections provide an overview of the current research and practical knowledge regarding the technical service life of pipe liners. Furthermore, the findings aim to inform revisions to the ageing curves used by Berliner Wasserbetriebe (as shown in Figure 1), guide future research efforts, and offer actionable recommendations for better estimating the ageing behavior and service life of pipe liners.

For simplicity, this report uses the term "service life" instead of "technical service life" and "liner" as a synonym for "CIPP sewer liner." Additionally, the liner survival curves for individual SEMAplus condition ranges are referred to as liner survival curves for ease of reference.

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[2] DWA Working Group ES-8.6 "Auskleidung von Abwasserleitungen und -kanälen mit örtlich hergestellten und erhärtenden Rohren" within the DWA Technical Committee ES-8 "Rehabilitation."

2. Methodological Approach of This Study

The aim of this study is to develop a more robust data foundation for creating a liner survival curve that can be applied within the SEMAplus ageing models for Berlin’s sewer network. Since no other survival curves for liners apart from those derived from the SEMA Berlin projects are known, and since the ageing behaviour of liners is typically addressed through specifications of technical service life, an analysis of the assumptions regarding technical service life commonly used by operators and in regulations is conducted.

The relationship between service life and survival curve is highly complex. Technical service life is a significant simplification of a statistically complex, time-variable relationship such as the survival curve. The question of how to move from a single value to a temporal condition curve remains undefined, particularly with respect to ageing behaviour. Therefore, the following assumption regarding the relationship between service life and survival curve was made for the creation of the liner survival curve at Berliner Wasserbetriebe:

According to the provisions of the SEMA-Berlin 2 project, by the "end of the technical service life," 50% of lined sewer segments are in a state requiring rehabilitation, corresponding to the SEMAplus condition classes "very poor" and "poor."

Since 2019, new findings in liner ageing have emerged, and more data on liner condition and installation are now available. Consequently, this study reviews and, if necessary, adjusts the liner survival curve. For precise calibration of a survival curve, a condition-based dataset covering the entire service life is generally required, which does not yet fully exist in the case of liners. Thus, the analysis of service life provides an additional reference point for calibrating the liner survival curve, guiding other necessary assumptions for modelling the survival curve. The methodological approach of this study is structured into a three-part process to establish a data basis for the creation of a general liner survival curve.

In the first step, all factors influencing the ageing process of liners are identified by literature review and assessed for their significance in the ageing process. Additionally, the existing data inventory and options for retrospective and future data collection are evaluated as far as current knowledge allows.

In the second step, an evaluation is conducted of an interview campaign involving experts from research and practice on the topics of liner service life and survival curve.

In the third step, it is examined whether any survival curves for liners already exist in the literature or among the interviewees that Berliner Wasserbetriebe could use, in combination with an evaluation of prepared data on known liner conditions within their sewer network, to update the liner survival curve calibrated under the described assumptions for use in SEMAplus simulators.

The factor analysis, results from the interviews, and the updated analysis of liner conditions in Berliner Wasserbetriebe's own sewer network form the foundation for further development of liner ageing modeling. Additionally, insights from parallel technical discussions between Berliner Wasserbetriebe, other operators, and technical experts from the DWA Working Group ES 8.6, as well as recommendations for further research activities, are considered.

3. Literature Review

3.1. Initial Situation

In 2017, Dr. Daniel Wicke published a literature review at KWB in German titled "Investigation of the Service Life of CIPP Liners". Wicke (2017) examined whether liners could achieve a service life of 50 years or more. The study led to the following conclusions:

- Increasing trend in quality and quality assurance during the installation of liners
- Materials used for liners in sewer operations were generally assessed as robust and durable
- Signs of wear and tear on liners in operation were, in most cases, attributed to installation errors
- Laboratory studies estimated a service life of over 50 years as highly probable, provided that installation was performed correctly (Allouche et al., 2014)

The study concluded that the assumed service life of 50 years is supported by the literature. However, due to a lack of long-term data, precise statements about the actual service life cannot yet be made. The aim of the current literature review is to incorporate new findings on the service life of liners that have emerged since Wicke's 2017 study.

3.2. Manufacturing and Installation of Liners

Liners are made from a composite material consisting of two main components: the carrier/reinforcement material and resin. The reinforcing fibers are typically composed of glass fibers, synthetic/polymer fibers (needle felt), or a combination of glass and synthetic fibers (Bosseler and Schlüter, 2003). For the resin material, which ensures the cohesion and stability of the fibers, unsaturated polyester resins (UP) are predominantly used. In cases of high chemical and thermal demands, vinyl ester resins (VE) are occasionally applied, while epoxy resins (EP) are often used for house connections (Wicke, 2017). Additionally, liners may include fillers such as quartz sand and are often equipped with inner and outer foils. According to Buchner et al. (2021), modern liner installations generally utilize one of three curing systems:

- Glass fiber liners cured with UV light initiated by a movable UV lamp system,
- Synthetic fiber liners (needle felt liners) cured with heat using hot water or steam, or
- Glass fiber liners cured with a combination of UV and thermal initiators

Glass fiber liners cured with UV light are increasingly becoming the standard method in CIPP lining. These liners exhibit significantly superior mechanical properties compared to conventional needle felt liners. Ji et al. (2020) demonstrated in a laboratory study that glass fiber liners using UP resin achieved strengths 8 to 13 times higher than the minimum requirements set by the American Society for Testing and Materials (ASTM F1216). This allows glass fiber liners to be installed with thinner wall thicknesses than needle felt liners. Despite the promising mechanical properties of UV-cured glass fiber liners, the UV curing process presents practical challenges due to the risks of curing deficiencies. These issues arise from the numerous influencing factors of the light-curing process, which are discussed in detail in Section 3.5.1. The various materials and installation methods (especially curing techniques) necessitate a differentiated assessment of the service life for these different types of liners.

Regarding the aforementioned material composites (glass fiber or needle felt liners), no studies specifically addressing their aging behavior as sewer liners are known. However, fiber-reinforced plastics are widely used in various industries (e.g., aerospace and sports), and there are publications on related composite materials. Studies on the aging behavior of fiber-reinforced plastics (Gibhardt et al., 2022; Meng and Wang, 2016; Xu et al., 2020) emphasize their high sensitivity to UV radiation, temperature, and humidity, exploring these relationships in depth. However, these findings have limited applicability to sewer liners, as the studies focus on high-temperature conditions above 30°C, which, along with UV radiation, typically do not occur during sewer operation—except during the liner curing process. Consequently, only information related to high humidity, such as the behavior of composite materials in shipbuilding environments, might be transferable to sewer conditions. Since aging processes typically result from a combination of multiple factors (e.g., the interaction between UV radiation, temperature changes, and mechanical stress), these findings cannot reliably be used to infer the aging behavior of liners. Therefore, the specific factors influencing the performance of liners in sewer environments require more detailed investigation, which will be addressed in the following sections.

3.3. Quality Parameters of Liners

The following measurable parameters are used to assess liner quality and can be evaluated either in the laboratory or in situ, i.e., directly on-site in the sewer.

3.3.1. Material Characteristics

Liners, like other plastics, exhibit viscoelastic material behavior. This means that they can show delayed and even permanent deformations under load, which can affect their stability. Therefore, it is important to distinguish between short-term and long-term properties when analyzing the mechanical properties of liners. In addition to mechanical properties, material properties also include water permeability. Table 1 summarizes the key material properties of a liner. Other material properties, such as residual styrene content, the density of the composite material, the infrared spectrum, and the determination of the degree of curing, are explained in more detail in Section 3.4 and are not included in Table 1 below.

Table 1: Essential material properties of liners with respective testing methods according to Wicke (2017); further information in Wicke (2017) and DWA-A 143-3

Parameter	Description	Testing method
Bending Strength	Point of liner failure due to high stress	Three-point bending test
Short-term Elastic Modulus	Stress-strain relationship in the liner	Three-point bending test
Long-term Elastic Modulus	Stress-strain relationship in the liner	Creep ring test (24h)
Creep Behavior	Deformation behavior of a liner under constant load	Creep test (24h)
Water Permeability	Liner tightness	Tightness test

The specified mechanical properties of installed liners must meet minimum values for DIBt-compliant execution[3] (see also Section 3.4). Failure to maintain these properties, particularly after

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[3] Compliance with the general technical approval of Deutsches Institut für Bautechnik (DIBt)

installation, compromises the expected service life. Several laboratory studies have examined the mechanical short-term properties and other characteristics of long-used liners to analyze potential links to aging behavior. Allouche et al. (2014) analyzed samples from four sites with needle-felt liners aged 25, 23, 21, and 5 years. Some samples showed reduced elastic modulus compared to original post-installation values, but the study concluded that this reduction was not directly linked to aging processes. They estimated a service life of 50 years or more as likely. Hoppe (2008) studied two needle-felt liners aged 25 and 19 years and a 12-year-old fiberglass liner, finding little to no deviation in mechanical short-term properties, regardless of material or manufacturing method. Bosseler et al. (2024) tested 18 needle-felt liners aged 8 to 26 years. While 11 met the minimum flexural strength requirements, only three passed the leak-tightness test, and none met both criteria. Deficiencies were attributed more to installation quality than aging. Earlier findings by Bosseler et al. (2009) revealed that 9 of 15 liners failed to meet mechanical, tightness, or wall thickness standards post-installation, including three of four needle-felt liners and six of 11 fiberglass liners.

A laboratory study on artificially aged glass-fiber-reinforced plastics (Laurikainen, 2017) found negligible changes in the elastic modulus of VE resin despite visible aging signs. While flexural strength and short-term elastic modulus are commonly measured (Allouche et al., 2014), no direct correlation between aging and these mechanical properties has been established. Further research is needed to determine whether this lack of correlation is due to small sample sizes, overlapping factors like installation quality, or an absence of a significant link between aging and mechanical characteristics.

3.3.2. Geometric properties

The geometric properties of liners are crucial for ensuring structural and operational safety. These properties include wall thickness, the annular gap between the liner and the host pipe, and any pre-deformations, all of which can be measured in situ. Wall thickness and the modulus of elasticity together define the stiffness of a liner. The geometric properties listed in Table 2 primarily address installation defects. Insufficient wall thickness, pre-deformations in installed liners, or the presence of annular gaps can be defects that compromise structural safety and the expected service life (details in Section 3.5). However, data on such defects can currently only be evaluated qualitatively, making them unsuitable for calibrating new survival curves for liners.

Table 2: Geometric properties of liners according to Wicke (2017), further information in Wicke (2017) and DWA-A 143-3

Parameter	**Description**	**Testing method**
Wall thickness	Average composite thickness of a liner	Measurement on sample
Annular gap	Distance between liner and host pipe	Impact-echo method, measurement during sampling
Pre-deformations	Wrinkles, flattening, or ovalizations that reduce buckling resistance	Optical inspection, roundness measurement, laser ring projection method

3.3.3. Resistance to Operational Stresses

Resistance to stresses arising from operation includes the material resistance to abrasion as well as the high-pressure flushing resistance of liners. Both properties (see Table 3) are intensity-dependent and can be simulated or determined through laboratory tests (Wicke, 2017). Due to their dependence on intensity, these measurements cannot be directly transferred to actual flushing or abrasion damage occurring in the sewer. A detailed assessment of such damages in situ could be conducted as part of optical inspections. The possible identification of signs of wear from operation can provide valuable indications for estimating the aging of the respective sewer section.

Table 3: Operational load capacity of liners according to Wicke (2017), with further information in Wicke (2017) and DWA-A 143-3

Parameter	**Description**	**Testing method**
Abrasion resistance	Wear resistance against sediments	Optical inspection, Darmstadt tipping trough test
Flushing resistance	Resistance of liners to high-pressure flushing	High-pressure flushing resistance test according to DIN 19523

3.4. Quality Testing of Liner

3.4.1. In Situ Testing

As of today, it is common practice to perform a sample collection with laboratory analysis, optical inspection, and leak testing when accepting a liner installation (Wicke, 2017). However, the preceding sections highlight that newer in situ testing methods for more comprehensive condition assessments already exist and are described in detail in Wicke (2017). Beyond the optical inspection as a standard method outlined in the regulations, it is possible to detect not only common damages found in non-renovated pipelines (e.g., cracks, roots, obstacles, etc.) but also liner-specific issues such as surface irregularities (e.g., wrinkles), defective house connections, deformations, and discolorations (DIN EN 13508-2 or DWA-M 149-2, damage code “BAK”). Experts largely agree that the most practical way to assess installation quality currently involves sample collection with subsequent laboratory analysis, alongside recording and evaluating process-related parameters during liner installation.

3.4.2. Sampling

At Berliner Wasserbetriebe, liner sampling is conducted immediately after the liner has cooled to ambient temperature from curing, typically in intermediate and end manholes. It is important to ensure that the sample is representative of the curing degree within the pipe section. Samples from UV-cured liners must be packaged in lightproof materials immediately after collection to prevent contamination from sunlight and artificial post-curing, which could differ from the installed liner in the sewer. Since samples are taken from the overhanging section in the manhole area immediately after liner installation, sealing the sampling site is unnecessary. However, if sampling is conducted later during the service life at the start of the pipe section or within the sewer, the missing sampling site on the installed liner must be sealed with a localized repair measure, such as patching or resin injection.

3.4.3. Laboratory Testing

The laboratory testing according to DWA-A 143-3 includes a water tightness test (based on DIN EN 1610) and a three-point bending test to examine the mechanical short-term properties, which is typically performed radially (in accordance with DIN EN ISO 178, DIN EN ISO 11296-4). If the specified target values for mechanical properties are not met, creep tendency and curing are further analyzed. A 24-hour creep tendency test (based on DIN EN ISO 899-2, DIN EN 761) is conducted to evaluate long-term behavior. Additionally, for UP and VE resins, the residual styrene content is determined (per DIN 53394-2), and for epoxy resins, differential scanning calorimetry (DSC analysis) is performed following ISO 11357-2. These measurements are often averaged over the liner wall thickness in current practice, potentially masking true curing deficits, particularly at the liner's outer surface. If the target values are still not met after these tests, a second sampling may be considered. The residual styrene content must not exceed 2% by mass relative to the laminate or 4% by mass relative to the resin content, as specified in DIN 53394-2 (see Table 4).

From the time of sampling, which must be conducted immediately after liner installation, it takes approximately 6–8 days to receive the laboratory report assessing these tests after submitting the sample to a testing laboratory (Buchner et al., 2021). However, this process has two significant drawbacks. First, there is no opportunity for corrective actions on the liner installation after completion, neither at the time of sampling nor upon receipt of the laboratory report. Second, passing a laboratory test does not guarantee complete curing of the liner, as the curing degree is only tested if the three-point bending test is failed. Buchner et al. (2021) observed little to no correlation between mechanical short-term values (flexural strength and short-term modulus of elasticity) and residual styrene content in practice. Conversely, a comparative study of fully and partially cured liners found lower elastic moduli in cases of insufficient curing (Nuruddin et al., 2020). Based on current knowledge, reduced mechanical short-term values do not directly indicate curing deficits. Further studies under controlled conditions could improve understanding of this relationship. To ensure complete curing of installed liners, the curing degree should always be assessed in laboratory testing alongside mechanical short-term properties. Due to stringent requirements for packaging, storage, and transport of samples, an in situ curing control during installation would be more suitable and preventive. Detailed information on in situ curing control is provided in Section 3.5.1.3. These measures offer greater reliability in predicting service life and developing survival curves.

3.5. Current Challenges and Problem Analyses Related to Liners

Building on the properties of liners discussed in the previous chapter, this section highlights potential deficiencies and challenges with liners as reported in recent literature from the past five years. Issues that can reduce the service life of liners include curing deficits, lack of geometric integrity, wrinkling, surface irregularities, and improperly constructed house connections.

3.5.1. Curing of Liners

3.5.1.1. Material-Specific Requirements for UV-Initiated Curing

The curing process during the installation of liners is determined by the choice of resin system (see Section 3.2). This system consists of several components, including the resin itself, the hardener, as well as various fillers and additives. An important control parameter for styrene-containing resins (typically found in UP and VE resins) is the styrene content. In its uncured state, the optimal styrene content ranges between 40-55%. Styrene is a monomer that plays a crucial role in impregnating and cross-linking the fibers into a polymer during the curing process (Buchner et al., 2021).

During the curing of the liner material, there is an increasing cross-linking of monomers into polymers. As curing progresses, however, it becomes more difficult for the monomers to find available reaction partners. This results in residual monomers inevitably remaining in the fully cured polymer. A low residual monomer content does not constitute a quality defect (Buchner et al., 2021). Achieving the lowest possible residual monomer content in the final product depends on the resin-to-fiber ratio during installation. For resin-impregnated liners prior to installation, this ratio typically ranges between 40-60% (Kopietz, 2023).

Complete curing of the material is possible if the precise composition of the resin is known and the curing conditions can be optimized. However, site conditions often pose a challenge, as they are frequently variable and not always ideal. Table 4 provides a comparison of the residual styrene limits after liner curing. The DWA, in its guideline DWA-M 144-3, limits the residual styrene content to 8 mass % based on the resin content or 4 mass % based on a sample. This limit is subject to professional debate. The authors of RSV-M 1.1 consider it too high and advocate for a revision. Given the DWA’s ongoing revision and the strict classification by the AVK, the residual styrene limit from DIN 53394-2 is currently recommended for practical application. Additionally, Kopietz (2023) advises basing the residual styrene limit on the pure resin content to avoid influence by variable resin-to-fiber ratios. This approach ensures a more precise threshold.

Table 4: Limitations for residual styrene from literature / standards in mass percent based on the laminate / a sample and based on the resin content; values marked with * are conversions assuming an average resin/fiber ratio of 50%

Standard / literature	**Residual styrene limit based on laminate**	**Residual styrene limit based on resin content**
DWA-M 144-3	4 wt. %	8 wt. %
DIN 53394-2	2 wt. %	4 wt. %*
Industry association for reinforced plastics (AVK): Handbook of fiber-reinforced plastics (Kunststoffe eV, 2010)	1 wt. %*	2 wt. %

3.5.1.2. Effects of Curing Deficiencies

The effects of curing deficiencies in UV-cured liners on the aging process were demonstrated in a study by Nuruddin et al. (2020) from the United States. In a field experiment, one group of liners was fully cured, while a second group was not completely cured. The incompletely cured liners exhibited a higher proportion of volatile components, lower temperature resistance, reduced shear strength, and a lower modulus of elasticity compared to the fully cured liners. The study also revealed that the moisture absorption of water and salt solutions in fully cured liners followed Fick's diffusion law, which describes the relationship between concentration gradients and material transport. However, this law was not applicable to incompletely cured liners due to disruptions in the material structure and a higher susceptibility to hydrolysis. As a result, incompletely cured liners exhibited irregular and unpredictable moisture absorption in the laminate, leading to potential leaks, reduced resistance to chemical stresses, and faster material failure under stress. The study further showed that conventional calculation methods and physical assumptions, which are based on fully cured liner products, lose validity when curing deficiencies are present. These deficiencies can significantly reduce the expected service life of the liners.

Quantifying the reduction in service life depends on the extent of the curing deficiency and currently remains a major uncertainty. Buchner et al. (2021) also highlighted the critical influence of the degree of curing on hydrolysis resistance and the resulting long-term behaviour of a liner.

In Buchner et al. (2021), curing deficiencies in liners were examined using the example of the city of Hamburg. Each year, approximately 10-12 km of sewers in Hamburg are rehabilitated using CIPP (cured-in-place pipe) lining. These are primarily brick egg-shaped profiles with heights of up to 1.30 m. According to Hamburg Wasser, the operator, the mechanical minimum values (modulus of elasticity, flexural strength) were achieved in about 90% of liner installations. In the approximately 10% of cases where material testing failed, it is suspected that the liners were not fully cured.

To address this issue, Hamburg Wasser has been performing curing control using dielectric impedance spectroscopy for every liner since 2020. The results indicate that in about 20% of UV- or hybrid-cured fiberglass liners (regardless of the manufacturer), the residual styrene content exceeds the maximum allowable limit of 2% set by Hamburg Wasser. Circular profiles up to DN 500 are particularly affected, with over 50% of liners exceeding this limit. Despite this, Hamburg Wasser emphasizes that there is no fundamental curing problem with its liners, and its overall experiences with liners in Hamburg remain positive (Buchner et al., 2021). Curing deficiencies highlight the potential for optimization in the installation process, thereby ensuring a durable liner product.

Curing deficiencies are frequently discussed in the context of the complex UV-curing process for fiberglass liners. In contrast, curing deficiencies in heat-cured needle-felt liners are not known, according to the literature. This is likely due to the uniform temperature distribution throughout the cross-section, achieved by water-filling the entire liner. This ensures consistent installation conditions across the full cross-section and length of the liner, theoretically preventing installation deficiencies caused by uneven conditions.

3.5.1.3. Quality Assurance in Curing

For heat-initiated curing, monitoring the temperature progression of the hot water or steam measured at the outer surface of the liner in the manhole area is critical to oversee the curing process. In contrast, UV-initiated curing involves new control parameters, such as light intensity, lamp pulling speed, and the number of layers in the liner. This process uses UV lamp trains, which must maintain a light intensity (uniformly across the entire cross-section: invert, haunch, crown) and pulling speed precisely aligned with the manufacturer's specifications. Figure 2 schematically illustrates this curing process for an installed liner using UV lamp trains. The monitoring and process control are carried out by measuring the internal temperature of the liner using an infrared sensor integrated into the UV system (Buchner et al., 2021). According to Buchner et al. (2021), the degree of curing can be determined in the laboratory by measuring the glass transition temperature. This is the temperature at which a liner sample softens or hardens. This method is well-suited for measuring the polymer content and, consequently, determining the residual monomer content. However, it cannot be applied in situ during the installation process. To measure the degree of curing during the installation process, Hamburg Wasser successfully applied dielectric impedance spectroscopy in situ, enabling intervention in the process if necessary (Buchner et al., 2021). Impedance spectroscopy, also known as dielectric analysis, is a method used to study the cross-linking of monomers and curing into polymers. It measures the mobility of polymer molecules during the curing process within an alternating electric field. Since this method provides information on the degree of cross-linking of polymers and thus the degree of curing of the liner being examined, Hamburg Wasser used this data to optimize the curing process. This contributed to increased confidence in achieving full curing for newly installed liners. Whether this improvement positively affects the lifespan of liners remains unclear. However, it can be stated with certainty that this approach eliminates a risk factor associated with reduced service life.

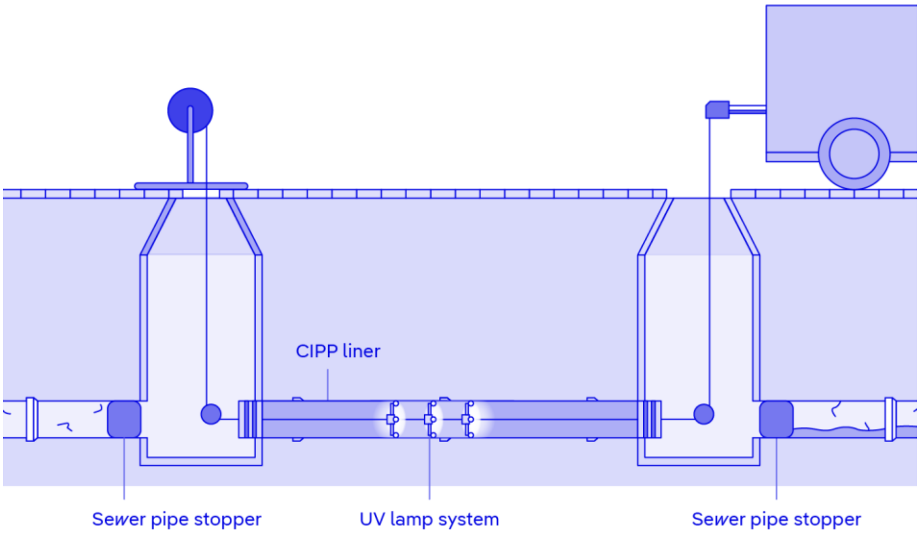

Figure 2: Curing process of an installed liner using a UV lamp system

3.5.2. Geometric Integrity of Liners

The factors influencing the geometric integrity of a liner within the host pipe, as described below, do not initially provide a direct and measurable connection to its aging behavior. However, these factors can cause defects in the liner that may, depending on the specific case, significantly impact aging. Therefore, the key sources of errors leading to improper installation, which should be carefully monitored, are outlined below.

3.5.2.1. Customization and Stretching Behavior

The use of liner systems is characterized by their high flexibility and stretchability. However, to ensure the proper installation of a liner in the sewer, it must be sized properly by the manufacturer before installation. Improper sizing, whether excessive or insufficient, can lead to problems during installation. Oversizing the liner can result in material surplus, causing wrinkles to form. Conversely, if the liner is undersized, it may exceed its stretch limit due to a lack of counterpressure from the host pipe wall. This can lead to the formation of an excessively large annular gap between the liner and the host pipe, as well as the creation of external pure resin layers (see Section 3.5.2.3 for further related issues). Liners are intentionally manufactured slightly undersized to accommodate their stretchability. The stretchability of the liner is defined as the range between its minimum elongation and its stretch limit (Leddig-Bahls, 2019).

According to Vogel (2018), the stretchability of liners is influenced by several factors. These include the liner's construction, particularly the chosen carrier material, which can vary in structure (stitched, wound, or laid) and type (synthetic fibers or glass fibers). The liner's profile shape also affects its stretchability; for example, the stretching behavior in non-standard profiles, compared to circular profiles, may vary significantly due to friction effects along steep sidewalls, as seen in egg-shaped profiles. Additionally, the profile dimensions, especially the circumference and wall thicknesses of the liner, play a crucial role in its stretching properties. Finally, the installation specifications for positioning the liner in the sewer set the framework for optimal stretching. This includes adhering to the specified pressure levels and dwell times under pressure during liner installation. Improper customization and insufficient or excessive stretching behavior can cause installation defects (e.g., annular gaps or wrinkles), which may have a minor but noteworthy impact on the liner’s aging behavior.

3.5.2.2. Host Pipe Geometry

The precise installation of a liner requires accurate knowledge of the internal diameter of the host pipe along its entire length prior to the liner’s customization. In current practice, this diameter measurement is typically limited to the starting, intermediate, and end manholes (Leddig-Bahls, 2019). Ensuring proper installation quality is only possible if high-quality calibration is implemented in practice. Excessively large tolerances in the dimensions of the sewer profile along the pipe section can lead to the formation of wrinkles and overly large local annular gaps (Vogel, 2018). These defects, in turn, can result in limitations to the service life of the liner, as described in the following sections.

3.5.2.3. Annular Gap

Despite the requirement that a liner should fit closely against the host pipe wall (RSV-M 1.1), voids, known as annular gaps, can still form between the installed liner and the host pipe. These gaps often remain undetected during visual inspections. The annular gap is caused by various factors, including the previously mentioned properties: insufficient expansion, excessive geometric tolerances in the host pipe, or reactive and thermal shrinkage during curing (particularly when a pre-liner or an outer protective foil without adhesive bonding to the host pipe is used, as noted by Vogel (2018). If the liner's expansion during curing is inadequate, the formation of an annular gap can lead to excessive laminate compression on the liner's inner side and resin extrusion on its outer side. Although laboratory testing might reveal higher material properties compared to the German structural approval (DIBt) in this scenario, it could, according to Vogel (2018), have unpredictable effects on the liner's structural stability, service life, and deformation behavior.

An annular gap could even allow the liner to move due to the lack of anchoring to the host pipe. If load transfer through the host pipe is not possible, this movement could result in stress peaks at connection points. These stress peaks can, in turn, cause damage to manhole and connection points or lead to foil tears due to excessive liner stretching (Vogel, 2018). Additionally, an annular gap increases the risk of reduced buckling stability, as the liner's bedding stability is insufficient due to the gap. As a result, the liner becomes more susceptible to external water pressure, which may cause permanent deformations or bulging in the liner.

In liner statics, excessively large annular gaps must therefore be considered. However, measuring annular gaps with today's technology is not non-destructive and can only be performed with great effort for more accurate results. The uncertainty about the actual size of an existing annular gap often means it cannot be reliably verified in static calculations (Vogel, 2018). The German guideline DWA-A 143-2 suggests, for safety reasons, assuming an annular gap with a width of up to 0.5% of the liner radius in the static calculation. As described, annular gaps and their sizes are difficult to measure. Therefore, the issue of annular gaps currently represents primarily a theoretical cause of consequential damage to liners and associated shortened service lives. Establishing a statistical correlation has not been possible so far. Practical examples of damage to liners and shortened service lives directly attributed to annular gaps are not publicly known at this time.

3.5.3. Formation of Wrinkles and Surface Irregularities

Wrinkles and surface irregularities can potentially impair sewer operation depending on their severity. Wrinkles, in particular, may lead to curing deficiencies in the wrinkled areas, localized leaks due to insufficient laminate stretching, and increased wear in the wrinkle zones during high-pressure cleaning operations. Longitudinal wrinkles, in particular, pose a threat to the buckling safety of the liner. These wrinkles can be considered as pre-deformations, compromising the circular shape required for buckling resistance.

However, the presence of wrinkles and surface irregularities in the liner does not always constitute a defect or operational restriction. Limits and a differentiated evaluation of wrinkles are necessary and can be assessed using guidelines such as DWA-A 143-3, DWA-M 144-3, DIN EN ISO 11296-4, RSV-M 1.1, or the evaluation methodology by Leddig-Bahls (2019). Depending on the classification of the observed wrinkle, it may present different risks. For example, a longitudinal wrinkle with reduced buckling safety represents a high risk, while a transverse wrinkle although associated with potential cleaning or wear damage poses a lower risk of shortened service life.

3.5.4. Problems at Lateral Connections

Long-term observations repeatedly show that damage due to connection detachment from liners occurs at the connection points of lateral pipes, regardless of the liner system used. The primary reason for these damages lies in the movement of the liner, which is, in turn, attributed to various factors. These include the presence of an annular gap, the lack of sufficient anchoring or fixation of the liner within the host pipe, as well as stresses caused by fluctuating groundwater levels and temperature-related loads (Vogel, 2018). For example, connections are often implemented using a hat profile between the lateral pipe and the liner, which is designed to be statically rigid. As a result, stresses from liner movements are transferred to the connection. A potential way to relieve stress at the connection point could be the creation of a static joint at the point where the liner connects. However, the practical implementation of such a solution has not yet been realized. Since connection points cannot be restored indefinitely due to material degradation, they represent a limiting factor for the service life of liners if frequent repairs are required.

3.6. Current Estimates on the Service Life of Liners

3.6.1. Definition of the Service Life of Liners

RSV-M 1.1 (Chapter 10.4) defines the service life (“operational suitability period”) of liners as the sum of the technically assumed service life and the “technical remaining service life.” The remaining service life can therefore be seen as a cost advantage for network operators through deferred renewal investments beyond the depreciation period.

The end of a liner’s service life is often difficult to define. According to RSV-M 1.1, the service life may end due to the occurrence of one of the following conditions:

- Lack of operational suitability
- Visible damage such as leaks, cracks, or laminate defects
- Deformations indicating problems with bonding to the host pipe or the surrounding ground

However, problems with connections are excluded from the service life of a liner according to DWA-A 143-3, as they are considered local repair measures. These are treated as standard repairs and are counted as measures contributing to the achievement of the liner’s service life.

3.6.2. Assessment of Service Life of Liners

The DWA-A 143-3, published in 2014, estimated the "economically reasonable service life, during which the liner must perform without repair costs," at 50 years. However, connection points may require repair measures. The RSV-M 1.1 (Chapter 10), released in 2021, also references a 50-year service life but suggests that the actual service life is likely to exceed the initially assumed 50 years, based on studies of liners in long-term operation. This statement is echoed and emphasized by Vogel (2022). Similarly, a study by Berglund et al. (2018) assumed a service life of 50 years, based on earlier studies (Alam et al., 2015; Allouche et al., 2014; Araujo and Yao, 2014; Macey et al., 2013) investigating a 50-year service life. Ji et al. (2018) also mentions a 50-year service life as the current industry standard for liners. However, the authors argue that the long-term behavior of liners, currently determined through regression methods, is based on conservative estimates. They base their argument on an earlier study by Nassar and Yousef (2002), which analyzed the long-term buckling behavior of liners. This study experimentally and analytically found an 80% probability that liners would withstand external hydrostatic pressure for a period of 50 years. Although the study did not specify material or manufacturing methods, it concluded that conventional service life estimates using least-square regression tend to be overly pessimistic. This conclusion suggests that the study's findings are applicable across different materials and installation methods, as long as the 50-year service life is estimated using least-square regression. An additional experimental study by Wong (2016) examined the mechanical properties of liners that had been in service for many years. The results showed that the liners maintained their mechanical properties for up to 30 years, meeting the minimum requirements (ASTM F1216 and WIS 4-34-04). Hicks et al. (2022) also reported a standard service life of 50 years for liners, which, in some cases, could be exceeded. The authors of Hicks et al. (2022) suggest that more precise assessments of the service life of individual material components within a liner system could improve predictions of future maintenance needs and subsequent rehabilitation measures. None of the cited studies assessing the service life of liners accounted for specific materials (e.g., fiberglass or needle felt liners) or installation and curing methods (e.g., hot water, steam, or UV curing). It remains unclear whether these factors are relevant to estimating the service life and aging behavior of liners and were simply overlooked in the studies or whether they genuinely have no impact on aging behavior.

3.7. Interim Conclusion

The expected service life of liners is consistently estimated at 50 years in the literature. However, this estimate is largely based on laboratory studies, often tied to installation deficiencies, and lacks differentiation between materials and installation methods. This generalization raises questions about the representativeness of the 50-year lifespan assumption. Investigations of liners in long-term use depend on the objectives of the research, which may include:

1. Assessing the condition of liners immediately after installation
2. Evaluating the condition of all liners in a network after years of operation
3. Investigating aging-related condition developments since installation

This report focuses on aging behavior (objective 3), whereas studies like Bosseler et al. (2024) emphasize condition assessments post-installation (1) and after years of operation (2) but do not derive aging gradients (3). To study aging, a comparison of initial and current liner conditions is essential. From the cited studies, only two provided relevant comparative analyses:

- Allouche et al. (2014) analyzed needle felt liners aged 25, 23, 21, and 5 years, finding some samples with reduced E-modulus compared to initial values.
- Hoppe (2008) examined needle felt liners aged 25 and 19 years and a fiberglass liner aged 12 years, finding negligible deviations in short-term mechanical properties regardless of material or manufacturing method.

No clear correlation between aging processes and mechanical properties (e.g., bending strength or E-modulus) has been proven, partly due to the limited number of studies and liners analyzed. Additionally, studied liners exhibited no severe aging-related damage. Nevertheless, laboratory testing of mechanical properties remains crucial for assessing long-term performance. Both Allouche et al. (2014) and Bosseler et al. (2024) recommend further sampling and testing of liners in long-term operation to build a robust data foundation. For this aim, Bosseler et al. (2024) highlight two laboratory methods as potentially relevant for assessing aging:

- Three-point bending tests, which may indicate aging effects
- 24-hour creep inclination tests, which could predict long-term creep behavior over 10,000 hours and remaining aging potential

Proper documentation and data management of inspections, laboratory tests, and in-situ measurements over a liner's lifecycle are critical. Only by comparing material properties over time can aging phenomena be identified and operational lifespan estimated.

Current literature provides no new data to revise liner survival curves but identifies avenues for further research, particularly regarding the impact of defects such as curing deficiencies and annular gaps on aging. Buchner et al. (2021) identified curing as a key factor affecting hydrolysis resistance and long-term behavior. Improper resin matrix curing can lead to water absorption, compromising structural integrity and sealing performance. While such defects are linked to shorter lifespans, no liner failures have been solely attributed to these issues due to the complexity of contributing factors and the relatively young age of most liners. Nevertheless, improperly installed liners are unlikely to meet the expected 50-year lifespan.

The lack of robust studies on liner lifespans and survival curves contrasts with material science research on fiber-reinforced plastics, which provides insights into aging under extreme laboratory conditions. However, these findings are difficult to generalize for liners in sewer environments. More studies involving sampling and laboratory testing of long-term liners are needed, though destructive sampling poses challenges, as liners showing no visible defects in inspections may not warrant damage for research purposes. Advancing non-destructive inspection techniques, as suggested by Buchner et al. (2021), and integrating them into quality assurance processes could address data collection challenges and improve liner lifespan assessments.

4. Interviews

4.1. Methodology of Interviews

As part of this research on the service life of liners, interviews with experts were conducted. These interviews aimed to gain practical insights into the challenges and experiences associated with liners. Additionally, the interview campaign was intended to complement the literature review, as many experiences remain unpublished. The interview campaign was structured according to a predefined methodology, which is explained below.

4.1.1. Interview Duration and -Structure

The planned interviews had an average duration of approximately 45 minutes. To ensure an efficient and consistent process, an interview guide was developed, structured into the following sections:

1. **Introduction to the Research Project**: An overview of the research project, including its objectives and background.
2. **Introduction of Interviewees and Their Organization**: Information about the interviewees and their organization to contextualize their experiences.
3. **Causes of Defects and Issues in Liners**: Interviewees were asked about their experiences with liner defects, the main causes, and their impact on service life.
4. **Experiences Regarding Liner Service Life**: Interviewees' estimates of liner service life, including challenges they have encountered.
5. **Recommendations for Further Research**: Suggestions for additional research and useful resources, such as contacts, literature, and data, were solicited.
6. **For Utilities**: If the interviewees represented operators, a specialized section addressed questions about the collection of sewer network data, the proportion of liners used in total network rehabilitation, risk assessments, and related topics.

The collected interview data were subsequently analyzed to identify patterns, insights, and relationships between the reported damages and preventative measures. These findings aim to contribute to answering the research questions on liner service life.

4.1.2. Selection of Interviewees

As part of the preparation for the interview campaign, a list of 85 potential interviewees was compiled, consisting of individuals involved in research, drainage operations, consulting firms, or liner manufacturing. This list was based on existing contacts as well as newly identified connections. Of these 85 candidates, 68 were contacted to send interview invitations or to request referrals for additional potential interviewees. Out of the 68 contacts, 17 helped in identifying further contacts, although they themselves were unavailable for interviews.

In total, 21 interviews were successfully conducted. Special emphasis was placed on selecting interviewees with extensive experience with liners. Prior to the interviews, email invitations were sent, including information about the study, expectations, and the interview guide to help participants assess whether they had the required expertise to address the questions. Efforts were made to ensure diversity among the interviewees in terms of geographical representation. Although a good geographic mix was aimed for, the majority of participants came from the DACH region (Germany, Austria, Switzerland, as shown in Figure 3, left). Additionally, interviews included participants from other European countries and one from the United States.

A diverse range of organizational types was also included to avoid biases or dominant viewpoints from any single group, thereby capturing a broad spectrum of opinions. As illustrated in Figure 3 (right), the largest proportion of interviewees were operators. The category "Consulting" included companies providing advisory services to operators and municipalities or offering sewer network modeling. Furthermore, testing laboratories, research institutions, and one glass fiber liner manufacturer were interviewed. This targeted selection ensured a wide variety of perspectives were integrated into the study.

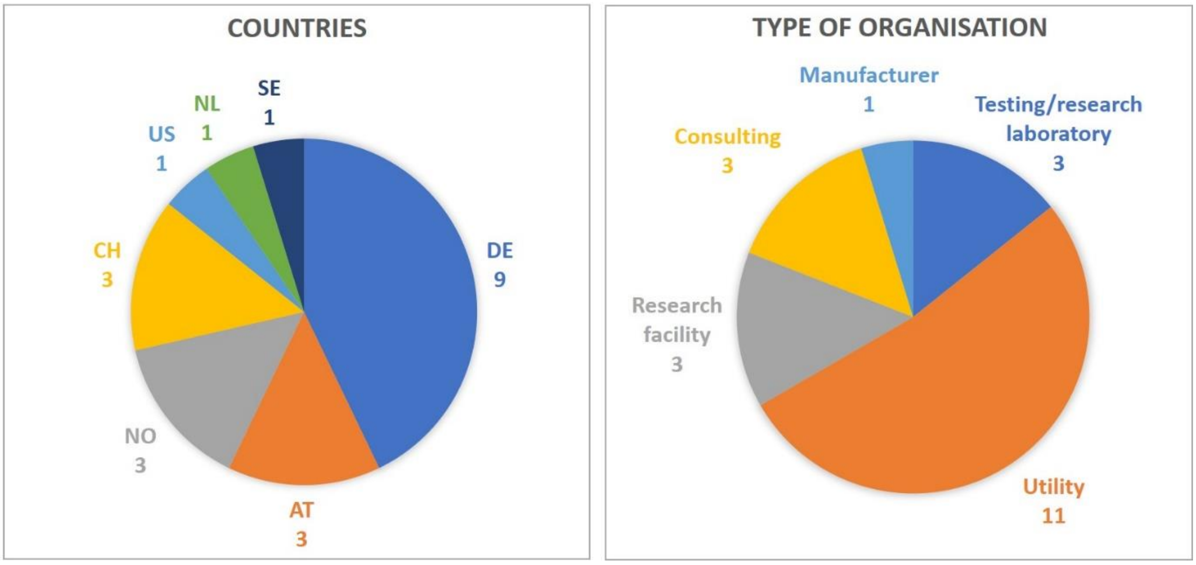

Figure 3: Distribution of countries, shown as ISO 3166-1 Alpha-2 codes (left) and types of organizations (right) from the total of 21 interviews

4.2. Interview Results

4.2.1. Liner Usage by Interviewed Operators

About half of the interviewed participants were operators. The 11 surveyed operators came from Germany (2), Austria (2), Switzerland (3), Sweden (1), Norway (2), and the Netherlands (1). The operators were asked about the total percentage of liners installed in relation to the total length of their respective sewer networks. The network lengths of the surveyed operators ranged from approximately 300 km to nearly 10,000 km of public sewer systems, with an average total network length of about 2,600 km. Of the 11 respondents, 7 operators reported having around 5% of their network lined, 2 operators reported about 15%, and one operator reported 30%. One operator did not provide a response. The liner lengths of the surveyed operators ranged from 15 km to 600 km. On average, the operators reported a liner share of around 10%, with an average length of approximately 200 km. In total, the 11 operators reported over 2,000 km of lined sewer systems, providing a significant practical experience base for the interviews.

The mentioned liner shares, as well as other facts presented here, could not be verified and are based solely on the statements of the interviewed personnel of the operators. A survey conducted in Germany by Berger et al. (2020) found an average rehabilitation scope of 1% annually, with 23.9% of this involving liner installation. Optimistically assumed that this annual rehabilitation scope for liners has been consistently implemented at 0.239% since 2000, this results in a liner share of around 6%. This hypothetically high estimated average liner share is still lower than the average liner share of 10% reported in this interview campaign. The reason for this discrepancy is that, when selecting interviewees, a strong emphasis was placed on operators with extensive practical experience with liners.

4.2.2. Liner Functionality

As shown in Section 3.3, liners are versatile and can serve different purposes depending on their design. They can function as a sealing measure or be used to contribute restoring the stability of a sewer pipe being rehabilitated. In the interviews, respondents were asked about the primary use of liners:

- 4 of the 21 interviewees stated that they use liners exclusively for sealing, without aiming for the liner contributing to the structural integrity of the rehabilitated pipe.
- In contrast, about 13 of the 21 interviewees use liners both for sealing and to maintain the stability of the pipeline.
- The remaining 4 interviewees did not provide a specific answer regarding the use of liners.

The evaluation of liner usage shows that, in addition to ensuring tightness, operators often expect liners to help maintain the structural stability of the pipeline.

4.2.3. Damage Analyses

The 21 interviewees (not limited to operators) were asked about their assessments of typical damages and issues related to liners and their impact on the service life of the systems. The identification of damages and issues was based on the personal experiences and evaluations of the interviewees and does not constitute a statistical survey of actual damage frequencies occurring in sewer networks. Rather, the analysis presented here highlights the damages and issues that were most prominently focused on by the various experts. As shown in Figure 4, with multiple responses possible, curing deficiencies were mentioned by approximately 48% of the 21 respondents, while wrinkling, flushing damage, inner foil damage, and connection problems were each cited by about 4%. Undersizing was reported in approximately 19% of cases, and bulging/deformations in about 14%. Except for the mentioned curing deficiencies, all major reported damages and defects are visually detectable.

A recurring and dominant topic throughout these discussions, which was already described in detail in Section 3.5.1, is the critical issue of curing deficiencies. Compared to earlier systems, where needle-felt liners with heat-initiated curing were used, there has been a clear trend since the 2000s toward the use of fiberglass liners with UV-initiated curing. This shift has also led to changes in the control parameters of the curing process. Consequently, parameters such as light intensity, temperature, and the speed of the lamp train introduce increased complexity in ensuring a fully cured liner product. According to the interviewees, in addition to the main influencing factors – light intensity and lamp train speed – several other factors can affect the degree of curing of an installed liner. These include the number of layers in the liner, external temperature and liner temperature at installation, potential groundwater influence, and moisture levels within the sewer. Experiences shared across multiple interviews indicate a current trend toward increasingly powerful lamp systems. This development aims to enable higher speeds when passing through the lined section, thereby reducing the curing time and required labor hours. However, the various experts interviewed unanimously evaluated this trend as counterproductive. The reason for this is that the crosslinking of monomers requires a certain amount of time, which cannot be fully achieved in practice through increased light intensities and faster traversal speeds. The consequences are, on the one hand, the described curing deficiencies on the outer wall of the liner or, on the other hand, excessive curing, which leads to a brittle inner surface of the liner with potential crack formation. Both extremes – excessive curing as well as curing deficiencies – pose risks of shortened liner service life. However, curing deficiencies are of significantly greater concern, as they cannot be detected through optical inspection, unlike excessive curing, which leads to brittleness and crack formation on the inner liner surface.

Without a process-integrated curing control method as mentioned in Section 3.5.1.3, curing deficiencies along the length of a sewer section cannot be measured non-destructively. Currently, the only available option for process-integrated optimization during curing is an adjustment of the lamp train speed. Given the numerous influencing factors mentioned, as well as the challenges posed by increased light intensities, real-time regulation of light intensity during the process would be urgently required. This would provide an effective solution to minimize significant curing fluctuations across the liner cross-section and along its length.

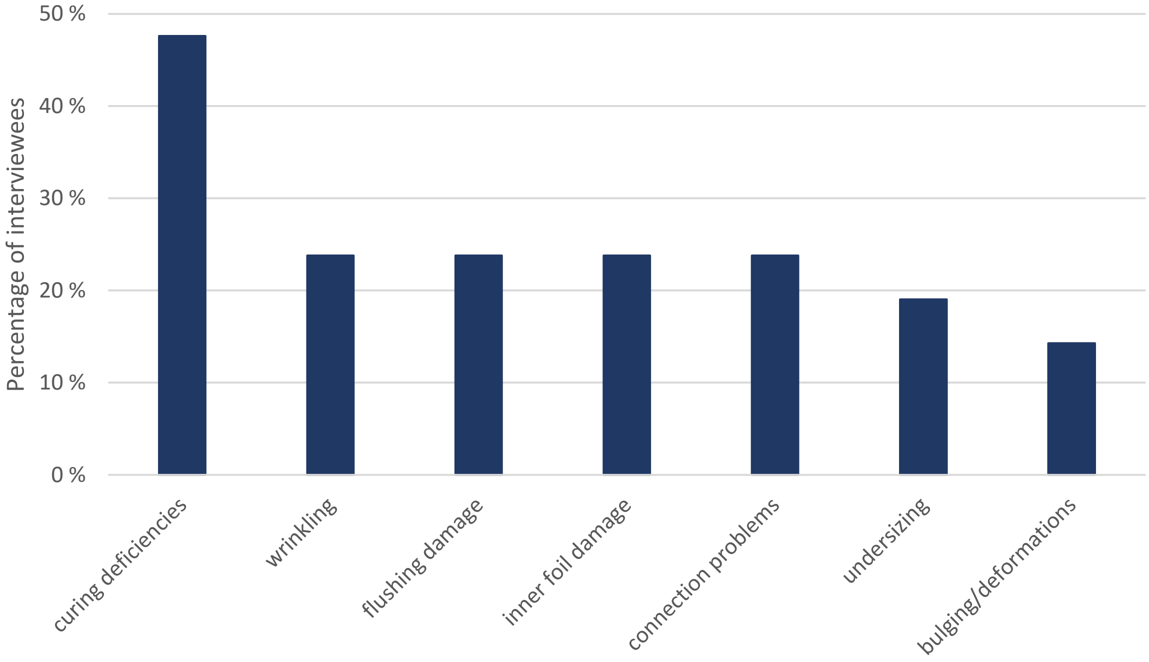

Figure 4: Frequency of mentions of potential service life-affecting issues related to liners (multiple mentions possible)

4.2.4. Quality Assurance Measures from Interviews

In the interviews, specific questions were asked about preventive measures that can contribute to ensuring a long service life for liners. Across the 21 interviews conducted, various preventive measures were suggested (with multiple responses possible). The analysis of the interview data identified the following key preventive measures:

- Stronger quality assurance of the installation process (approx. 33% of respondents)
- More precise temperature control during UV curing (approx. 19%)
- Control of flushing pressure in flushing vehicles, adherence to cleaning guidelines & minimization of flushing operations (approx. 33%)
- Explicit curing control during liner curing (approx. 33%)
- Awarding contracts exclusively to experienced installation companies (approx. 28%)
- Thorough inspection of the host pipe before liner installation (approx. 19%)

In addition to the statements already mentioned, further individual insights regarding preventive measures for ensuring a long service life emerged during the interviews:

- **Application of CIPP lining:** It was recommended that pipes with non-circular profiles should generally not be rehabilitated using liners due to potential vulnerabilities, particularly regarding expansion behavior and fit accuracy. The use of liners was recommended for host pipes classified as condition grade 1 or 2 (according to DWA-A 143-2), particularly to prevent deterioration to condition grade 3. One manufacturer supported the use of CIPP lining even in host pipe condition grade 3, where the liner must absorb partial loads from soil, traffic, and superimposed loads, citing the high structural integrity of fiberglass-reinforced liners. However, an operator and a consultant opposed this for safety reasons.
- **Process control during installation:** Process control, along with the ability to intervene and adjust the process during liner installation, is crucial for a defect-free installation. The flexible use of different materials and curing methods allows targeted adaptation to specific requirements, thereby increasing process reliability and influencing the service life of the liner.
- **Curing:** The exothermic chain reaction initiated by UV radiation during curing loses effectiveness in the outer layers. Therefore, it was emphasized that temperature measurement should be continuously conducted at the coldest point (the outer liner surface) using a temperature cable. Additionally, for thicker liners with more than three fiber layers, the use of peroxides was suggested to enhance reaction propagation. A further recommendation was to conduct random sampling of liners to test for residual styrene content.
- **Monitoring & data management:** During the warranty period, it was proposed to implement specialized monitoring (optical inspections and possibly additional non-destructive methods). The idea of collecting more data related to liners and promoting data availability among different operators was also suggested.
- **Connection points:** It was noted that hat profiles are not always the optimal solution for connecting lateral pipes, and alternative solutions should be explored. The use of stainless-steel end seals (liner end sleeves) at shaft connection areas was recommended to ensure watertightness and provide mechanical protection for liner ends against operational influences.
- **Operation of the sewer:** Compliance with regulations requiring decentralized treatment of chemically contaminated industrial wastewater is essential for protecting liners installed in the sewer system. Monitoring wear due to sedimentation was highlighted as an important measure.

4.2.5. Subsequent Rehabilitation of Previously CIPP-Renovated Sections

Another key focus of the interviews was the question of how the subsequent rehabilitation of previously renovated sewer sections using CIPP liner was carried out or should be performed. Some operators were able to share initial experiences with follow-up rehabilitation due to installation defects. It is important to note that, according to the interviews, no liner has yet reached the end of its service life due to aging and subsequently required rehabilitation. Instead, the necessary follow-up measures were due to defects and damages occurring during the installation process and were carried out shortly thereafter.

The interviews indicated that localized damage to a liner should preferably be repaired through targeted spot repairs, particularly for sealing issues at connections. Repairs should generally be applied to isolated defects, as with other materials, without requiring a more extensive rehabilitation process, provided that the damage density remains low enough to ensure the economic feasibility of the repair method. Milling out an old liner was generally perceived as labour-intensive and therefore not the preferred approach. Some operators reported experiences using high-pressure water jetting to break down and remove liners. This method was found to require less effort but demands high precision and expertise due to the significant force applied also to the host pipe. In general, these methods should only be considered if the underlying host pipe remains structurally sound.

A simpler and commonly preferred method discussed in the interviews is installing a new liner within the old one, referred to as a "liner-in-liner" approach. This method is viable provided that hydraulic and operational conditions allow it and that both the damaged liner and the underlying host pipe maintain sufficient structural integrity. However, providing the necessary structural verification for this approach may present a challenge, particularly if the defective liner is expected to serve as a load-bearing base for the new liner. Additionally, questions arise regarding the long-term service life of this increasingly complex system consisting of the new liner, the old liner, and the original pipe. Another possibility could be the application of an alternative trenchless rehabilitation method that may be better suited to the specific conditions.

If none of the previously mentioned follow-up rehabilitation methods are feasible, the final remaining option – albeit the most time-consuming and costly – would be a full replacement of the sewer section using either open-cut or closed-construction methods.

4.2.6. Statements on the Service Life of Liners

Liners are designed for a service life of 50 years, which serves as the primary reference point for most interviewees' assessments. However, many respondents, based on their experience, expressed optimism regarding a longer lifespan. There was a recurring view that, under ideal installation conditions and in the absence of chemical exposure or damage from high-pressure cleaning, liners could last significantly longer than previously assumed. The majority of the 21 interviewees estimated the service life of liners to be at least 50 years, with some expecting 75 years or more. A few even compared the durability of liners to that of factory-manufactured plastic pipes, which, according to some references, can last over 100 years (Folkman, 2014; Meerman, 2008; Whittle and Tennakoon, 2005). The distribution of these assessments is illustrated in Figure 5. It is important to note that these estimations are solely based on the interviewees' subjective assessments, which were formed according to varying levels of knowledge and experience.

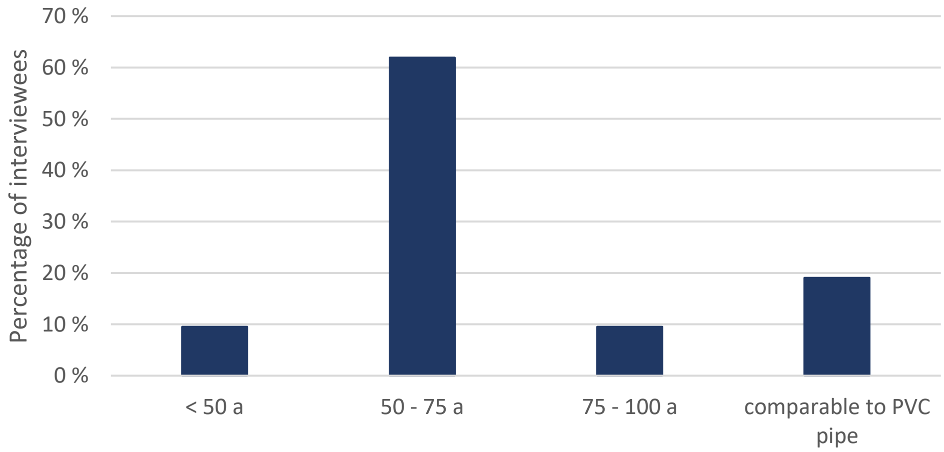

Figure 5: Assessment of the service life of liners from the 21 conducted interviews

Despite the promising durability of liners and their comparison to plastic pipes, several interviewees questioned this perspective when considering the entire liner-host pipe system. When rehabilitating old sewer systems that may already be 70, 100, or more years old, it must be considered that in host pipe conditions classified as 1 or 2 (according to DWA-A 143-2), the liner is only designed to withstand external water pressure, while the original pipe continues to bear the higher loads from soil and traffic. In these cases, a failure of the original pipe would also lead to deformations and subsequent failure of the liner. In cases where rehabilitation is performed on pipes classified as condition 3, the liner is dimensioned to partially absorb soil, traffic, and surface loads. However, according to the underlying static model, it remains questionable whether the liner could fully take over the structural load in the event of original pipe failure, leading to a high risk of deformation and at least a limited usability. Consequently, according to some interviewees, the question of a liner's service life is inherently linked to the expected durability of the underlying host pipe. During optical inspections of rehabilitated sewer sections, the lack of knowledge about the condition of the original pipe behind the liner introduces significant uncertainties in estimating the actual service life of the liner.

4.3. Interim Conclusion

The interviews did not yield new data on the aging behavior of liners. However, the following key insights can be noted for the development of a corresponding data foundation:

- The 11 surveyed sewer network operators who frequently use liners reported consistently positive experiences with their liner inventory. Apart from a few cases of failure occurring immediately after installation and various defects, primarily caused by the installation process, no critical liner conditions have been observed that indicate an end of service life due to aging. Consequently, the estimates for the service life of liners were generally optimistic, with expectations of 50 years or more.
- None of the respondents used a calibrated model approach to depict the aging behavior and condition assessment of liners. One interviewee from the consulting sector indicated the use of an uncalibrated, assumption-based approach but was unable to share further details or the model itself.
- Both the interviews and the literature review in Chapter 3 identified numerous factors that can influence the service life of a rehabilitated sewer section. Figure 6 summarizes these influencing factors, categorizing them into four main groups: installation, environmental influences, properties of the original pipe, and operational conditions.
- Data monitoring combined with process optimization during installation – particularly in the curing process – can provide a valuable data foundation to assess installation quality under volatile construction site conditions.

The discussion on the service life of liners highlights the existing uncertainties, despite 20 to 30 years of experience with liner systems in many cases. Although the first liner is now over 50 years old (Bueno, 2021), materials and installation techniques have evolved significantly since the first needle-felt liner was introduced. This makes direct comparisons between older and newer liners difficult. The interviews revealed widely varying opinions regarding estimated service life. Recent problems with UV-cured fiberglass liners, as discussed in Section 3.5.1, were emphasized in particular. While curing deficiencies have been known for some time, they have only recently gained greater attention due to measurement campaigns and more detailed analyses, which have identified them as a significant factor in reducing service life.

The latest challenges in liner curing underscore the complexity of the process and highlight the need for more in-depth research to make reliable assessments of service life and to calibrate survival curves. Furthermore, according to some interview statements, the service life of a liner is strongly dependent on the remaining service life and damage condition of the supporting host pipe. This influence is also described by Bosseler et al. (2024); however, neither the literature nor the interviews have reported any cases of liner failure due to the failure of the underlying host pipe.

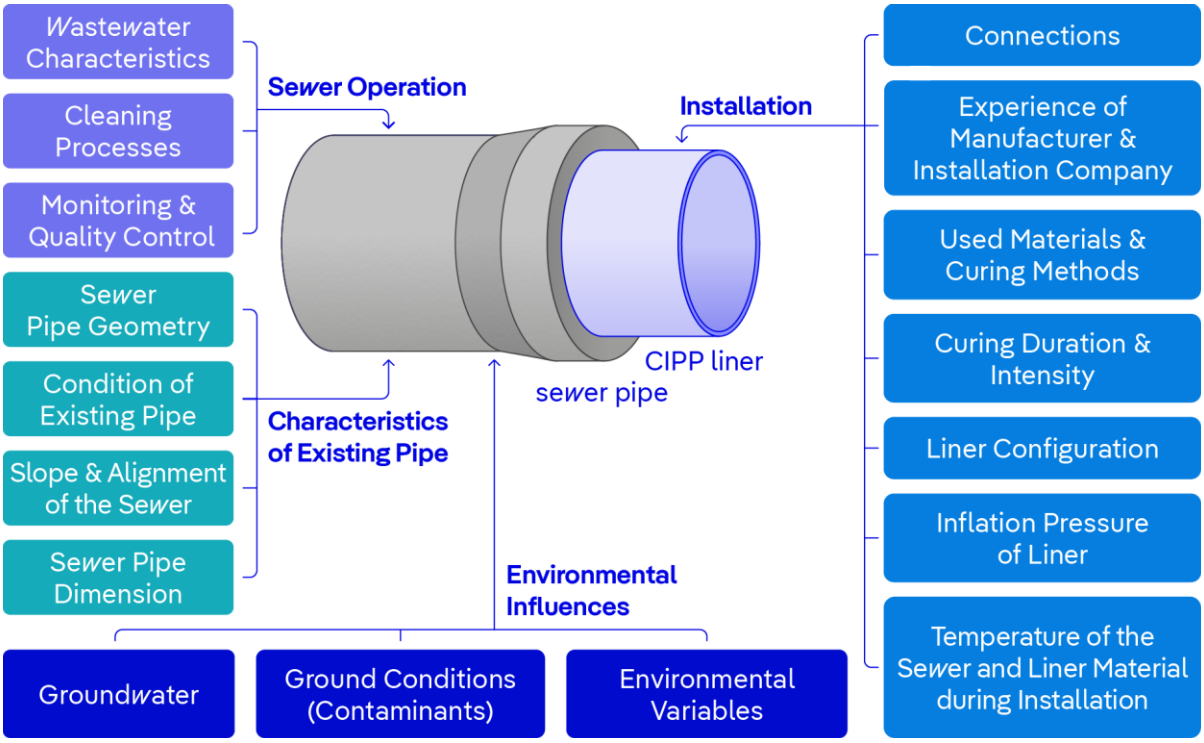

Figure 6: Factors that can influence the service life of the combined system of liner and host pipe

5. Data Processing of Berliner Wasserbetriebe

5.1. Methodology of Data Processing

The literature review in Chapter 3 and the interviews in Chapter 4 indicate that there are no new data available for deriving survival curves to describe the liner aging behaviour, except for the long-term optical condition assessments conducted by operators and laboratory tests on liners that have been in service for many years. Therefore, this chapter presents an updated survival curve for liners based on the analysis of optical condition data from Berliner Wasserbetriebe.

The updated data analysis considered 332 km of liners installed in Berlin's sewer network, with defects recorded and assessed according to Defect Catalog 11[4] of Berliner Wasserbetriebe. The analyzed CCTV inspection reports for these 332 km of rehabilitated sewer sections do not exclusively document liner conditions; in some cases, they also capture visible damages to the host pipe. For example, some liners still require house connection integrations, meaning that damages to the house connections of the host pipe are visible and thus recorded. Another example includes damages to the host pipe at manhole connections, which were documented for liners installed before 2012 due to the absence of liner end seals.

Pre-existing damages in the host pipe prior to liner installation may influence the condition of a rehabilitated section but do not represent the aging behavior of the liner itself. Since 2012, such damages have been explicitly recorded in the inspection protocols as pre-existing conditions. To ensure that the dataset primarily reflects structural integrity and leak-tightness-related damages and conditions of liners, a multi-stage filtering process was applied, which is described in detail in the appendix. Subsequently, the condition assessments of the rehabilitated sections were assigned to the corresponding SEMAplus condition categories based on Damage Catalog 11 (see Table 5).

Table 5: Definition of SEMA conditions based on the time horizon and urgency of the need for action

SEMAplus-Condition	Time horizon	Urgency of need for action
Very bad	0 – 5 Jahre	immediate
Bad	6 – 10 Jahre	short-term
Medium	11 – 20 Jahre	medium-term
Good	> 20 Jahre	long-term or none

5.2. Results of Data Processing

Figure 7 illustrates the distribution of liner lengths by age at the time of inspection for the analyzed 332 km of liners. The data reveal that more than half of the liners (in terms of total liner length at the time of inspection) were up to two years old. This is largely due to acceptance inspections carried out immediately after liner installation[5]. In addition to the predominantly very young inspected liners, the dataset also includes some older ones, with approximately 400 meters over 28

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[4] The Berlin damage catalog is comparable to the requirements of the DWA guidelines. It is based on ATV-M 143 Part 2 (04/1999). In adaptation to DIN EN 13508-2 and the revision of the guideline as DWA-M 149-2 (12/2013) and DWA-M 149-3, the Berlin damage catalog has additionally integrated condition classification separately for structural stability and watertightness.

[5] Due to the 10–20 year inspection cycle based on area prioritization by Berliner Wasserbetriebe and the generally young age of most liners, relatively few have been recorded within the area strategy.

years old, around 3.4 km between 23 and 27 years old, and approximately 8.1 km between 18 and 22 years old at the time of inspection.

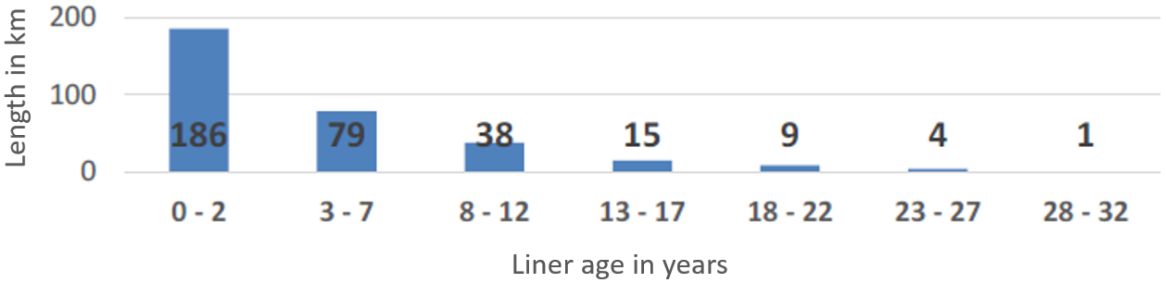

Figure 7: Distribution of liner lengths (rounded to whole km; ordinate) of the evaluated liners for the liner age groups at the time of inspection (abscissa); Figure from BWB

Based on the processed condition data, the SEMAplus condition distributions for different age groups, as shown in Figure 8, were determined. Across all analysed age groups, only 1.5 km of the examined liners are in poor or very poor SEMAplus condition (marked in orange or red). This corresponds to a very small proportion of just under 0.5% of the total examined liners. The most common types of damage found in these two rehabilitation-relevant SEMAplus condition categories include leaks, shards (holes in the liner with visible "liner fragments"), deformations, surface damage, material wear, and root intrusion. The latter remains classified in the poor SEMA category due to the incomplete review of all inspection videos. Overall, the proportion of liners requiring rehabilitation within each age group is low.

Damage analysis through the inspection of video recordings also revealed that the assessment of damage is subject to a significant degree of subjectivity by the evaluators. This is partly because the codes in Damage Catalog 11 were not designed for a sufficient description of typical liner defects. The use of the damage code "shard" for torn holes in the liner is a prominent example of this. Furthermore, the condition evaluation within Damage Catalog 11 is currently inconsistent for similar defects. For instance, the condition assessment of torn holes in the liner is not correlated with that of holes caused by missing house connection joints. Expanding Damage Catalog 11 to include liner-specific damage patterns and their engineering-based condition evaluation would be necessary for a more consistent assessment of liner conditions. However, such an expansion is not planned by Berliner Wasserbetriebe, as they are currently transitioning to the Eurocode (Damage Catalog 12, based on the latest valid DWA-M 149-2/3 and DIN EN 13508-2). A corresponding review of whether Damage Catalog 12 better and more consistently covers liner-specific damage has not been conducted.

In Figure 8, a trend can be observed in the increasing proportion of liner lengths in the medium SEMAplus condition (marked in yellow) up to the age group of 13-17 years. According to data analysis, more than 95% of this deterioration is due to pre-existing damage that was rehabilitated using the liner, affecting approximately 165 km of liners classified in the medium condition category out of the total 332 km examined. This includes the previously mentioned manhole connection damages, which impact around 45 km of liners.

An interesting observation in Figure 8 is the trend of increasing shares of sections in good SEMAplus condition for age groups beyond 18 years. However, the representativeness of data in these older age categories is limited due to the significantly lower number of liners. Consequently, only the condition distributions of liners up to 17 years old will be used as the basis for deriving an updated liner survival curve. This trend provides a suitable foundation for adjusting the survival curves for liners used by Berliner Wasserbetriebe, as described in the introduction (Chapter 1), within the scope of available data. The assumptions derived from this data analysis for Berliner Wasserbetriebe and used for this adjustment are described in the following sections.

Figure 8: Condition distributions (ordinate) of the evaluated liners for the liner age groups at the time of inspection (abscissa); Figure from BWB

5.3. Interim Conclusion

The data analysis in this chapter revealed primarily non-relevant conditions for the 332 km of lined sewer pipes based on optically detectable defects. Due to the lack of other available data on the aging behaviour of liners, as described in Chapters 2 and 3, the condition distributions considered representative (up to the 13-17 year inspection age group) are used as the basis for adjusting the liner survival curve. These data do not include aging-related factors like curing deficiencies or annular gaps. A liner in a "good" SEMAplus condition, based on optical data, could still have quality issues and may not meet its expected lifespan due to such deficiencies. To improve condition assessments, additional data on aging-related data (e.g., short- and long-term properties, annular gap widths, curing quality) would be needed. The findings of this condition analysis show:

- Minimal immediate need for rehabilitation, which could all be addressed through repairs
- No complete structural failure of any liner observed in Berlin, except for a few failed installations that were immediately replaced

The survival curves mentioned in Chapter 1 were based on initial assumptions about liner aging. Based on the evaluated SEMAplus condition distributions and relevant age categories, new calibration points can be generated to more accurately model the aging behaviour of Berlin's liners. Table 6 shows the newly established calibration points for the Berlin liner aging process, marked in Figure 9 as black crosses on the adjusted survival curves. These calibration points are based on the distribution of the 13-17 year age group, with further points derived from expert estimates from Berliner Wasserbetriebe. After 50 years, it's assumed that 50% of the liners will be in good or acceptable condition, while the other 50% will require rehabilitation. This assumption is consistent with the expected service life of liners, which is assumed to be around 50 years (as discussed in Chapter 2). The study assumes 20% of liners will be in very poor condition after 50 years, based on a previous study by Nassar and Yousef (2002), which is referenced in Section 3.6, and which implies an 80% survival probability. At 75 years, 70% are expected to be in very poor condition, 20% in poor condition, 10% in medium condition, and none in good condition. These assumptions are based on extrapolating the aging trend and modeling the transition from medium to very poor conditions, with an adequate proportion of liners expected to be in the "poor" condition category at that time.

Table 6: Proposal of the calibration points based on earlier conclusions and assumptions made

Condition	**15 years**	**50 years**	**75 years**
Very bad	0.005	0.200	0.700
Bad	0.006	0.300	0.200
Medium	0.594	0.450	0.100
Good	0.395	0.050	0.000

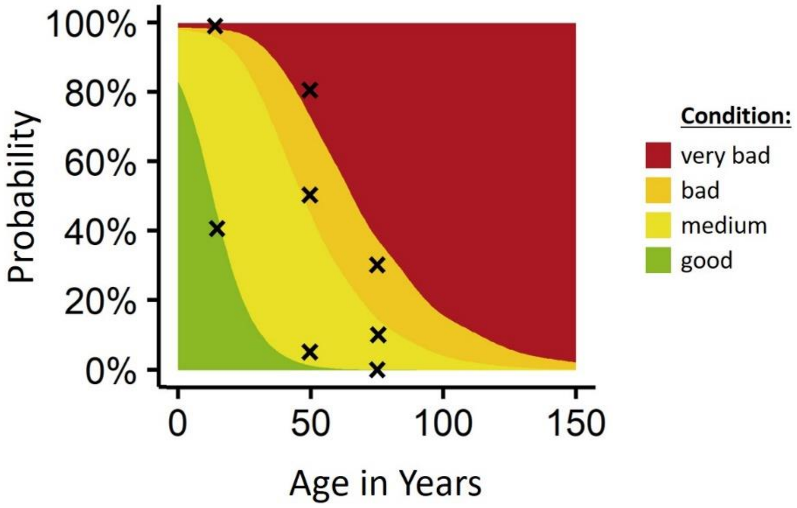

Figure 9: Proposal of revised and acceptable survival curves for Berliner Wasserbetriebe to model the aging behavior of liners; calibrated through marked points from updated data evaluations, assumptions, and conclusions of this research

A closer look at the survival curves resulting from the calibration in Figure 9 shows that these curves partially miss the defined calibration points. The reason for this lies in the fact that the calibration points cannot be fully represented by the mathematical forms of a Gompertz distribution (Riechel, 2021) used. The uncertainties in the depicted survival curve are seen by the Berliner Wasserbetriebe in the data foundation, the assumptions made, and the deviation of the mathematical modelling from the calibration points. The magnitude of these uncertainties cannot currently be estimated due to the lack of additional data as described in this report. Further clarification of the survival curve is the goal of future research activities by Berliner Wasserbetriebe as part of the planned continuation of the SEMA Berlin projects.

The survival curve for liners presented in Figure 9 is used within the SEMAplus strategy simulator at Berliner Wasserbetriebe. It has been created based on Berlin-specific framework conditions and foundations and represents the current state of knowledge on the aging of Berlin's liners. It is not transferable to liners in other sewer networks without adjustments and therefore does not claim general applicability or validity.

6. Additional Insights

In parallel with this study, Berliner Wasserbetriebe engaged in extensive discussions with other operators and experts from the DWA working group ES 8.6 to deepen their technical understanding and clarify open questions regarding the service life of CIPP liners and the adjustment of the Liner Survival Curve. These discussions led to additional, significant insights that will have a decisive impact on Berliner Wasserbetriebe's approach to revising the liner survival curve. These findings are incorporated into the final recommendations and are explained below.

6.1. Documentation of the Installation Process

For the majority of existing liners, data on the installation process (installation records) are available, allowing for an assessment of the conditions at the time of installation and potential curing deficiencies. However, what is neither found in the literature nor mentioned by interviewees is the standard practice of systematically documenting data collection during the installation of CIPP liners. Installation data provide a crucial source of information regarding the quality of installation and the expected service life of liners, which has so far been largely overlooked. With the appropriate expertise in composite CIPP liners and the interpretation of recorded installation data, it is possible to retrospectively draw conclusions about curing quality and, consequently, the overall installation quality of the liners. Therefore, installation data serve as an additional database that should be further analyzed regarding its informational value in relation to questions about service life and the liner survival curve.

6.2. Detection of Liner Damage in Optical Inspections

The extent to which the most severe damage that shortens liner service life can be detected through optical inspection is currently a topic of discussion among experts and should be the subject of further research. TV inspections can reveal liner-specific characteristics such as exposed fibers, glittering effects, or resin exudation, which may indicate liner damage if properly documented during the inspection. Although standards such as DIN EN 13508-2 and DWA-M 149-2/3 provide codes for recording some of these damages, operational experience at Berliner Wasserbetriebe suggests a need for additional training to ensure inspectors properly recognize and document these issues. Furthermore, it should be examined whether the classification of these liner-specific optical damages in the existing regulations is comprehensive or whether further amendments are necessary.

7. Conclusion

The problem statement outlined in the introduction of this report emphasized the growing use of liners and the associated questions regarding their technical service life. Municipalities and sewer network operators face the challenge of estimating the long-term durability of liners and incorporating this into their investment planning. The uncertainty surrounding service life and potential risks necessitates a thorough investigation of the aging and failure behavior of liners. Based on findings from the literature review, interviews, and data analysis, several conclusions can be drawn:

1. Confidence and uncertainty in estimating service life: The literature review shows that the expected service life of liners is still based on conservative estimates of 50 years. Although no new scientific findings on service life have emerged, operators have gained significant experience due to the increasing number of installed liners, the aging of liners in the network, and operational observations of different failure cases. Literature formulations and expert opinions suggest that liners installed without defects could last beyond 50 years. However, further investigations are needed to assess additional, previously unconsidered damage that could reduce service life. Particularly, improper liner installation that is not visually detectable and limited experience with newer fiberglass liners—especially recent findings regarding the UV curing process—introduce uncertainties into service life estimations. In this context, the commonly assumed 50-year service life is not necessarily guaranteed. At the same time, around 70% of interviewees estimate that liners will last beyond 50 years if installed without defects and if the host pipe remains structurally stable. The original 50-year service life assumption, as adopted in industry standards, should be scientifically reviewed and adjusted if necessary to reflect current knowledge and developments. More studies of long-used liners, including sampling and laboratory material testing, are needed. Additionally, it remains unclear what types of failures should be expected, as age-related collapse of liners has not been observed, unlike the visible structural failures in concrete or vitrified clay pipes. Respondents suggested that wear, leakage, and deformation might be the primary aging-related failure modes of liners.

2. Installation quality has the greatest impact on service life: Both the literature review and interviews indicate that most severe liner damages stem from installation errors, particularly curing deficiencies, annular gaps, and critical folds. The installation process occurs under volatile construction site conditions, making quality assurance a challenge. The composite nature of liners allows for significant variability in onsite production and quality control, unlike other industries where composite materials are manufactured with factory precision. Strengthening monitoring efforts, especially of the curing process during installation, represents a key step toward quality control with the potential for intervention and optimization.

3. Lack of reliable data: Few studies provide solid data on the actual service life of liners. Investigating long-used liners through optical inspections, as done in this report's data analysis, offers a preliminary, data-driven aging assessment but remains insufficient for a comprehensive evaluation of liner conditions. Further research is needed on optical damage detection methods related to aging. Most laboratory tests are conducted on samples taken at installation, with only a few material tests performed on liners that have been in service for many years. Obtaining new samples presents a challenge, as it is not feasible to take destructive samples from liners in good optical condition. It is recommended to further explore non-destructive testing and monitoring methods in sewer systems to develop a practical approach for operators.

4. Damage detection and condition assessment requires standardization: A comprehensive assessment of the liner-host pipe system is necessary for rehabilitated sections. There is a need to monitor pre-existing damage in host pipes even after liner installation, as highlighted in the data analysis. For non-visible defects, such as underlying pipe damage or hidden liner issues like curing deficiencies or annular gaps, the current standards (DIN 13508-2 and DWA-M 149-2/3) are insufficient. Furthermore, suitable non-destructive inspection and measurement techniques should be established as a standard alongside optical inspections for sewer monitoring.

5. Calibration approach for liner survival curves at Berliner Wasserbetriebe: The findings from this report contributed to the development of a calibration approach for predicting liner conditions over time. Based on the conclusions regarding service life, the core calibration assumption is that after 50 years, 50% of liners remain in a non-rehabilitation-required condition (per SEMAplus criteria), while the other 50% require rehabilitation. However, it is uncertain whether these survival curves accurately represent different liner materials and manufacturing methods, as well as whether the underlying assumptions are precise. This initial calibration approach should be continuously reviewed and revised if new findings or suitable aging-related data sources become available.

6. Initial trials on potential follow-up renovation methods: The interviews provided examples of cases where follow-up renovation was performed on defective rehabilitated sections due to poor installation. Interviewees agreed that follow-up renovation depends heavily on specific conditions. If the existing host pipe-liner system remains structurally sound and provides sufficient hydraulic capacity, a second liner can be installed within the old liner. In some cases, the defective liner had to be removed before a new one could be installed. However, all reported cases involved follow-up renovation due to poor installation, with full knowledge of the underlying host pipe condition. No follow-up renovation of a liner that failed due to aging alone has been documented in either the literature or the interviews conducted for this report. The uncertainty regarding the condition of the host pipe behind an aging liner remains a significant risk. It is still an open question whether these trenchless rehabilitation methods would be suitable at the end of a liner’s long service life.

This report highlights the need for further research to better understand and model the aging behaviour of liners over their lifespan. This is crucial for sound investment planning, safe operation, and enabling future rehabilitation strategies for liner systems in sewer networks.

8. Recommendations for Action

1. Evaluation of installation protocols: The data from the standard installation protocols, which have so far been largely overlooked, should be retrospectively assessed concerning installation quality and potential curing deficiencies. Experts in composite liner materials should be consulted for this evaluation. Until confirmed research results are available, the assessment of curing quality should be used as a preliminary assumption for an initial categorization of liner aging behavior. Depending on the findings regarding the correlation between curing deficiencies and aging behavior, further conclusions on the aging of installed liners may be drawn (see recommendation on data collection for liners in operation).

2. In-depth analysis of optical damage detection: To determine whether the most significant durability-reducing damages can be identified through visual inspections, the following measures should be taken:

- Consultation with materials science experts to determine whether visually detectable liner-specific features, such as protruding fibers, glittering effects, or resin exudation, can indicate liner damage that affects aging behavior.
- Examination of whether current standards adequately address liner-specific, optically detectable, aging-relevant damages or if additions are necessary. If needed, provisional additions to damage classification should be defined.
- If necessary, training inspectors based on expert findings to enhance recognition of aging-relevant liner damages during optical inspections.

3. Data collection for liners in operation: The report's conclusions highlight a lack of reliable condition data for long-used liners. Routine optical inspections provide an initial foundation for monitoring. If visually conspicuous liners show suspected aging signs, sampling followed by laboratory testing of short- and long-term mechanical properties is recommended. However, given the current data gap, large-scale sampling of long-used liners is advisable, even in the absence of visible aging signs. Comparing material properties with earlier samples (ideally from installation) is essential for assessing aging effects and determining whether the liner remains operationally suitable. Evaluating current laboratory results without a historical comparison, as done in several studies in Section 3.3, does not distinguish between installation defects and aging effects, thus providing limited insight into aging behavior. Additionally, further studies under controlled conditions should improve the understanding of how reduced short-term mechanical properties and curing deficiencies (as recorded in installation protocols) relate to liner aging.

4. Data collection during liner removal: If long-used liners are removed in the future, it is crucial to subject them to extensive material sampling for research purposes and to document the condition of the host pipe if possible. Care should be taken to remove liners as gently as possible to preserve the host pipe. To compare the host pipe's condition over the liner's service life, the pre-installation condition of the host pipe should also be documented where available. Central organizations such as the DWA are well-suited for overseeing data collection, issuing recommendations, and coordinating data gathering and analysis in collaboration with operators.

5. Expanding quality assurance during liner installation: Post-installation inspections and laboratory tests do not allow for corrections or optimizations, as the liner is already cured. Therefore, quality assurance should be integrated into the installation process. Real-time monitoring, particularly during the critical curing phase, is essential to enable immediate intervention and optimization. Dielectric impedance spectroscopy, as described by Buchner et al. (2021), has shown promising results. A market for in-situ curing monitoring has already emerged, offering significant improvements in quality assurance and data collection. Implementing real-time installation monitoring ensures high-quality liner production, which is fundamental for ensuring long-term service life.

6. Research on new in-situ monitoring methods: Conventional optical inspections are insufficient for a comprehensive assessment of the liner-host pipe system over its lifespan. This is because (a) the visual indicators of liner aging are not yet fully understood, and (b) the liner itself obstructs inspection of the host pipe and surrounding soil system. Research on new in-situ measurement methods that complement optical monitoring of liners and liner-host pipe-soil systems is therefore crucial for expanding the data base and achieving more comprehensive assessments. A study by Alam et al. (2018) suggests a potential correlation between surface hardness (particularly the inner surface) of liners and their aging. The study proposes testing inner surface hardness in-situ using sewer robots to assess liner aging. An overview of tested sewer inspection techniques, along with their advantages, disadvantages, and applications, is provided in Hao et al. (2012). Testing suitable methods for in-situ condition assessment of liner-host pipe systems remains an open research topic.

7. Differentiated investigation of liners: Due to the various liner types, studies and conclusions regarding service life and aging behavior should always specify the exact materials and installation methods used. This allows for a differentiated analysis of composite systems and representative damage types, which has not been adequately addressed in existing literature and standards. Depending on differences in aging behavior, distinct survival curves could be developed for different liner types, such as needle-felt and fiberglass liners. If research confirms uniform aging behavior across liner types, differentiation may be unnecessary. However, no conclusive findings exist on this topic yet.

8. Investigation of damage impact on service life and knowledge exchange: This report provides an overview of known liner damages and their potential impact on service life and aging behavior. Building on this, further research should analyze the influence of specific damages on liner aging. Additionally, previously undocumented damage types may be identified through ongoing studies. Statistical analyses of liner aging, considering various liner types, geometries, and environmental factors, are essential for modeling aging behavior. These analyses should account for external and inert factors affecting aging and aim to isolate influencing variables. Suitable modeling approaches for predicting the aging and condition of rehabilitated pipelines should be prioritized and compared. Knowledge exchange among operators, along with the sharing and publication of new findings, is critical and strongly encouraged.

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