article

Corrosion Control in Drinking Water Distribution Using Simple Methods

Determination of Corrosion Rate and Instationary Corrosion of Low-alloy Steel

Norbert Konradt, Monika Konradt and Peter Janknecht, Trinkwasser Consulting, 45355 Essen, Germany

Abstract: To investigate the effects of a corrosion inhibitor settling over an extended period, a two-part low-alloy steel pipe was taken from the drinking water network and installed in a test system. After an equilibration phase with inhibited water, the connected pipe sections were operated with inhibitor-free water for 600 days. During this time, stagnation tests were conducted to measure the increase in turbidity, oxygen consumption, and iron release. Corrosion rates and iron release rates were calculated from these parameters. Comparing the values at the beginning and end of the tests showed that the test pipe without the phosphate inhibitor did not exhibit a significant increase in the corrosion or iron release rate. The turbidity rates indicate that the legal limit for drinking water is reached after six hours of stagnation in the tested water. Under stable conditions, turbidity increased linearly over time, while oxygen consumption decreased linearly. Flushing significantly disturbed the corrosion system and increased the turbidity rate.

The results obtained can be used to assess the risks associated with changes in water properties, in this study by discontinuing the addition of corrosion inhibitors, but also with modifications to water treatment such as aeration, softening, and desalination. In these cases, the impact on corrosive materials should be investigated beforehand. The results allow for the derivation of recommendations for optimizing the corrosion properties of the water or for implementing countermeasures in the supply network. The test procedure requires minimal personnel and financial resources, yet provides valuable insights into corrosion processes in the water-metal system.

Keywords: Brown water formation, corrosion of low-alloy steel, corrosion measurement, corrosion rate, instationary corrosion, inhibition, iron release rate, oxygen corrosion, surface corrosion, stagnation test, turbidity rate.

Foreword: What is the purpose of this series of article?

With this article, we want to provide information about the possibilities of corrosion control in drinking water distribution networks and drinking water installations. To this end, we will explain the significance of corrosion for the materials used in drinking water supply and for drinking water as a medium, describe investigation methods, and discuss possible problem-solving strategies for corrosion protection. The aim is to provide water suppliers, large consumers, and interested private individuals in particular with a deeper understanding of metal corrosion in drinking water systems.

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1. Determination of the instationary corrosion of a low-alloy steel pipe

1.1. Introduction

The study aimed to investigate how changes in water properties impact corrosion rates and instationary corrosion, resulting in "brown water" formation. The focus was on adjusting the long-term dosage of corrosion inhibitors. This method can also be used to study and evaluate changes in water properties caused by developing additional raw water resources or altering treatment processes, such as softening, desalination, or aeration. For example, aeration increases the oxygen concentration in water, reduces the carbon dioxide content, and raises the pH value. These parameters influence corrosion processes. Even if treated water complies with DIN EN 12502-5 requirements [1], it cannot be assumed that corrosion rates will not vary significantly. Such standards only specify probabilities, so they do not eliminate the risk of corrosion in practice. They also do not account for corroded pipes in the distribution network that have been in operation for decades. Therefore, it is recommended that the behavior of the corrosion system be investigated before changing the properties of the water in the supply network.

1.2. Use of low-alloy steel in drinking water distribution

Low-alloy steel has long been used for larger pipe diameters in drinking water distribution systems. However, due to its lack of resistance to corrosion caused by water, an internal coating is required for protection. Technologies available before 1970 did not offer sufficient long-term protection against internal corrosion. Only the application of a cement layer enabled permanent protection against internal corrosion [2].

1.3. Surface corrosion of low-alloy steel

For low-alloy steel pipes installed in a distribution network without inner protection, **oxygen corrosion** is the only relevant **corrosion mechanism**, and **surface corrosion** is the only relevant **type of attack**. As the main constituent of low-alloy steel is the element iron, the **corrosion rate of steel** is determined by the amount of iron oxidized per unit of time. With an iron molar mass of 55.85 g/mol and an iron density of 7.87 kg/dm^3, corrosion rates for iron materials can be converted as follows [3]:

1 g/(m^2*d) = 0.0464 mm/year ≙ 46.4 µm/year = 1.81 mpy (0.001 in/year).

Typical corrosion rates for unprotected steel pipes that have been in operation for several years are in the range of 0.2 g/(m^2*d) or 10 µm per year [4].

In surface corrosion, the attack on the material surface occurs uniformly. This type of corrosion is diffusion-controlled and depends mainly on the oxygen concentration in the water. According to DIN EN 12502-5 [1], the **formation of a protective layer** is likely if the water in question meets the following requirements:

- **Oxygen concentration > 2.8 mg/L**
- **pH value > 7**
- **Bicarbonate concentration > 122 mg/L**
- **Calcium concentration > 44 mg/L**

Furthermore, it is known that corrosion is enhanced by chloride and sulfate ions, while bicarbonate, carbonate, hydroxide, and calcium ions have an inhibitory effect. However, the extent of their influence and how they interact with each other has not been fully investigated [5].

Surface corrosion can result in **instationary corrosion**, which can lead to the formation of "**red water**" or "**brown water**." After several hours of stagnation, red or brown, cloudy, particle-laden water emerges from low-alloy steel pipes. Increased turbidity can often be prevented by replacing the pipe contents (contaminated water and sediments) through flushing and adjusting the **flow velocity to > 0.1 m/s**.

1.4. Oxygen consumption and corrosion rate of ferrous material

For surface corrosion, oxygen in drinking water is the dominant oxidizing agent. Therefore, it can be assumed that oxygen consumption corresponds to iron corrosion rates. For pipes covered with corrosion products, the corrosion rate depends on the diffusion rate of oxygen through the rust layer [3]. In flowing water, the oxygen concentration depends on saturation, flow rate, and temperature. Thus, these parameters also influence the transfer of dissolved oxygen to pipe surface. With continuous flow, the oxygen concentration in the water at the corrosion surface remains relatively constant. In stagnant water, however, the oxygen concentration decreases, so the oxygen consumption should also decrease. As the temperature increases, the water's viscosity decreases and the diffusion coefficient for oxygen in the corrosion layer increases, thus increasing the corrosion rate. The diffusion coefficient of oxygen through a corrosion layer depends on factors such as layer thickness, mineral composition, and porosity.

The **corrosion rate**—the amount of oxygen consumed by the corrosion system per unit area and time—can be determined **by measuring the oxygen concentrations** in the test tube. First, the pipe is flushed continuously with water. Then, it is switched to circulation mode, and the decrease of oxygen is measured and evaluated as a function of time [4,6,7,8]. **The corrosion rate of the material can be determined from the negative slope of the oxygen concentration versus time curve, the test tube's specific geometric properties, and the circulation apparatus's volume.** For ferrous materials, stoichiometry according to Equation 1 applies, assuming a negligible formation of iron(II) species.

$$4\ \mathrm{Fe} + 3\ \mathrm{O_2} = 2\ \mathrm{Fe_2O_3} \qquad (1)$$

With an iron molar mass of 55.85 g/mol and an oxygen molar mass of 32 g/mol, three moles (96 g) of oxygen are needed to oxidize four moles (223 g) of iron into two moles (319 g) of iron(III) oxide. If oxygen measurements are taken at specific intervals (e.g., every 10 minutes), the difference between subsequent measurements is calculated and normalized to one hour. The average of these values gives the **oxygen consumption per hour** (unit: mg/(L*h)). This can be converted to the **iron corrosion rate**, expressed in units of g/(m^2*d), by multiplying it by the stoichiometric factor of 0.55847. This calculation is based on a circulating volume of 10 L (0.01 m^3) and an inner surface area of the test tube of 1 m^2 [9]. **An EXCEL spreadsheet for data collection and calculation of corrosion parameters is available as supplement.**

It is known that the of corrosion rate doubles or triples with every 20°C increase in temperature, corresponding to a 5-10% increase per degree Celsius [9]. Therefore, it is important to keep the temperature of the test pipes as constant as possible during the stagnation phase. This is difficult in practice, especially with larger pipe diameters. In this case, the initial temperature of the stagnation test and the temperature increase supplied by the oxygen sensor must be determined. If changes in the water are expected, it is also advisable to measure the pH value and electrical conductivity.

1.5. Iron release rate and turbidity rate

Metal release and removal through water transport is the difference between corroded metal and metal stored in the corrosion layer. Studies have shown that there is no generally valid correlation between corrosion rate and metal release rate [3,10]. Therefore, the **iron release rate** can only be determined by **time-dependent sampling and analysis of the iron in the circulating water**. Dissolved iron (mg/L) can be converted to the iron release rate (unit: g/(m^2*d)) by multiplying it by the stoichiometric factor of 0.024, based on a circulation volume of 10 L over 1 h and an inner surface area of the test tube of 1 m^2. However, examining a single sample at the end of the stagnation phase introduces uncertainties, and analyzing a large number of samples is time-consuming and costly. Therefore, the increase in turbidity over time, or the turbidity rate, was determined using the unit FNU/h. FNU stands for "Formazin Nephelometric Units," which is synonymous with Nephelometric Turbidity Units (NTU). For most waters, there is a direct linear correlation between turbidity and iron content. At pH values above 6.5, this correlation is due to the hydrolysis of the formed iron(III) species into solid, finely distributed (colloidal) iron(III) hydroxide oxide according to the Pourbaix diagram for iron [9]. By plotting turbidity values over time, the turbidity rate can be determined, as well as the estimated time when the limit value of 1.0 FNU will be exceeded.

1.6. *Instationäre Korrosion*

The term "**instationary corrosion**" was introduced by F. Kuch [6] to **describe the visually noticeable formation of corrosion products in water during stagnation** in unprotected steel and cast iron pipes which is in English-speaking countries known as “Kuch mechanism” of red or brown water formation [3]. Uniform surface corrosion ceases due to decreased dissolved oxygen, giving way to another corrosion process. At the surface of the corrosion layer, the sparingly soluble γ-iron(III) oxide hydroxide (lepidocrocite) is reduced to form iron(II), which then dissolves into the water. This corresponds to a reduction of the coating material. Simultaneously, oxidation processes occur at the interface between the metal and the corrosion layer. The oxygen present in the water oxidizes the iron(II), leading to the precipitation of brown iron(III) oxide hydroxides. Initially, an increase in turbidity is measurable. When fresh water is added, oxygen is supplied, resulting in a high iron content and, visually, brown water. The fact that not all combinations of water and pipe materials exhibit instationary corrosion is attributed to the different compositions of the surface layers. In particular, the presence of lepidocrocite is considered problematic, while α-iron(III) oxide-hydroxide (goethite) is less conducive to unsteady corrosion.

However, several studies have demonstrated that changes in water properties lead to increased brown water formation [3]. For instance, the iron release rate increases with higher carbonic acid content and lower pH levels, but decreases with higher bicarbonate concentrations. Therefore, the carbonic acid dissociation equilibrium is an important factor. Additionally, other studies have shown that changes in sulfate concentration promote red water problems [11].

2. Determination of the corrosion rate in instationary corrosion experiments

2.1. *Description*

Changes in water properties can significantly impact the corrosion of unprotected low-alloy steel pipes within a supply network. In this case, the discontinuation of corrosion inhibitor dosing was investigated. For this purpose, the pipeline was initially operated with inhibited water and then switched to non-inhibited water. During **flow-through operation**, the pipe sections were operated with a continuous flow, whereas the flow stopped in the **stagnation phas**e. To monitor changes in the stagnant water, it was circulated at a low flow rate using a separate pump in closed-loop mode. The recirculation mode should cause only minor disturbance to the stagnation and has been previously described in the literature [6,7,8].

2.2. *Test setup*

Two sections of steel pipe were cut out from operational water mains in 2016. Built in 1940, the low-alloy steel pipe had a diameter of 100 mm (DN 100), and a thin internal layer of cement was added to the pipe in 1978 (Figure 1a). Its inner diameter was 0.084 meters, resulting in a surface area of 0.44 square meters. The pipe sections were transported to a temperature-controlled room at the waterworks where they were inspected and kept moist until the adaptation phase began a week later. This was done to prevent the corrosion layer from drying out. Flanges with reducers to 3/4-inch connections were then fitted to the pipe sections (Figure 1b), which were used to connect the pipe sections to the test water inlet and outlet via hoses.

(a) (b)

Figure 1. **(a)** DN 100 steel pipe upon delivery, **(b)** sequential arrangement of 2 * 1 m DN 100 steel pipes.

The closed-loop system included a peristaltic pump (Ismatec BVP, Glattbrugg, Switzerland) with a flow rate of 50 L/h; an inline turbidity meter (Sigrist Aquascat 2P, Ennetbürgen, Switzerland) with a measuring range of 0 to 100 FNU and a resolution of 0.001 FNU. Turbidity measurements were performed according to DIN EN ISO 7027-1 [12] at 880 nm and a 90° angle to the incident light. Electrodes for electrical conductivity (EC), pH, and an optode for oxygen were installed in an airtight 1.5 L plastic flow cell, which also served as a buffer volume. In-situ parameters were measured and recorded using a Multi 3430 IDS connected to the following sensors: TetraCon® 925 (EC), SenTix® 980P (pH) and FDO® 925 (oxygen) from WTW, Weinheim, Germany. Oxygen was measured according DIN ISO 17289 [13], EC according DIN EN 27888 [14], pH according DIN EN ISO 10523 [15] and temperature according DIN 38404-4 [16].

Samples for total iron analysis were collected from the flow cell immediately following the end of stagnation and were acidified with 5% nitric acid. Element analysis was performed according to DIN EN ISO 17294-2 [17] using an Agilent 7900 ICP-MS with MassHunter 4.2 software (Agilent Technologies Germany GmbH & Co., Waldbronn, Germany).

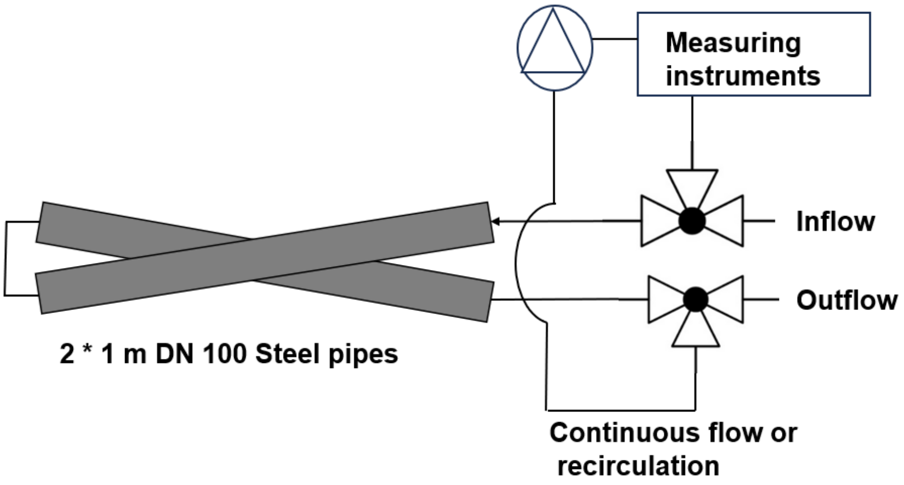

Figure 2. Schematic representation for the two coupled steel pipes for continuous flow and closed-loop operation.

The tubing for the closed-loop system was made of 8 x 1 mm silicone (inner diameter x wall thickness). The two pipes were stored at a 20° angle to facilitate the flushing of solid corrosion products. The outlet of the first pipe was connected to the inlet of the second pipe, creating a sloping, sequential arrangement (Figure 2). Inlet water was taken from the waterworks before inhibitor dosage and outlet water was discarded in flow-through mode.

Two three-way valves, one at the inlet and one at the outlet, made it possible to shut off the continuous flow at certain times and switch to closed-loop mode using a peristaltic pump. In this mode, a turbidity meter and a flow cell equipped with sensors to measure oxygen, electrical conductivity, pH, and temperature were integrated. The test facility had a total volume of 18.5 liters. Data from the sensors and the turbidity meter were recorded, stored, and evaluated later.

2.3. Test procedure

To equilibrate the test pipe sections, the test setup was operated for 106 days with inhibited water containing 1 mg/L ortho-/polyphosphate (1:1), similar to the distributed water. The system was then switched to inhibitor-free water, with one exception caused by increased turbidity and oxygen consumption (see Chapter 2.4). Stagnation experiments were carried out from the 102nd to the 600th day of inhibitor-free operation. The long test duration was chosen because it was known that after many years of inhibition, the material would not immediately react to a change in the water, but corrosion may increase after several months.

As shown in Table 1, the inhibitor-free test water had a chemical composition that complied with DIN EN 12502-5 [1]. This suggests uniform corrosion and formation of a protective layer inside the pipe. The water can be described as hard and well mineralized.

Table 1. Chemical analysis of the test water (average of 4 samples).

Parameter [1]	Average	DIN EN 12502-5
pH	7.47	> 7
Oxygen (mg/L)	6.7	> 2.8
Electric conductivity (µS/cm)	754	-
Acidity to pH 8.2 (mmol/L)	0.39	-
Alkalinity to pH 4.3 (mmol/L)	4.2	-
Bicarbonate calc. (mg/L)	256	> 122
Carbon dioxide, calc. (mg/L)	17	-
Calcium (mg/L)	95.5	> 44
Magnesium (mg/L)	13.2	-
Sodium (mg/L)	32.6	-
Potassium (mg/L)	4.0	-
Nitrate (mg/L)	15	-
Sulphate (mg/L)	72.8	-
Chloride (mg/L)	61.5	-
Phosphate total (mg/L)	< 0.08	-
Total organic carbon (mg/L)	0.30	-

[1] Methods employed were according to the German standard methods for the examination of water, wastewater and sludge.

A total of 29 stagnation experiments were evaluated. In-situ parameters and the turbidity of the test water were measured during each experiment; the results are shown in Table 2. The fluctuations in oxygen content (46%) and pH (4.6%) were mainly caused by the water treatment process, which included ozonation and aeration. The fluctuations in electrical conductivity (19%) and temperature (27%) were due to changes in the properties of the raw water. Temperature variation included the difference between summer and winter and also influenced the solubility of oxygen. During the test period, the average temperature of the test water corresponded to the average temperature of the water in the supply network (14.9 ± 1.5 °C).

Table 2. In-situ parameters and turbidity of the inflow water.

Parameter [1]	**Number of experiments**	**Minimum**	**Maximum**	**Mean**	**Median**
Temperature (°C)	29	12.2	16.1	14.7	15.0
pH	29	7.23	7.57	7.40	7.39
Oxygen (mg/L)	29	5.7	9.1	7.00	7.23
Electric conductivity (µS/cm)	29	681	826	762	762
Turbidity (FNU)	29	0.010	0.26	0.070	0.069

[1] Methods employed were according to the German standard methods for the examination of water, wastewater and sludge.

The flow rate was 300 L/h under continuous flow conditions, which corresponds to a flow velocity of 0.011 m/s in the DN-100 pipe. This flow velocity is within the typical range for the supply network. The calculated Reynolds number was 818, which was below the limit of 2300 for the transition to turbulent flow. In circulation mode, the peristaltic pump operated at 30 L/h.

2.4. *Results and interpretation*

The examination of the steel pipes revealed an uneven, 5 to 10 mm thick corrosion layer on the inside, on which individual pustules and isolated, larger rust spots were located (Figure 1a). The previously applied cement coating was no longer discernable.

During flow-through operation, no turbidity abnormalities were observed in the test pipe. The effluent had low turbidity similar to the inflow turbidity (see Table 2).

Stagnation phases of a few hours led to a linear increase in turbidity due to iron release and a linear decrease in oxygen concentration due to iron corrosion, as shown by the stagnation on day 103 (Figure 3). This behavior has also been described in the literature [8]. The electrical conductivity and pH value showed no significant changes. During stagnation experiments, the temperature of the circulating water increased depending on the ambient temperature and how long it had been stagnant.

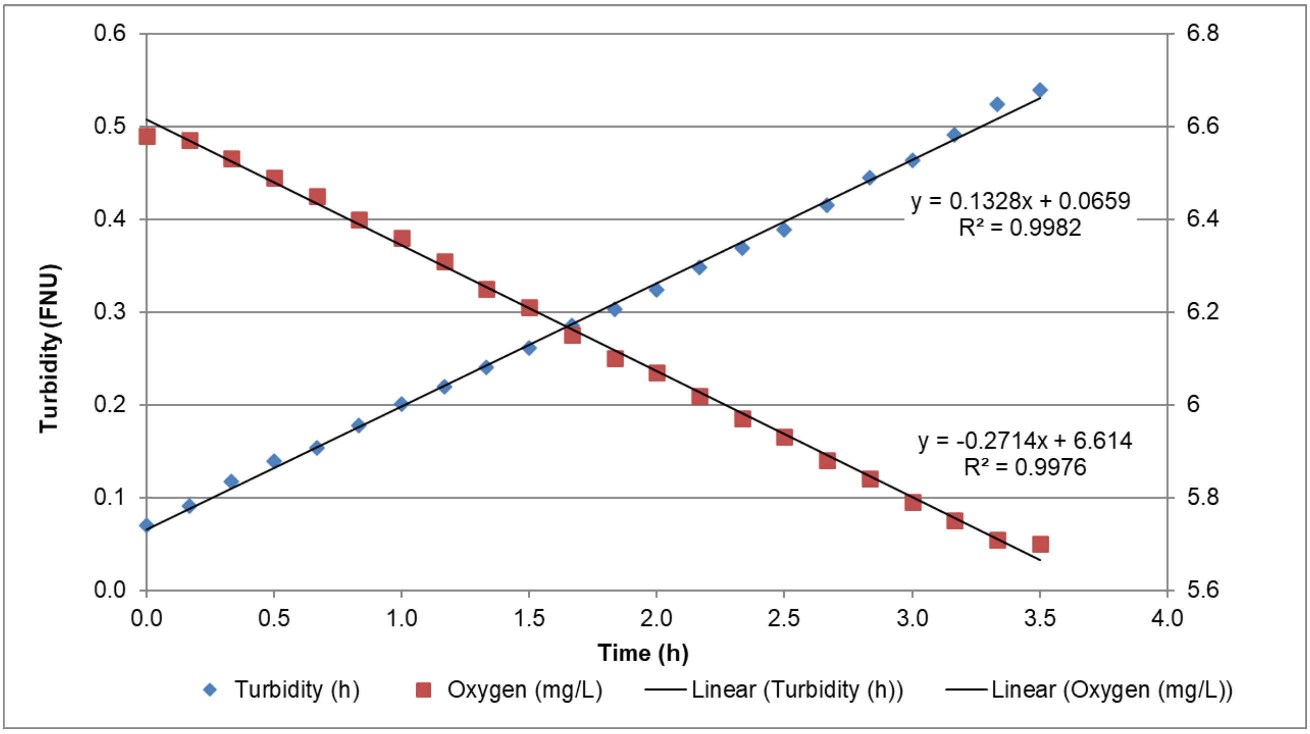

Figure 3. Time-dependent turbidity and oxygen in stagnation at day 103.

As stagnation time increased, the drinking water limit of 1.0 FNU was exceeded, as demonstrated by the last stagnation experiment carried out on day 600 (Figure 4).

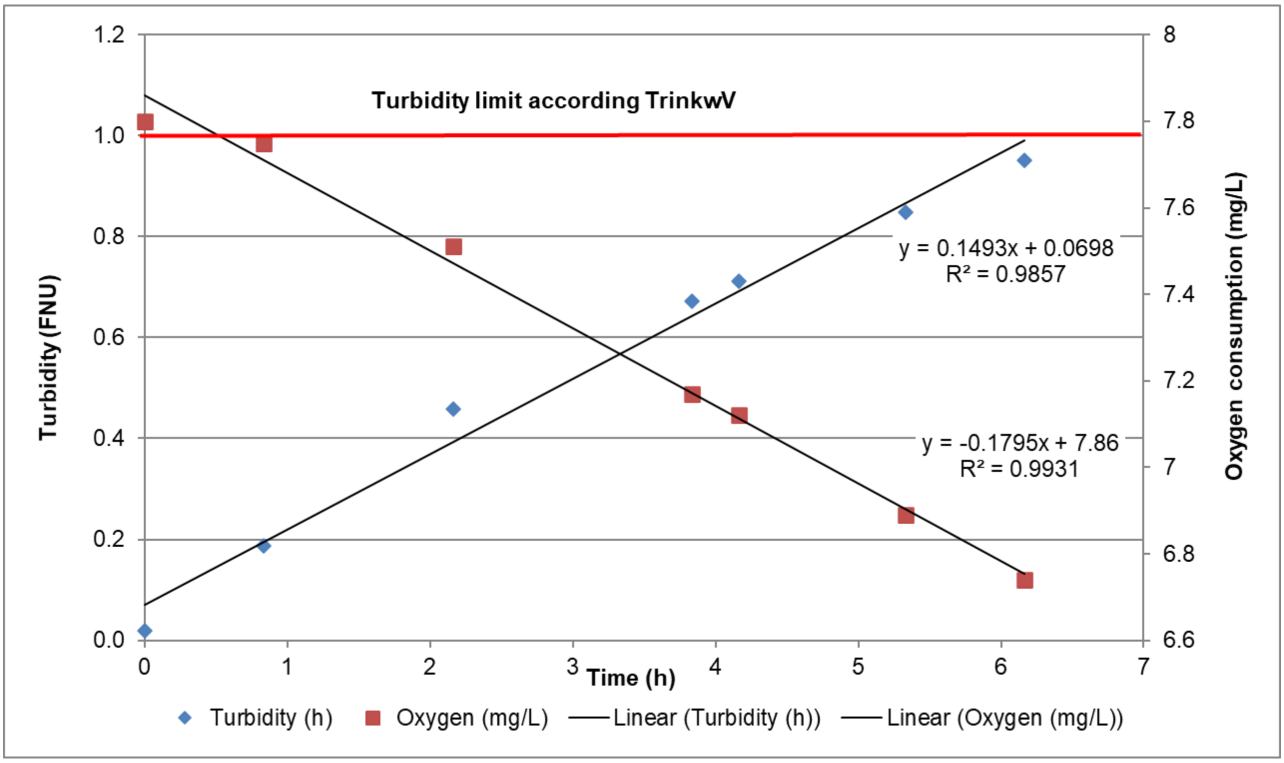

Figure 4. Time-dependent turbidity and oxygen in stagnation at day 600.

The initial conditions for the two stagnation tests on days 103 and 600 without inhibitor are listed in Table 3.

Table 3. Initial conditions of the stagnation experiments from Figures 3 and 4.

Operating days	Temperature (°C)	pH value	Electrical conductivity (µS/cm)	Oxygen (mg/L)	Turbidity (FNU)
103	16.1	7.24	760	6.58	0.070
600	13.0	7.51	717	7.80	0.018

The corrosion parameters and their corresponding errors for the two experiments are shown in Table 4. The corrosion, turbidity, and iron release rates are comparable.

Table 4. Corrosion parameters of the stagnation experiments from Figure 3 and Figure 4.

Operating days	Temperature increase (°C)	Oxygen consumption (mg/(L*h))	Corrosion rate (g/(m²*d))	Increase in turbidity (FNU/h)	Total iron in circulating water (mg/L)	Iron release rate (g/(m²*d))
103	0.4	0.27 ± 0.01	0.64 ± 0.03	0.133 ± 0.003	0.107 (3.5 h)	0.031 ± 0.003
600	1.3	0.18 ± 0.03	0.42 ± 0.06	0.16 ± 0.03	0.223 (6.2 h)	0.036 ± 0.003

[1] For the error estimation, the standard deviations were multiplied by the statistical factor 3.

A complex picture emerges when considering the oxygen consumption and turbidity measurements from all the stagnation experiments (see Figure 5). From day 102 to 175, the oxygen consumption range was 0.218 to 0.326 mg/(L*h). Then, it increased to 0.383 mg/(L*h) on day 209 and remained high at days 251 und 280. As a countermeasure, a flushing with 500 l/min was carried out on day 286, which removed the particles, but subsequently led to high oxygen consumption (data not included). Following phosphatization with 50 mg/L orthophosphate for 24 hours on day 292, oxygen consumption stabilized and decreased slowly in the absence of further intervention until the range of initial values was reached on day 454.

Initially, the turbidity rate decreased from 0.171 FNU/h (day 102) to 0.049 FNU/h at day 175 (see Figure 5). Subsequently, the turbidity rate increased concurrently with oxygen consumption. Following phosphatization, the turbidity rate showed strong variation, until reaching its maximum on day 505. Afterward, turbidity rates decreased and returned to its initial value by the end of the study.

Historic experiments carried out in 2004 with fresh low-alloy steel pipes prior to introduction of inhibition revealed a corrosion rate of approximately 2.0 g/(m²*d) iron in the non-inhibited drinking water after about 4 - 5 months of operation. The iron release rate remained practically constant during this period at approximately 0.75 g/(m²*d) iron. By using an inhibitor mixture (1 mg/L *ortho*-phosphate, 1 mg/L *poly*-phosphate and 4 mg/L silicate), the corrosion rate decreased to approximately 0.2 g/(m²*d) [18]. Compared to the historical value with an inhibitor, the corrosion rate at the end of the test period without an inhibitor is approximately twice as high but still within the same order of magnitude.

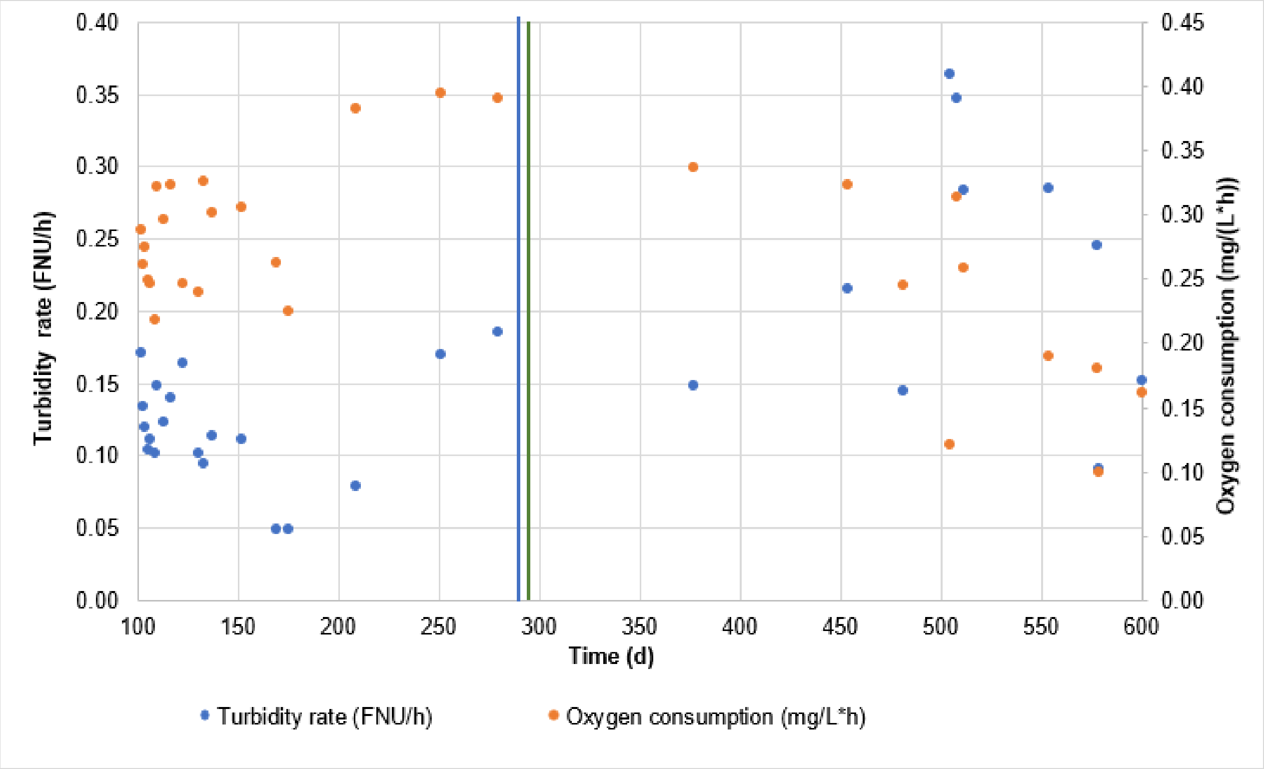

Figure 5. Development of oxygen consumption and turbidity rate during the test phase for the two connected DN 100 St pipes in inhibitor-free operation with blue line (flushing) and green line (phosphatization).

The historical iron release rate without an inhibitor was approximately 0.7 g/(m²·d) and decreased significantly after the inhibitor was added [18]. In this study, the iron release rate remained nearly constant at approximately 0.03 g/(m²·d), which is much lower than in an earlier study. This could be due to the aeration system integrated into the drinking water treatment process 15 years ago. This system reduces the carbon dioxide content and increases the pH and oxygen concentration. Thus, it reduces the iron release rate.

The evaluation of the results showed that the inhibitor could be gradually reduced, but the iron concentration had to be monitored at various points in the drinking water distribution network. Respectively, the dosage was reduced over three years and then discontinued. In retrospect, it can be stated that the decision was correct and that no corrosion problems occurred in the low-alloy steel pipes, provided that the operating conditions, in particular the flow velocity of > 0.1 m/s, were maintained.

Can further conclusions be drawn regarding the dependence of corrosion on water parameters?

As expected, a strong correlation ($R^2 = 0.8945$) was found between the concentration of iron in stagnant water and its turbidity up to 1.7 FNU (see Figure 6). This correlation is valid when sampling is made directly after the stagnation experiment and before the colloidal iron oxide hydroxide coagulates into larger particles and sediments. As demonstrated in Figure 6, the legal turbidity threshold limit of 1.0 FNU is equivalent to an iron limit of 0.200 mg/L for the water under investigation. A similar correlation with an R^2 value of 0.82 was found between apparent color and total iron [5].

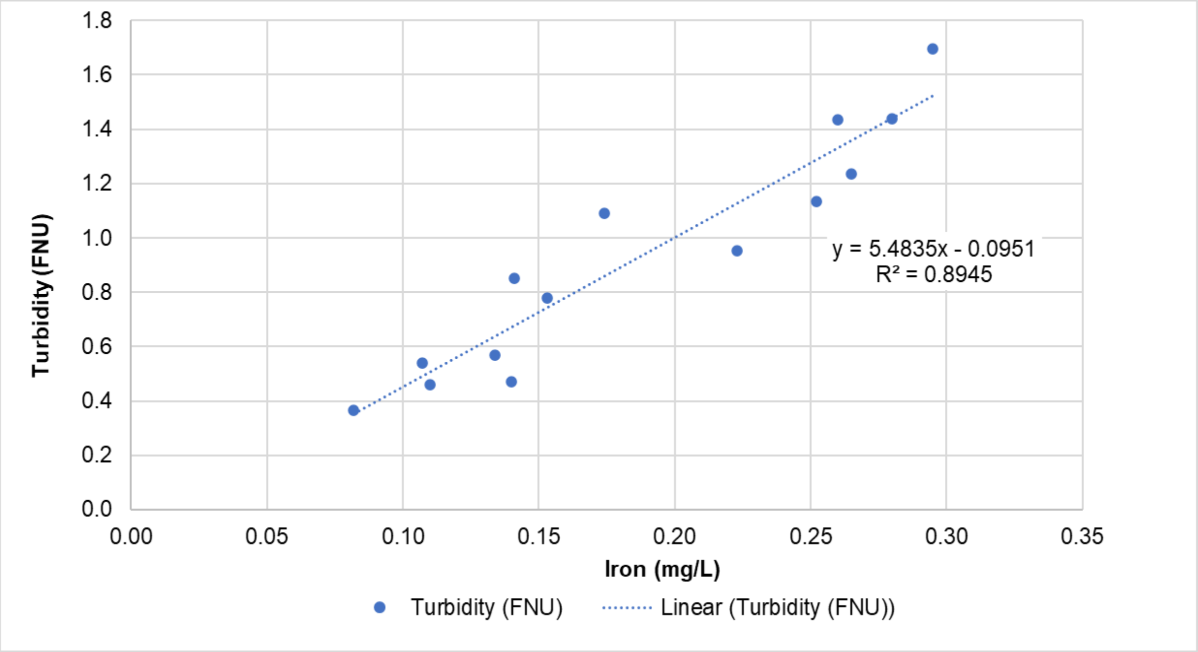

Figure 6. Dependence of turbidity from the iron concentration in closed-loop water.

However, the correlation between total iron and turbidity is not precise enough to determine iron release rates based on turbidity alone. Therefore, iron release rates were evaluated using measured iron concentrations instead.

Turbidity measurements can be performed quickly and easily, without sample preparation, to determine if water meets legal requirements. However, analyzing the iron parameter is significantly more time-consuming and requires sample preparation. Additionally, turbidity measurement can be used for online monitoring.

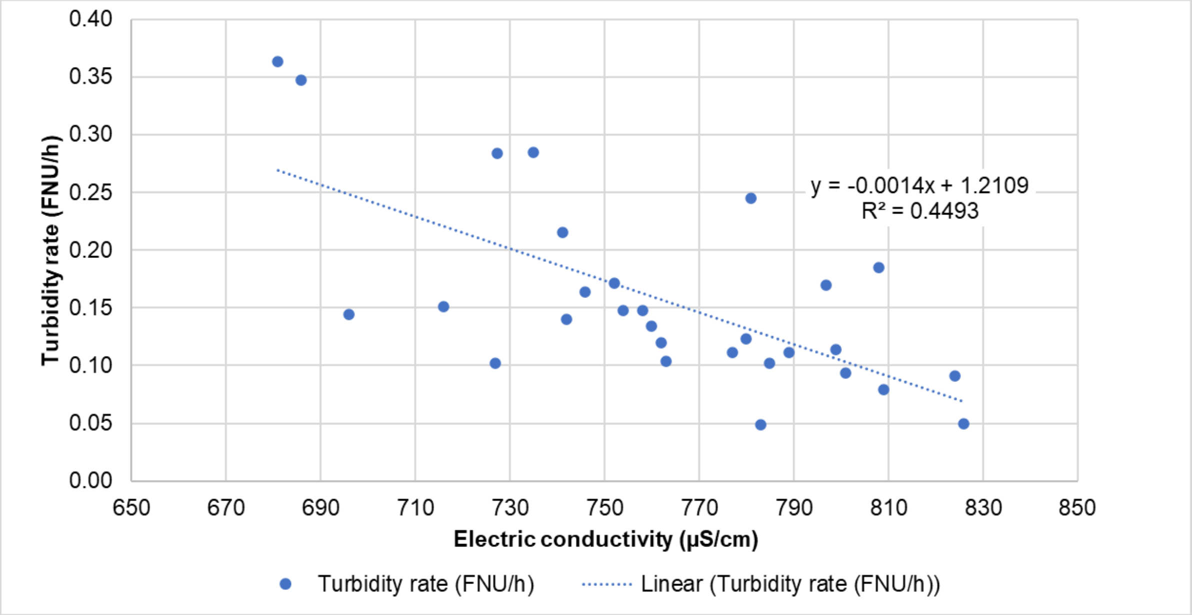

Figure 7. Dependence of the turbidity rate on the temperature increase.

Interestingly, a weak negative correlation was found between electrical conductivity and turbidity rate, with an R^2 value of 0.4493 (see Figure 7). This could be explained by the fact that calcium and bicarbonate inhibit iron corrosion more strongly than chloride and sulfate promote it (see Chapter 1.3 and [19]).

3. Summary

A study of an old, low-alloy steel pipe from the supply network demonstrated that discontinuing inhibitor dosing poses a low corrosion risk. The test pipe showed no significant increase in corrosion or iron release rates between days 102 and 600 in the absence of an inhibitor. This may possibly be attributed to less corrosive properties of the specific drinking water brought forward by installing an aeration system in the water treatment process. The evaluation of the study indicated that the inhibition should be reduced gradually, and that the iron concentration must be monitored at various points throughout the drinking water distribution network. Upon reflection, there were no significant issues with the unprotected steel pipes during implementation. However, when deciding whether to discontinue inhibitor dosing, it is important to also consider other materials such as cast iron, galvanized steel, copper, and brass alloys.

The turbidity rates showed that the limit for drinking water of 1.0 FNU is reached after approximately six hours of stagnation. Under stable conditions, the turbidity increases linearly over time. Under unfavorable conditions, such as after flushing the network, the increase may be enhanced.

The data depicted a linear correlation between iron concentration and turbidity in stagnant water. For the non-inhibited water under investigation, 1.0 FNU of turbidity corresponds to 0.200 mg/L of iron. This correlation can be used for rapid corrosion analysis or online measurement.

In the tested water, an inverse relationship was observed between corrosion rate and electrical conductivity. This could be due to calcium and bicarbonate having a stronger inhibitory effect on corrosion than chloride and sulfate.

The stagnation tests could not determine the effect of temperature on the corrosion rate. According to the literature, the corrosion rate increases by approximately 5–10% per degree Celsius [9]. Due to climate change, shorter stagnation periods are expected to lead to increased corrosion of low-alloy steel and cast iron pipes in the future. This increase can intensify corrosion and lead to the formation of red water, which causes problems for drinking water quality. Pipes that are laid at shallow depths, are located near district heating lines, or whose ground temperatures are significantly increased due to climate change are particularly at risk.

Therefore, water suppliers should consider corrosion of unprotected, low-alloy steel and cast iron pipes a danger to drinking water quality and include corrosion in their risk management plans. Countermeasures include lining pipes with materials such as cement, inlining, and replacing pipes with corrosion-resistant materials. Operating conditions are also important, especially maintaining a flow velocity of > 0.1 m/s. Meanwhile, continuous monitoring of turbidity at central nodes of the supply network is recommended.

4. Conclusion

The financial and personnel costs of the simple corrosion test described above are relatively low. However, the test provides valuable information about how the corrosion system behaves when water properties change. This information is necessary for assessing the risks associated with changes in water properties due to aeration, softening, or desalination and for initiating countermeasures.

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