Preventing the growth of iron bacteria in water wells by copper and silver coating

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ABSTRACT

The growth of iron-related bacteria and their deposition of iron oxides often impedes the operation of water wells, resulting in costly rehabilitation measures. The microbicidal potential of a silver and copper coating was investigated. Field-scale experiments on a riser pipe showed that silver coating only slightly subdued the growth of iron bacteria, while copper coating was highly effective. However, the coating was eroded and oxidized over the course of the experiment, rendering it ineffective. Model experiments with different types of copper coatings showed that only polished copper metal was able to prevent the growth of an iron bacteria biofilm for a longer period of time, while thinner coatings were overcome after some months. While the coating of screens, casings and riser pipes might thus not be sustainable, protecting parts of the submersible pump prone to iron oxide deposition by a copper coating could be an interesting option.

Key words | copper coating, iron-related bacteria, prevention, silver coating, water well

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INTRODUCTION

The growth of iron-related bacteria (IRB) and their deposition of iron oxides negatively affects the operation of many water wells, e.g. by clogging of gravel pack, screen, pump inlet and riser pipe (Houben 2003; Houben & Treskatis 2007). In Germany, of the wells plagued by incrustations, about 90% are affected by iron and manganese oxides, with the former being much more important than the latter (Houben & Treskatis 2007). The resulting rehabilitation measures are costly and time-consuming.

Several preventive measures, such as disinfection at regular intervals and radioactive irradiation, have been tried to subdue the growth of IRB in wells, but have met with limited success (Houben & Treskatis 2007; Menz 2016). The Großenkneten-Hagel well field of the water supply company Oldenburgisch-Ostfriesischer Wasserverband (OOWV), northern Germany (Figure 1), is a typical example of wells with IRB problems. They need to be rehabilitated on a regular basis to remove the incrustations, which involves high cost and downtimes. Figure 2 shows a typical

example of the reduction of the open area of a riser pipe from the well field after around six months of operation.

The microbicidal effects of native silver and copper have been known and applied in medicine for centuries (e.g. Lansdown 2002, 2006; Borkow & Gabbay 2005, 2009; Wheeldon et al. 2008; Edwards-Jones 2009; Grass et al. 2011; Armstrong et al. 2016). The mechanism is not fully understood, but probably involves multiple pathways (Feng et al. 2000; Dibrov et al. 2002; Morones-Ramirez et al. 2013; Yousuf et al. 2016): (a) interaction with sulphur present in proteins and DNA, disabling their folding and replication, (b) disruption of the metabolic uptake, (c) generation of reactive oxygen species which damage proteins, DNA, and cell membranes, and (d) chemiosmotic proton leakage through the cell membrane. The multiple mechanisms are probably also the cause of bacteria being unable to develop resistance (Morones-Ramirez et al. 2013). In water systems, silver and copper, especially in nanoparticle form, have shown some potential to remove bacteria (e.g. *Escherichia coli*), phages and viruses and thus
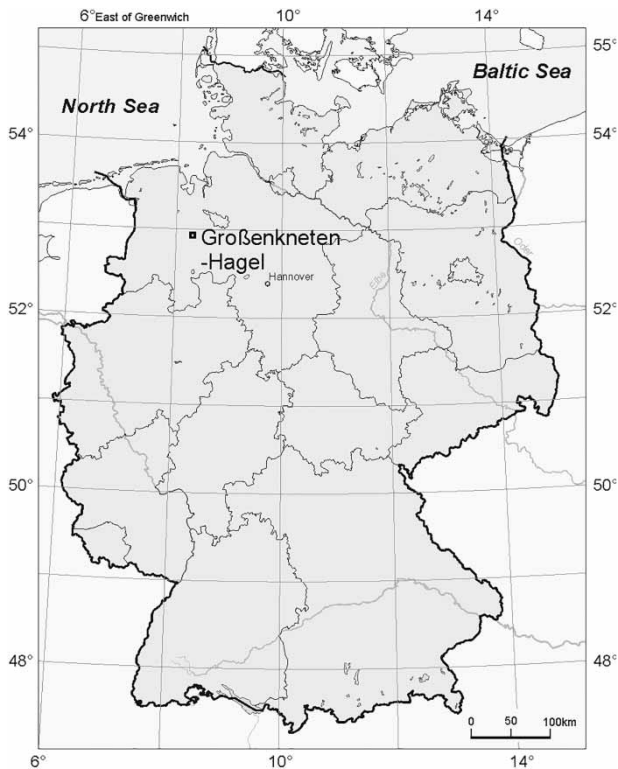
Figure 1 | Location map of Großenkneten waterworks.

to control biofilm growth and biofouling (De Gusseme et al. 2010; Nangmenyi et al. 2011; Sharan et al. 2011; Sintubin et al. 2011; Mukherji et al. 2012; Rubio et al. 2015).

Most studies mentioned so far, however, focus on the elimination of pathogenic bacteria. The effect of silver and copper on IRB, however, and especially those present in water wells, has not been studied so far. The objective of this study is to investigate the effect of silver- and copper-coated surfaces in wells on IRB and their production of iron oxides.

Investigations of their microbicidal mechanisms suggest that silver- and copper-coated surfaces release metal ions into water (e.g. Molteni et al. 2010). Since both are heavy metals, their concentration in drinking water, resulting from the application of coated surfaces, has to be taken onto account. It should be noted, however that copper is an essential micro-nutrient and the drinking water limit for it is relatively high at 1.3 mg/l, compared with silver at 0.1 mg/l (US EPA). The release, of course, means that the coated surface may become weaker with time. Effects of passivation, that is the formation of an oxidized surface layer, also have to be considered.

METHODS

Two wells of the Großenkneten-Hagel well field (Figure 1), numbers 7 and 2, were chosen for the experiment, due to their constructional and hydrochemical similarity. Both

Figure 2 | Typical examples of iron oxide deposits in a riser pipe (125 mm diameter) and on a submersible pump of the Großenkneten well field after roughly six months of operation.

wells were drilled in 1968 with a drilling diameter of 1,000 mm. A ceramic screen of 250 mm was installed and the annulus was filled with a dual gravel pack, the inner having a 6–8 mm grain size, the outer 1–2 mm. Well 7 is screened between 32 and 72 m depth, Well 2 between 32 and 60 m. The hydrochemistry of both wells is similar and has been stable over the course of recent years. The pH of Well 7 fluctuates between pH 5.6 and 6.0, with a mean at pH 5.8, while dissolved iron varies between 3 and 6 mg/l (mean at 4.5 mg/l). The pH of Well 2 varies between pH 5.2 and 6.0, with a mean at pH 5.6, while dissolved iron varies between 2 and 5 mg/l (mean at 4.0 mg/l). Iron oxide incrustations are a major problem for both wells, requiring frequent rehabilitations and repeated, often annual, cleaning of pump and riser pipes. It should be noted that the pH values considered here, although not uncommon under the predominantly sandy soils of northern Germany, are somewhat acidic. While this promotes chemical attack on the coatings, low pH is known to decrease the oxidation rates of ferrous iron (e.g. Houben 2003). Therefore, the results presented here cannot be transferred indiscriminately to other aquifers with higher pH buffering capacities.

In Well 7, the inside of a half-metre section of stainless steel riser pipe (inner diameter of 125 mm) was coated electrochemically with a 20–30 μm native silver layer by a commercial galvanization company. To promote silver adhesion to the stainless steel surface, a base layer of nickel (1 μm) was applied first. In Well 2, an identical riser pipe section was coated with native copper, with the same thickness and base layer as for the silver. In both cases, the pump and the other riser pipes were not coated. The coated pipe was, in both cases, installed directly above the pump. Before and after installation, water samples were taken to check for the liberation of silver or copper. Considering a solid, void-free metal coating layer with an average thickness of 25 μm and metal densities of 10.49 g/cm³ for silver and 8.96 g/cm³ for copper, the masses would be 51 g and 44 g, respectively. For the much thinner nickel layer (density 8.908 g/cm³), the mass would be 1.8 g.

The silver-coated riser pipe in Well 7 was installed on December 8, 2015, and extracted on September 14, 2016, after 281 days, for a first inspection. During this time, the well ran for 4,384 hours (65.0% of the total time). With a nominal pumping rate of 50 m³/h this corresponds to a pumped volume of 219,185 m³. The pump and both the coated and the uncoated riser pipes were cleaned by low-pressure water jetting and immediately re-installed. They were recovered for a second inspection on June 15, 2017, after a further 274 days and 6,576 hours (63.7%) of operation, corresponding to a pumped volume of 209.550 m³ during the second period.

The copper-coated riser pipe in Well 2 was installed on November 26, 2015, and recovered on September 19, 2016, after 298 days. During this time, the well ran for 4,467 hours (62.5%), which, at a nominal pumping rate of 50 m³/h, corresponds to a pumped volume of 223,340 m³. The pump and both the coated and the uncoated riser pipes were cleaned and immediately re-installed. They were recovered for a second inspection on June 13, 2017, after 267 days and 4,073 hours (63.6%) of operation, corresponding to a pumped volume of 203,640 m³ for this second period.

The data show that both wells are not only similar in constructional and hydrochemical characteristics, but were also operated in a similar pattern and both sampling periods had a similar duration, allowing a comparison of results.

Mineral phases were investigated using X-ray diffraction (XRD), via a PANalytical X'Pert PRO MPD Θ-Θ diffractometer (Cu-Kα radiation generated at 40 kV and 30 mA), equipped with a variable divergence slit (irradiated length 20 mm), primary and secondary soller collimators, and Scientific X'Celerator position sensitive detector (active length 0.59°). The samples were investigated from 2° to 85° 2Θ at a step size of 0.0167° 2Θ and counting times of ten seconds per step.

The chemical composition of the solids was determined by X-ray fluorescence (XRF), using a PANalytical Axios and a PW2400 spectrometer. To determine the loss on ignition (LOI), 1,000 mg of sample material were heated to 700 °C for 15 minutes and then to 1,030 °C for 20 minutes. Samples were prepared by mixing powdered samples with a flux material (lithium metaborate, Spectroflux, Flux No. 100A, Alfa Aesar). The mix was subsequently converted into glass at 1,200 °C for 20 min. The samples are analyzed by wavelength dispersive X-ray fluorescence spectrometry (WD-XRF).

The carbon and sulphur contents were measured with a LECO CS-444-Analysator. Samples of 180 mg of the

air-dried material were ground and used to measure the total carbon and sulphur content simultaneously: samples were heated to 1,800–2,000 °C in an oxygen atmosphere in order to expel carbon and sulphur as CO_2 and SO_2, which were then detected with an infrared detector. The organic carbon content (C_{org}) was determined in the same way on a subsample treated beforehand with hydrochloric acid at 80 °C, until no further gas evolution was observed, in order to dissolve the inorganic carbonate content. Inorganic carbon (C_{inorg}) was derived as the difference between total and organic carbon.

An Environmental Electron Scanning Microscope (ESEM) of the type FEI Sirion D1625 (low vacuum, 0.6 mbar) was used to investigate air-dried samples.

The analysis of the molecular biology of the biofilms was performed on samples taken in the field, immediately after recovery of the pipes. Samples were taken with sterilized equipment, kept in alcohol and refrigerated throughout transport to the laboratory. The analysis was performed by Blue Biolabs GmbH, Berlin, Germany. There, the bacterial DNA was extracted, amplified and cleaned, followed by sequencing (16S rDNA).

In order to test the performance of different copper coatings, a plastic rack was constructed as a sample holder (Figure 3). It contained two coupons of copper metal (4 cm × 4 cm) cut from material recovered from an abandoned water well of the OOWV. One coupon was polished in order to obtain a fresh surface; the other was left in its oxidized state. Additionally, four identical pieces

of PVC pipe (50 mm diameter each) were installed, cut from a casing pipe used for observation wells. The first was left uncoated as a control sample. In the second, the interior was coated manually with a commercial copper metal spray paint (50% copper in dry film, pigment purity 99.9% copper), supplied by Weicon GmbH & Co. KG, Münster, Germany. A zinc metal spray paint by Weicon was used as primer (70% zinc in dry film, pigment purity 99.9%). The third pipe had a galvanized copper coating (10–15 μm thickness), custom-made by Galvotec GmbH, Switzerland. The fourth was covered with a copper metal foil (18 ± 5 μm thickness) based on a non-conductive acrylic adhesive tape (32 ± 5 μm thickness), supplied by Conrad Electronic SE, Hirschau, Germany. Granite cobbles were attached to each side of the rack to prevent it from moving (not shown in Figure 3).

The sample holder was submerged into the inlet of the iron removal filter of the Großenkneten waterworks on June 14, 2017, and left there for seven months. There, it was exposed to a continuous flow of about 2.0 m³/h of iron-rich groundwater, similar in composition to that produced from Wells 2 and 7. Since the inlet is open, the exposure to air induced iron oxide formation. The rack was recovered for visual inspection on a monthly basis. It was not cleaned after the individual inspections to assess the long-term growth. In 2017, inspection was done on July 11, August 28, September 11, October 17, November 17 and December 19. The final inspection was done on January 29, 2018.
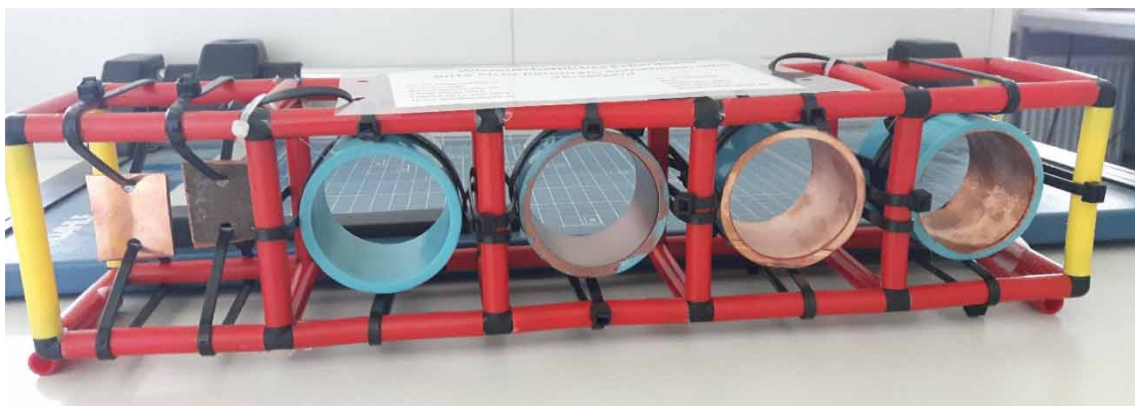

Figure 3 | Sample holder with (from left to right): polished copper metal coupon, oxidized copper metal coupon, blank PVC pipe (control), PVC pipe with copper spray coating, PVC with galvanized copper coating, PVC pipe with copper foil coating. Diameter of pipes is 50 mm (photograph: Dietrich).

RESULTS

Pump and riser pipes in both wells were recovered first in September 2016, after around nine months of operation. In Well 7 (silver coating), the coating had not prevented the growth of iron bacteria and the deposition of iron oxides (Figure 4(b), left). However, the thickness of the incrustations was between 5 and 7 mm and thus significantly smaller than in the uncoated sections, which showed thicknesses of 20–30 mm, similar to what is shown in Figure 2. In a few spots, even the original surface was visible. Higher thicknesses were observed only at the flanges, where the silver apparently did not attach well to the weld seams. The material on the silver-coated surface was significantly denser and less easy to remove than the material from the uncoated sections.

After cleaning (Figure 4(b), right), large parts of the coating were found to be missing, shown by the white color left of the centimetre scale in Figure 4(b) (right), which indicates a steel surface. To the right of the scale, the blackish coating

Figure 4 | Riser pipe of Well 7 (silver coating): (a) initial, fresh coating, (b) first inspection after 281 days, left: iron oxide incrustations on inside, right: inside after cleaning, (c) second inspection after 274 further days, left: incrustations on inside, right: inside after cleaning (photographs: Houben, Sander).
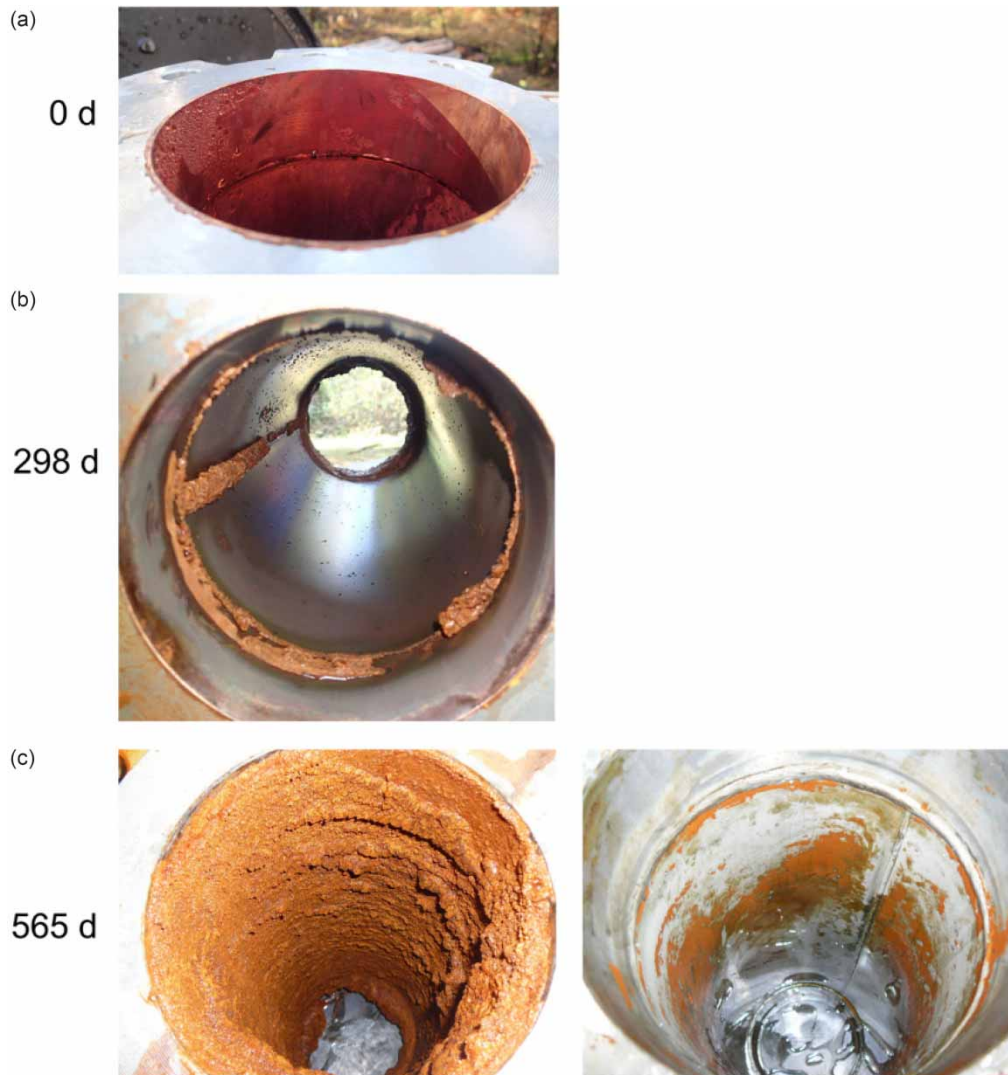
Figure 5 │ Riser pipe of Well 2 (copper coating): (a) initial, fresh coating, (b) first inspection after 298 days, (c) inspection after further 267 days: (left) before cleaning, (right) after cleaning (photographs: Houben, Sander).

indicates that the silver had become oxidized there. The second inspection after 274 more days showed no discernible difference in the amount of incrustations between the uncoated and the silver-coated riser pipe (Figure 4(c), left). After cleaning (Figure 4(c), right), it became evident that most of the silver coating had gone, either by mechanical erosion or chemical consumption. Only small patchy blackish remnants of the silver and its nickel base layer were still visible. This explains the inefficiency of subduing the iron bacteria.

In Well 2 (copper coating), after 298 days, the inner pipe surface was basically free of iron oxides. The copper coating had effectively suppressed the growth of iron bacteria and the formation of iron oxides. Incrustations were only found at the welding seams of the flanges and the pipe, where the copper apparently did not attach well (Figure 5(b)). The different surface texture or chemical composition of the seams apparently prevented the good adhesion of the copper. The copper coating showed some effects of oxidation after 298 days, as the initial metallic luster had diminished (compare Figure 5 to 5(b)).

The promising result found during the first inspection, however, could not be repeated in the second (Figure 5(c), left). The copper-coated pipe now showed a continuous

iron oxide precipitate, almost of the same thickness as in the uncoated sections. The reason for the diminished efficiency of the copper coating became clear after cleaning (Figure 5(c), right). Chemical consumption and mechanical erosion had removed most of the coating and only patches of a greenish taint, probably oxidized copper or nickel, remained (the orange patches in Figure 5(c), right, are iron oxides).

Dividing the total masses of silver and copper of 51 g and 44 g, respectively, contained in the coating by the total pumped volume during both phases gives a rough estimate of the concentrations of both metals that could be expected in water. This assumes, however, a full dissolution, while in reality parts of both metals remained on the surface as insoluble silver and copper oxide (Figures 4(c) and 5(c)) and some may have been abraded as suspended particles. The calculated concentrations are 0.12 μg/l for silver and 0.10 μg/l for copper, respectively, far below the drinking water limits. Concentrations for nickel are negligible (<0.01 μg/l). The actual water samples taken during the experiments never showed any concentrations above the detection levels for all metals. This shows that the coatings do not pose a health risk.

Microbiological aspects

Under the electron microscope, the iron oxide precipitate sample from the uncoated riser pipe of Well 7 shows a variety of shapes (Figure 6(a)), from dominant very small

(<1 μm) cell-shaped aggregates to some interspersed twisted stalks of the iron-oxidizing bacterium *Gallionella ferruginea*. The genetic analysis shows a very diverse composition, consisting of various species with different metabolisms, iron oxidation (*Sideroxydans*, *Geothrix*), sulphur oxidation (*Sulfuricurvum*), methane (*Methylobacter*) but also raptor bacteria such as *Bacteriovorax*, indicating an active and complex biofilm. The iron oxidizer *Sideroxydans* is the predominant species (52.6%).

The sample from the silver-coated pipe of the same well is dominated by bundles of *Gallionella* stalks of 40–100 μm length under the electron microscope (Figure 6(b)). Other shapes are less abundant. The genetic analysis shows a composition similar to that of the uncoated riser pipe. However, the iron oxidizers are more abundant here, compared with samples from uncoated surfaces, confirming the visual observation above. *Sideroxydans* is the most abundant species (64.3%). This could indicate a competitive advantage of stalk-building IRBs over non-stalk-building bacteria. Maybe the former can use the stalks to outgrow the toxic surface, while the latter are attached directly to the toxic surface and thus are more prone to the microbicidal effect.

The genetic analysis revealed that the uncoated riser pipe from Well 2 (copper) shows a composition similar to that from the uncoated riser pipe of Well 7. Again, iron oxidizers are the dominant group, with *Sideroxydans* as the most abundant species (40.3%). The concentration of biomass on the copper-coated surface itself was too small for
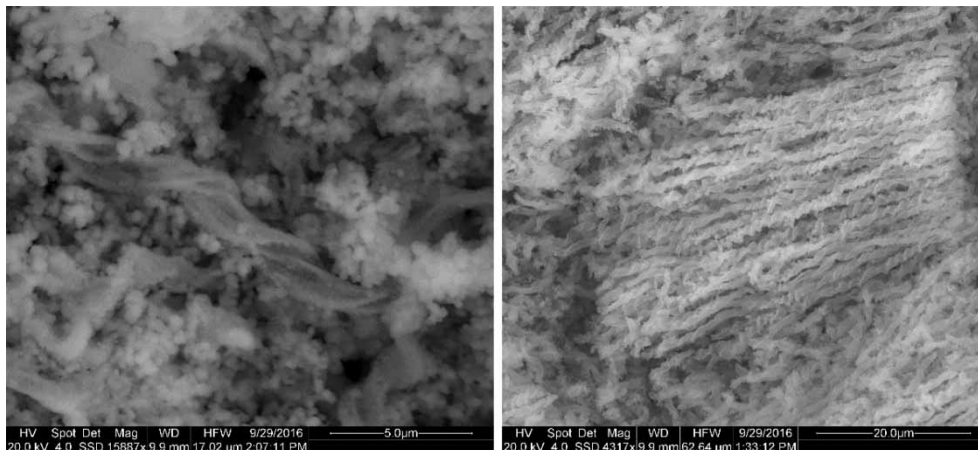

Figure 6 | Electron microscopy pictures of iron bacteria (a, left) from the uncoated and (b, right) from the silver-coated riser pipe from Well 7.

Table 1 │ Selected results of geochemical analysis (SSA = specific surface area)

		Fe_2O_3	P_2O_5	SiO_2	[wt.-%] CaO	C_{inorg}	C_{org}	Sulphur	[m²/g] SSA
	uncoated	60.96	2.49	4.15	0.049	0.59	2.54	0.31	250
Well 7	pump	60.60	2.55	4.23	0.043	0.85	2.40	0.25	242
	Ag coated	61.41	2.53	4.00	0.045	0.88	2.24	0.28	266
Well 2	uncoated	59.40	2.29	3.02	0.063				228
	Cu coated	59.62	2.27	3.15	0.061				290

Samples from Well 7 were taken after first inspection, from Well 2 after second.

analysis after the first inspection. Instead, a sample was obtained from the incrusted weld seams of the copper-coated pipe (Figure 5(b)). This sample is much more homogeneous than the previous samples. *Sideroxydans* is clearly dominant with 79.8%. This could indicate a younger, still developing biofilm, however, all samples had the same time for growth. More likely is that the (incomplete) copper coating imposed a higher selection pressure, which favored iron oxidizing bacteria.

Mineralogical and geochemical analysis of incrustation material

Solid samples were taken from the incrustation on the pump, the uncoated and the silver-coated riser pipe of Well 7 during the first inspection. For Well 2, samples from the uncoated and coated riser pipe were taken during the second inspection. In all cases, ferrihydrite, a low-crystallinity iron oxide, was the predominant mineral phase, which is very common in well incrustations (Houben 2003). As Table 1 shows, the geochemical results also indicate a rather homogeneous composition of all samples.

Physical model experiments

The performance of different types of copper coatings was investigated by qualitatively assessing the degree of iron oxide build-up on a monthly scale over a period of seven months (Table 2, Figure 7). A quantitative approach was not feasible for two reasons: (1) due to the geometry of the inlet, flow through the sample holder was uneven, and the central part was exposed to more flow than the left and right, (2) due to the soft character of the material, parts of it sometimes became detached by flowing water or during inspection. As expected, the control sample (uncoated PVC) showed strong iron oxide build-up immediately after exposure. The spray-coated PVC pipe was also quickly overwhelmed. The galvanized and the foil-coated samples withstood for some time but were finally overcome. The oxidized copper metal coupon showed a slow but steady increase of deposition. The polished copper coupon showed the best performance and remained almost free of deposits for several months, although it did show increasing surface oxidation. At the end of the experiment, the sample holder was recovered and carefully cleaned from iron oxide

Table 2 │ Performance of copper coatings in model experiment, expressed as qualitative amount of iron oxide deposited (ranking order: free, almost free, partially, strong)

| Time [date]	Copper polished	Copper oxidized	PVC blank	PVC spray-coated	PVC galvanized	PVC foil-coated
July 17	free	free	strong	strong	partially	almost free
Aug 17	free	partially	strong	strong	strong	partially
Sept 17	free	partially	strong	strong	partially	partially
Oct 17	almost free	partially	strong	strong	partially	partially
Nov 17	almost free	strong	strong	strong	partially	partially
Dec 17	partially	strong	strong	strong	partially	strong
Jan 18	partially	strong	strong	strong	strong	strong
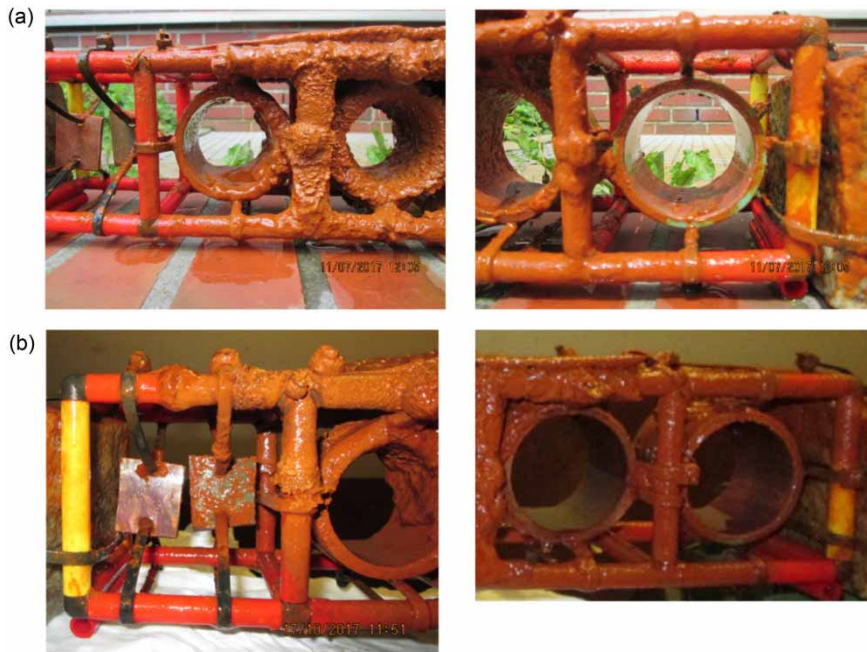
Figure 7 | Sample holder recovered (a) after one month: (left) from left to right: metal coupons (no clogging, little oxidation), PVC blank and spray-coated PVC (high degree of clogging), (right) galvanized and foil-coated PVC (partially clogged), (b) after four months: (left) metal coupons (partially clogged and oxidized), PVC blank, (right) galvanized and foil-coated PVC (clogged and coating eroded).

deposits. The polished copper coupon showed strong oxidation effects, including a green patina, resembling the initial state of the unpolished coupon. Surprisingly, the copper spray paint was still present, although strongly oxidized. In the galvanized PVC tube, only small oxidized copper patches remained, covering roughly 25% of the original surface. In the foil-coated tube, about 60% of the tape was still present, with the copper cover heavily oxidized.

DISCUSSION

Copper coating is an effective way to suppress the settlement of iron bacteria onto well material (Figure 5). As both the field and model experiments showed, the effect is limited in time to a few months to maybe a year. Thin coatings are consumed within this time-span, by chemical consumption and possibly particle erosion. The effect of coatings could probably be prolonged by applying a thicker layer. Polished copper metal showed the highest and longest-lasting potential. However, the chemical passivation of the metal surface decreases the effect over time.

Installed copper-coated well screens and casings cannot be re-coated in-situ, e.g. when the coating has been consumed. A surface passivation of solid metal parts could, at least in theory, be removed by brushing, at least on the inside or by chemical treatment. The latter is, however, critical in drinking water wells. The potential of copper coating for a well is thus limited. Instead, it could be useful and much more practical to coat important parts of the submersible pump, e.g. the motor cover and the inlet sieve. This would improve motor cooling and intake hydraulics, thereby extending pump life and expanding pump efficiency.

It remains unclear why silver is less effective than copper. Under the hydrochemical conditions prevailing in wells, less silver than copper might be released. Sintubin et al. (2011) noticed that the presence of salts and organic matter decreases the antimicrobial activity of silver. Copper, on the other hand, retains its antibacterial effect even when oxidized to CuO (e.g. Yoosefi Boosheri et al. 2015). The groundwater in the wells investigated here is quite reducing and contains dissolved sulphide, evidenced by a smell of rotten eggs. This may lead to the formation of silver sulphide, which in turn may lead to a passivation

of the surface. After cleaning, some parts of the silver-coated pipe from Well 7 indeed showed a blackish taint. Another possibility is that copper specifically interferes with IRB biochemical processes in a way that silver does not. Unfortunately, no information on this is available to our knowledge.

Indirect evidence of the efficiency of copper against IRB comes from wells equipped with copper tubing. At least in Germany, copper has a long tradition as casing and screen material for water wells (Mohr 1907). Copper wells were still being installed in significant numbers in Germany in the late 1960s and early 1970s, especially for mineral and thermal water wells but also for drinking water production. They fell into disregard later, not only because of the comparatively high material cost, but also their weaker mechanical stability, compared with steel. A particular problem was the widening of screen slots by chemical metal dissolution and the abrasive action of suspended sand. This decreased the mechanical strength and often led to sand intake. Their use is also restricted to water of circumneutral pH. In acidic groundwater, copper is prone to chemical attacks, leading to further mechanical weakening and release of elevated copper concentrations.

The OOWV operated several copper wells, drilled between 1969 and 1970, in the Großenkneten well field. After some years of operation, several of them had to be reconstructed, e.g. by insertion of a stainless steel wire-wound screen, due to mechanical failure related to the problems described above (Figure 8). Today, only a few are still running. Over the more than 45 years of operation their yield, defined as the ratio of pumping rate over steady state drawdown (Q/s), showed a decline from initial values of 17–24 m²/s to recent values of 16–18 m²/s. Compared with other iron-affected wells from the region, this decline is comparatively small (Houben & Treskatis 2007). This is even more surprising when considering the small screen diameter of 150 mm (louvered vertical slots of 0.9 mm opening width), which is problematic from a hydraulic point of view, resulting in elevated entrance and upflow velocities (Houben 2015). The dissolved copper concentrations at the same time are very small and usually below the detection limit of 0.01 mg/l, although the pH may be as low as 5.0.

In Well 29, where the casing and screen were pulled during reconstruction, the recovered pipes and the screen slots were remarkably clean (Figure 8), especially when compared with pictures from other reconstructions of old wells (Houben & Treskatis 2007). The relative indifference of the copper wells to iron oxide clogging was often attributed to favorable local hydrochemical conditions and overshadowed by their mechanical deficiencies, which even required the insertion of a wire-wound screen to prevent a collapse.

CONCLUSIONS

Copper coating shows an interesting potential to suppress the growth of iron bacteria in wells and thus the accumulation of their product, iron oxide incrustations. It can thus contribute to minimizing hydraulic well losses by preventing or diminishing the clogging of screen, casing, pump and riser pipes. This can significantly lower the energy demand of the wells. Cost savings are also attained by less frequent well rehabilitations and pipe cleanings. This has the

Figure 8 | Pictures of recovered copper screen (150 mm diameter, with stainless steel wire-wound screen insert) and casing from Well 29, Wildeshausen (photographs: Sander).

additional benefit of a more continuous operation. However, the effect is limited in time, and copper coatings, at least of the thickness studied here, are apparently consumed within a year or less by copper release and abrasion. While coatings on screens and casings might therefore not be a long-term solution, the inlet sieves and motor covers of submersible pumps could be an interesting target to increase the maintenance interval. They are relatively small and can be replaced or re-coated when needed, e.g. during regular pump maintenance. Many wells contain non-metallic components, e.g. plastic screens and tubing, usually made of PVC or PE, sometimes of ceramic material. Modern techniques allow coating or incorporation of copper also for such materials (e.g. Yoosefi Boosheri et al. 2015; Mohammed Saffiullah et al. 2016), so there is some potential for also equipping non-metallic well components with an, at least temporary, anti-IRB capacity. Even a coated gravel pack would be possible.

It should be noted that copper is prone to chemical attack when exposed to water of low pH. Copper coatings should not be used in such aggressive conditions, because of a potential weakening of the material, potentially resulting in mechanical failure, and release of excessive concentrations of copper to the pumped water. Wells with sand intake will also quickly destroy coatings by mechanical erosion.

Silver shows a much weaker performance against IRB than copper, probably due to quicker chemical passivation and erosion. The mechanisms of the interaction between IRB and copper and silver, respectively, are so far unknown and require the attention of microbiologists.

The release of silver, copper and nickel into the pumped water is of minor concern, at least under the conditions studied here, considering the slow release and the high drinking water limits.

Whether copper or silver will also be able to subdue manganese-related bacteria needs to be shown. They are, however, much less common in wells than IRB (Houben 2003; Houben & Treskatis 2007).

ACKNOWLEDGEMENT

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