**Preferential Site for Scaling on Carbon Steel with Corrosion Products**

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Although it has been pointed out that corrosion products are the preferred scaling site, the detail research has not been conducted. In this study, the initial scaling sites on carbon steel with corrosion product were investigated and scaling mechanisms were discussed. Carbon steel sheets were immersed in a solution supersaturated condition for magnesium silicate under normal standard state. Scaling at a corroded part on carbon steel was easier to occur than that at non-corroded part on carbon steel. The corrosion product was comprised of Fe₂O₃ (Hematite), Fe₃O₄ (Magnetite), and β-FeOOH (Akaganeite). When the particles of Fe₂O₃, Fe₃O₄, and β-FeOOH were individually immersed in the solution, the formation of magnesium silicate occurs only on β-FeOOH. One of the preferred scaling sites for magnesium silicate was β-FeOOH. The physical and chemical interactions were investigated. The physical interactions were evaluated by zeta potential, and the results suggested that the repulsion occurs between them. On the other hand, the chemical interaction was evaluated by IR and Raman analyses. Only IR spectrum of β-FeOOH changed. The change was derived from absorption range of Fe–OH in β-FeOOH. The OH group in β-FeOOH may react with silanol group by the dehydration-condensation reaction.

**KEY WORDS:** scaling; fouling; silica; magnesium silicate; corrosion product.

1. Introduction

Since geothermal water is comprised of various mineral components, the mineral phases become supersaturated in the solution due to evaporation and temperature variations, and scaling occurs. Scaling on the surfaces of pipes and heat exchangers reduces the flow rate and causes thermal resistance. As a result, it significantly reduces the thermal efficiency of the entire system. Representative mineral phases deposited as scale are calcium carbonate, silica, and silicate.¹²) To develop technology to inhibit the deposition of their mineral phase, it is necessary to understand the preferential scaling sites on carbon steels. Demadis³) reported that corrosion products are scaling sites for mineral phases, but this has not been experimentally verified and has only been discussed empirically. Moreover, previous experimental studies only reported microstructural analysis showing that corrosion products were scaling sites for silica and silicate.⁴) The scale formed on a carbon steel pipe Obama Onsen, Unzen, Nagasaki Prefecture, exhibited a layered structure comprised of corrosion products, silicate, and calcium carbonate in that order, starting from the inner wall of the carbon steel. The silicate formed on the corrosion products containing magnesium, and therefore it was identified as magnesium silicate.⁴⁵) To understand the effect of corrosion products on the scaling of magnesium silicate on carbon steel, we synthesized a solution in which magnesium silicate precipitates at room temperature, immersed carbon steel with and without corrosion product in it, and evaluated the scaling characteristics of both steels. Morphological and microstructural analyses were conducted on the magnesium silicate scale. In addition, the scaling of magnesium silicate, which originated from the corrosion products, was demonstrated in the laboratory environment. Furthermore, the physical and chemical interactions between the corrosion products and magnesium silicate generated in the experimental system were evaluated to clarify the iron oxides or hydroxides in the corrosion products that became scaling sites. The corrosion products that became initial scaling sites were identified, and the initial scaling process was discussed.

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2. Experimental

2.1. Materials

2.1.1. Plate Sample
Carbon steel (SPCC) was used as the specimen. The chemical composition is shown in Table 1. The size of the specimen was 60 mm × 60 mm × 1 mm. The corroded carbon steel was prepared by immersion in a 20 mg/L sodium chloride solution at 25°C for 24 hours.

2.1.2. Powder Sample
Powder samples of Fe₂O₃ (Hematite), Fe₃O₄ (Magnetite), and β-FeOOH (Akaganeeite) were prepared for the scaling test. The commercial reagents of iron(III) oxide and Triiron tetroxide were used as Fe₂O₃ and Fe₃O₄, respectively. Test. The commercial reagents of iron(III) oxide and Triiron tetroxide (MgCl₂·6H₂O) and sodium silicate hexahydrate (Na₂SiO₃·9H₂O) were both adjusted to be 200 mg/L, which is twice the concentration of the iron(III) chloride hexahydrate (FeCl₃·6H₂O), which was synthesized from a 27.03 g/L solution of iron(III) chloride hexahydrate (FeCl₃·6H₂O), which was placed in a thermostatic bath at 40°C for 8 days. The samples before testing were stored in a sufficiently low humidity condition and were immediately removed for measurement.

2.2. Scaling Test

2.2.1. Scaling Test for Plate Samples
Plate samples were immersed in a solution formation of magnesium silicate to evaluate the scaling characteristics of the samples. The solution contained 100 mg/L magnesium chloride hexahydrate (MgCl₂·6H₂O) and 100 mg/L sodium silicate hexahydrate (Na₂SiO₃·9H₂O). The samples were immersed in the solution for 24 hours at 25°C. The scaling characteristics of the samples were evaluated by measuring the weight of the samples before and after the test.

2.2.2. Observation of Temporal Changes
Non-corroded carbon steel plates were immersed in the scaling solution, and the change in scaling over time was observed. To make corrosion and scaling more pronounced, the solution was used in which the concentrations of magnesium chloride hexahydrate (MgCl₂·6H₂O) and sodium silicate hexahydrate (Na₂SiO₃·9H₂O) were both adjusted to be 200 mg/L, which is twice the concentration of the scaling test solution for plate samples (2.2.1). An optical microscope was used to observe the boundary between the edge of the plate and the solution from the direction of the plate surface every 60 minutes. Typical observation results are shown for the case where no corrosion occurred and the case where corrosion occurred.

2.2.3. Scaling Test for Powder Samples
Each 30 mg/L powder sample was placed in a scaling solution containing magnesium chloride hexahydrate (MgCl₂·6H₂O) and sodium silicate hexahydrate (Na₂SiO₃·9H₂O) at a concentration of 100 mg/L each and stirred. The experimental conditions were the same as in the scaling test for plate samples (2.2.1), and each sample was immersed in the scaling solution for 24 hours at 25°C. For the scaling test of β-FeOOH, pH buffering was performed using a boric acid buffer solution because a decrease in pH inhibits the precipitation of magnesium silicate. The boric acid buffer solution was adjusted to 74.2 mg/L boric acid (H₃BO₃) and 76.3 mg/L sodium tetraborate decahydrate (Na₃B₄O₇·10H₂O), respectively.

2.3. Microstructural Analysis
SEM/EDS was used to observe the microstructures of the scaling areas. In the observation of the plate samples, the samples were marked with a punch, and the same area was observed before and after the test.

XRD was used to identify the corrosion products and to evaluate the presence of phase transformation before and after the scaling test. A Cu source was used as the X-ray source, a high-speed one-dimensional semiconductor detector was used as the detector with a kβ filter inserted, and the PHA method with a wave-height analyzer was used to monochromatize the X-rays to reduce the influence of fluorescent X-rays from Fe elements. The tube voltage and current were set to 40 kV and 15 mA, respectively, and the scan speed and step width were set to 4.0 deg/min and 0.02 deg, respectively. The divergence slit was set to 0.625 deg, the light-receiving slit to 8.0 mm, and the scattering slit to Open.

Fourier transform infrared spectroscopy (FT-IR) and Raman spectroscopy were used for molecular bonding analysis. IR spectra were acquired using the ATR method and were measured at a wavenumber of 400–4000 cm⁻¹, a resolution of 2 cm⁻¹, and an integration frequency of 40 times. A DLATGS detector with a temperature control mechanism was used as the detector. Raman spectra were recorded in the wavenumber range of 50–1800 cm⁻¹ with a resolution of about 3 cm⁻¹ using a green laser of 532 nm excitation wavelength at an output power of 1 mW, an exposure time of 40 s, and three integration times. The sample was diluted 20 times with KBr, and the laser beam was irradiated and detected with a spot diameter of about 1 μm using a 100× objective lens.

2.4. Zeta Potential Measurement
To investigate the electrostatic physical interaction, the zeta potential was measured for powder samples in an aqueous solution at 25°C, pH=11. The electrophoretic mobility was measured using the laser Doppler method at five locations in a cell with an average electric field of about 16 V/cm and three times the amount of integration. The true electrophoretic mobility was calculated from the equation of Mori and Okamoto, and the zeta potential was determined from the equation of Smoluchowski.

3. Results

3.1. Weight Change by Scaling Test and Surface Photograph
Figure 1 shows the mass difference of a plate sample before and after the scaling test, and Fig. 2 shows a photograph of that. In the magnesium silicate solution, the mass of non-corroded carbon steel decreased by 0.50 g/m². In the corroded carbon steel, the mass increased by 5.28 g/m². The non-corroded carbon steel became slightly corroded, with
some corrosion products forming during the scaling test. In the corroded carbon steel, the distribution of corrosion products formed before the test did not change after the test, but some corrosion was observed.

3.2. Observation of Temporal Changes

Figure 3 shows the results of the observation of temporal changes. The white dotted line indicates the boundary between the carbon steel and the solution. In the area where no corrosion occurred, magnesium silicate did not adhere even after 600 minutes (Fig. 3(a)). On the other hand, in the area where corrosion of carbon steel occurred, corrosion products were generated by 120 minutes, and magnesium silicate covered the entire surface of the corrosion products after 240 minutes, and then the thickness of the magnesium silicate increased as it grew (Fig. 3(b)). The white color change on the surface of the carbon steel in the photo taken after 600 minutes (Fig. 3(a)) is due to the automatic expo-

![Fig. 1. Mass difference between specimens before and after the scaling test.](image1)

![Fig. 2. Photographs of SPCC and corroded one before and after scaling test. (Online version in color.)](image2)

![Fig. 3. Temporal changes of optical photographs at (a) non-corroded part and (b) corroded one on the carbon steel immersed in the test solution. (Online version in color.)](image3)
sure function of the photographic equipment, and the actual surface of the sample did not change.

3.3. Microstructural Analysis

3.3.1. Initial Microstructure before Testing

Figure 4 shows the XRD diffraction patterns of corrosion products collected from the corroded carbon steel surface before the scaling test. The corrosion products consisted of three types of corrosion products: Fe$_2$O$_3$, Fe$_3$O$_4$, and β-FeOOH. Figure 5(a) shows the SE image of the corroded carbon steel before the scaling test and the elemental mapping by EDS. The area where O is distributed shows the formation of iron corrosion products.

3.3.2. Microstructure and Distribution of Scaling Sites

Figure 5(b) shows the SE images and elemental mapping of corroded carbon steel plate samples after the scaling test. After the test, Si was distributed over the entire corrosion product. Mg was detected in the area with high Si concentration, but not in the area with low Si concentration. As a result of high magnification observation, a scale could not be seen in the low Si concentration area. Therefore, either Si was detected because the corrosion products reacted with the magnesium silicate synthesis solution, or the particles were too small to be observed by SEM. Figure 6 shows a high-magnification SEM photograph of magnesium silicate powder precipitated from a solution synthesized under the same conditions as the scaling test on plate samples, and an SEM photograph of magnesium silicate observed in the area with high Si concentration after the scaling test on plate samples. The magnesium silicate powder was in the form of a series of particles (Fig. 6(a)). Similarly, magnesium silicate was observed on the corrosion product of corroded plate carbon steel, and it was confirmed that magnesium silicate covered the corrosion product (Fig. 6(b)), where Si and Mg were detected (Fig. 6(c)).
Fig. 6. High magnified SE images of (a) magnesium silicate precipitated in the test solution and (b) magnesium silicate scale on corrosion product, and (c) the element maps in figure (b). (Online version in color.)

3.4. Microstructural Changes of Each Corrosion Products in the Scaling Solution

3.4.1. Microstructural Analysis

Figure 7 shows the SEM/EDS images of the corrosion products after the scaling test for the powder samples, in which Si was detected. In all the corrosion products, Si and O as the main components were found. Fe₂O₃ was composed mainly of Si and O, and Fe₃O₄ was composed mainly of Si, Al, and O, with a smooth surface and flat shape. β-FeOOH. The surface of β-FeOOH consisted of Mg, Si, and O. The surface was rough, like a series of particles.

3.4.2. Microstructural Changes of Each Corrosion Products

Figure 8 shows the XRD diffraction profiles of corrosion products before and after the scaling test for powder samples. There was no change in the peak position of each sample before and after the test, and no phase transformation occurred in the solution. The peak intensities of Fe₂O₃ and Fe₃O₄ did not change before and after the test, and their crystallinity did not change either. On the other hand, the peak intensity of β-FeOOH after the test was higher than that before the test. When β-FeOOH was immersed in a solution of pH buffer solution only and removed, the peak intensity decreased and the crystallinity decreased, indicating that β-FeOOH was decomposed in the buffer solution.

Figure 9 shows the fingerprint region of the IR spectra of the powder samples before and after the scaling test, and Fig. 10 shows the functional group region. In the fingerprint region, the peaks at 514 and 472 cm⁻¹ in Fe₂O₃ are due to the Fe-O bond vibration.⁷ The peak at 535 cm⁻¹ in Fe₃O₄ is also an absorption peak due to Fe-O bond vibration.⁸ The peak at 840 cm⁻¹ in β-FeOOH is the bending vibration between Fe-O and H, and the peak at 640 cm⁻¹ is related to the symmetric stretching vibration or lattice vibration of Fe-O or Fe-OH.⁹ The spectra of β-FeOOH only changed before and after the test. In the fingerprint region, the peak intensities at 840 and 640 cm⁻¹ were attenuated, and a new peak at 800 cm⁻¹ appeared. A peak shift from 3 300 to 3 400 cm⁻¹ in the functional group region and decay in intensity was observed, and this band was attributed to the internal OH group.¹⁰ The Raman spectra of the peaks of β-FeOOH are shown in Fig. 11. The strong peaks at 310, 390, and 720 cm⁻¹ are characteristic of β-FeOOH, of which the 390 cm⁻¹ peak is composed of two peaks at 390 and 430 cm⁻¹, and the 720 cm⁻¹ peak is composed of two shoulder peaks at 720 and 680 cm⁻¹.¹¹ Except for the IR active part, the peak decay was observed at 539 and 392 cm⁻¹. The low wavenumber region is related to the Fe-O stretching and Fe-OH bending vibrations, which is similar to the results of IR measurements. In agreement with the IR activity, the decay of the peaks at 680 and 840 cm⁻¹ and a new peak at 800 cm⁻¹ were also observed in the Raman spectrum.

3.4.3. Zeta Potential of Corrosion Products

Table 2 shows the zeta potential of corrosion products and magnesium silicate at pH=11. The zeta potentials of Fe₂O₃, Fe₃O₄ and β-FeOOH, which were identified as corrosion products, were -42.2, -33.9, and -35.2 mV, respectively, with negative charges. The zeta potential of magnesium silicate precipitated by acceleration with increasing concentration while maintaining the Mg/Si ratio in this experiment was -7.0 mV, and magnesium silicate also showed a negative charge.

4. Discussion

4.1. Scaling Site of Magnesium Silicate

Empirically, it has been considered that scales are easily
formed on corrosion products.\textsuperscript{3)} The weight of corroded carbon steel increased after the scaling test (Fig. 1), and scaling was observed on the corrosion products (Fig. 5). On the other hand, the non-corroded specimens showed only a small amount of corrosion and a decrease in weight. It is thought that the weight loss due to corrosion was more dominant than the weight gain due to corrosion product formation or scale formation. Therefore, the weight gain on

Fig. 7. SE images and element maps of (a) Fe$_2$O$_3$, (b) Fe$_3$O$_4$ and (c) $\beta$-FeOOH after the scaling test. (Online version in color.)
the corroded carbon steel is considered to be due to scaling. From the observation of the temporal change of the carbon steel immersed in the scaling solution, it was observed that the scale did not scale on the part of the base material, but preferentially scaled and grew on the part where corrosion occurred (Fig. 3). In this study, it was experimentally demonstrated that the scaling on the corrosion products was easy.

There are various types of corrosion products, which can be mainly classified into iron oxide and iron oxyhydroxide. In this study, corroded carbon steel plates were prepared, and the corrosion products on the sample included Fe₂O₃ and Fe₃O₄ as iron oxide and β-FeOOH as iron oxyhydroxide (Fig. 4). Any of these corrosion products may be involved in the scaling. The scaling tests performed on Fe₂O₃, Fe₃O₄ and β-FeOOH powders showed the presence of Si in all of them (Fig. 7). On Fe₂O₃, the silica was composed of flattened Si and O (Fig. 7(a)). The form of the scaled material
showed Si and Al contamination. The silicate observed in that study was susceptible to moisture in the air. It is thought Fe$_3$O$_4$ in the reagent used. In the scaling test on the powdered powder samples of Fe$_2$O$_3$ and Fe$_3$O$_4$ before the scaling test purity of the standard sample used. EDS images of standard aluminosilicate is considered to be an impurity due to the solution adjusted in this experiment. Therefore, the observed observed on Fe$_2$O$_3$ is considered to be an impurity contained change before and after the scaling test, and it did not react with the solution, aluminum silicate does not precipitate because the solubility of aluminosilicate in the standard state is 10 mg/L, which is not exceeded in the scaling tate because the solubility of aluminosilicate in the standard experimental system, precipitation of aluminosilicate could not occur. Even if the impurity aluminum dissolves and reacts with the solution, aluminum silicate does not precipitate because the solubility of aluminosilicate in the standard state is 10 mg/L, which is not exceeded in the scaling solution adjusted in this experiment. Therefore, the observed aluminosilicate is considered to be an impurity due to the purity of the standard sample used. EDS images of standard powder samples of Fe$_2$O$_3$ and Fe$_3$O$_4$ before the scaling test showed Si and Al contamination. The silicate observed in β-FeOOH contained Si, O, and Mg in the same positions and had a shape similar to a series of particles (Fig. 7(b)). However, since no aluminum was added in this experimental system, precipitation of aluminosilicate could not occur. 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It is known that β-FeOOH converts to α-Fe$_2$O$_3$ in an alkaline environment. When Fe(OH)$_3$ transforms to α-Fe$_2$O$_3$ via β-FeOOH, since the transformation starts from a low crystallinity state, it is considered that β-FeOOH with high crystallinity transforms to α-Fe$_2$O$_3$ after the crystallinity decreases. It was confirmed that the β-FeOOH used in this study was susceptible to moisture in the air. It is thought that β-FeOOH continued to absorb moisture in the air and transform to α-Fe$_2$O$_3$ during XRD analysis, resulting in a decrease in crystallinity. On the other hand, the transformation of β-FeOOH after the scaling test was suppressed and stabilized by immersion in the silicate solution. The results suggest that the crystallinity of β-FeOOH after the scaling test is higher than the original β-FeOOH. After the scaling test of the corroded carbon steel plate, Si elements were detected on the corrosion products (Fig. 5(b)). However, no silica particles were observed. Since the solubility of amorphous silica is 115 mg/L under standard conditions, no silica particles were precipitated under the test conditions. Therefore, it can be said that β-FeOOH did not react with silica particles but with Si ions in the solution. The IR spectra of β-FeOOH changed before and after the scaling test (Figs. 9 and 10). This result also suggests that the ions in the scaling solution reacted with β-FeOOH. Kwon et al. pointed out that the inhibition of the transformation of β-FeOOH by the presence of silicate ions is due to the adsorption of silicate ions from the solution on the surface of β-FeOOH. The results of this study are in agreement with these results, and the Si detected in Fig. 5(b) is considered to be the result of the reaction of silicate ions with β-FeOOH.

In summary, β-FeOOH in the corrosion products was the scaling site for magnesium silicate, while Fe$_2$O$_3$ and Fe$_3$O$_4$ were not.

### 4.2. Magnesium Silicate Scaling Mechanism on Corrosion Products

There are two possible mechanisms of scale formation in this experimental system: one is the physical interaction between the magnesium silicate particles precipitated in the solution and the iron oxides, and the other is the chemical reaction of the silicate in the dissolved state with the iron oxides, causing the magnesium silicate to precipitate on the iron oxides. The physical interaction is physical adsorption. Physical adsorption is also caused by stagnation due to the effect of gravity, etc. However, in this study, stirring is performed, so the effect of gravity is ignored, and only the electrical adsorption is discussed. Normally, electrical adsorption is expressed by DLVO theory, but according to Ohsako et al., dispersion and condensation of particle systems can be explained by the concept of electrostatic interaction by zeta potential, such as attraction if the sign of the charge of zeta potential is different, and repulsion if it is the same. All the iron oxides had a negative potential, and magnesium silicate also had a negative potential (Table 2). This indicates that iron oxides and magnesium silicate have repulsion. For the same sign, the larger the potential difference, the stronger the repulsion. Therefore, physically, Fe$_2$O$_3$, β-FeOOH, and Fe$_3$O$_4$, in this order, are not easily accessible to magnesium silicate particles. In the experimental results, β-FeOOH was the easiest to scale, and the electrostatic interaction was not involved in the difficulty of scaling.

The chemical interactions include phase transformation of materials in solution and reaction between functional groups of corrosion products and scale materials. Fe$_2$O$_3$ and Fe$_3$O$_4$ did not change in both crystalline phase and molecular bonding and did not undergo chemical interactions (Figs. 8 and 9). On the other hand, β-FeOOH showed changes in the absorption peaks related to the Fe–OH bond and the large

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**Table 2. ZETA potential of Fe$_2$O$_3$, Fe$_3$O$_4$, β-FeOOH and magnesium silicate at pH=11.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Zeta potential (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_2$O$_3$</td>
<td>−42.2</td>
</tr>
<tr>
<td>Fe$_3$O$_4$</td>
<td>−33.9</td>
</tr>
<tr>
<td>β-FeOOH</td>
<td>−35.2</td>
</tr>
<tr>
<td>Magnesium silicate</td>
<td>−7.0</td>
</tr>
</tbody>
</table>
peak after 3 300 cm\(^{-1}\) in the functional group region (Fig. 10). In particular, the Fe–OH bond showed clear changes in both IR and Raman spectroscopies (Figs. 9 and 11), indicating that a chemical reaction occurred at the Fe–OH bond of \(\beta\)-FeOOH. As mentioned earlier, the observation after the scaling test suggested that the \(\beta\)-FeOOH reacted with silicate ions in the solution. The IR spectra of \(\beta\)-FeOOH were normalized to compare the functional group regions, as shown in Fig. 12. The decay of the peak after the scaling test indicated a decrease in the amount of OH groups. Therefore, it is considered that the hydroxyl group of the silicate ion reacted with the OH group of Fe–OH on the surface of \(\beta\)-FeOOH by dehydration condensation.

In the scaling test on the corroded carbon steel plates, only Si elements were detected on the entire corrosion product, and magnesium silicate was only partially formed. On the other hand, in the accelerated aging test, the magnesium silicate scaling progressed to cover the entire corrosion product. Based on the above results, the initial scaling process on carbon steel in this study can be summarized as follows.

(1) Corrosion occurs on carbon steel, and corrosion products including \(\beta\)-FeOOH are formed.

(2) \(\beta\)-FeOOH and silicate ion undergo dehydration-condensation reaction.

(3) Magnesium silicate grows to cover the corrosion product, using the reacted part as a nucleus.

The reaction of silicate ions with \(\beta\)-FeOOH resulted in the formation of magnesium silicate. It was suggested that the scaling could be slowed down by controlling the corrosion products.

5. Conclusions

In this study, to understand the effect of corrosion products on scaling on carbon steel, we synthesized magnesium silicate precipitation solutions at room temperature, observed their adhesion and analyzed their microstructure, and discussed the initial scaling process on corrosion products. As a result, the following points were found.

(1) Non-corroded carbon steel and stainless steel showed similar scaling characteristics, but corroded carbon steel showed higher scaling characteristics. It is easy to form scale on the corrosion products.

(2) Among FeO\(_3\) (Hematite), FeO\(_4\) (Magnetite), \(\beta\)-FeOOH (Akaganeite), the scaling of magnesium silicate was more pronounced in \(\beta\)-FeOOH (Akaganeite).

(3) The electrostatic interactions between FeO\(_3\), FeO\(_4\), and \(\beta\)-FeOOH and magnesium silicate were evaluated, and repulsion was observed between the three species and magnesium silicate. The scaling on the corrosion products was not caused by physical interaction.

(4) Immersion of FeO\(_3\), FeO\(_4\), and \(\beta\)-FeOOH in solutions synthesizing magnesium silicate resulted in no chemical reaction in FeO\(_3\) and FeO\(_4\). In \(\beta\)-FeOOH, Fe–OH and silicate ions underwent dehydration-condensation reaction. This reacted \(\beta\)-FeOOH is considered to be the initial formation site of scaling.

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REFERENCES