Measurements of the Extension of the Magnetite Piles on Steam Generator Tubing with Eddy Current Techniques

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Abstract. Eddy current method is the main method in the nuclear power plant in-service inspections to inspect the integrity of the steam generator tubing. The method has high inspection speed and it is sensitive to both inner surface and outer surface defects. The applied inspection techniques are based on the use of bobbing probes. During operation of the pressurized water reactor magnetite deposits precipitate on the outer surfaces of the steam generator tubing. After deposits have grown thick enough, the deposits peel as flakes from the surface of the tubes. These magnetite flakes can form magnetite piles.

In this study experiments were conducted to detect the extension of the magnetite piles. For this purpose a simple mock-up simulating the horizontal steam generator tubing with parallel horizontal tubes was constructed. Piles of magnetite flakes were heaped up between the tubes. In the tests a single bobbin probe and a novel two-probe technique was used. The goal of the experiment was to study the eddy current signal on different piles of magnetite in order to map the existence and location of the magnetite piles within the steam generator tubing. The conducted experiments showed that the existence of the magnetic piles can be detected with the applied techniques. The results of the experiments are presented.

Introduction

During operation of the pressurized water reactor (PWR) deposits precipitate in the secondary circuit, inside the steam generator (SG) and in the case of the horizontal SGs, e.g. VVER-440 type reactor in Loviisa plant, the deposits precipitate on the outer surface of the SG tubing. Material of the deposits is mainly composed of magnetite. After deposits have grown thick enough, the deposits peel off as flakes from the surface of the tubes. These magnetite flakes can form piles between the tubes, on the tube supporting plates or on the bottom of the SG.

The NDE development target is to detect corrosion product, magnetite, in the secondary circuit side in SG. Corrosion products in SGs have caused serious tubing degradation in the past. Deposit induced corrosion problems still are an issue regarding nuclear safety. Deposits can be removed during outages by mechanical means such as sludge lancing or by chemical dissolution treatments. In order to determine the extent and nature of deposit formation more precise NDE techniques need to be developed. Eddy current method (ET) has been proved promising as a detection method, and needs more
development to become a quantitative and reliable tool. The deposits and magnetite piles can be detected in standard eddy current in-service inspections by using absolute technique and low inspection frequency (e.g. 25 kHz).

In this report the measurements were conducted using eddy current method with bobbin probes [1-2]. The results of absolute eddy current techniques in sizing the height and thickness of magnetite piles within the SG tube bundle are given. Several eddy current frequencies were used.

Magnetite on steam generator tubing

The iron oxide particles in the secondary water circuit form magnetite layers on the SG tubes. Material of the deposits is ferromagnetic and is mainly composed of magnetite. When deposit is thick enough, magnetite layers peel from the surfaces of the tubes as flakes. The magnetite flakes build up magnetite piles when falling on the tubes, tube support plates or on the bottom of the horizontal SG. The piles restrict free flow of secondary water and thus decrease the heat transfer of the SG tubes. Under magnetite piles the conditions are also favourable for corrosion induced defect initiation and growth.

![Figure 1. Peeled magnetite flakes from the SG tubing. The biggest flakes are about 18x10 mm. The thicknesses of the flakes are 0.2 – 0.35 mm.](image)

The thickness of the magnetite deposit on the surface of the tube has been successfully measured with eddy current techniques in laboratory scale [3, 4]. In the experiments the magnetite layer was circumferentially symmetric, i.e. extended around the tube. The thickness of the magnetite was constant at each cross-section and the thickness was changing in axial direction. The amplitude of the eddy current signal correlated well with the thickness of the magnetite deposit. However, the respective graph of the data (the amplitude versus deposit thickness) can be used as a reference graph when analysing actual inspection results, only if the magnetite layer on the outer surface of the tube is circumferentially symmetric. This was also detected in the studies of Le Lostec et.al. [5]. In their studies the amplitude of the indication of the 0.7 mm thick deposit extending the whole circumference of the tube was compared to the indication due to magnetite deposit extending only 180° of the tube circumference. The amplitude of the indication decreased 30 %, if the deposit was only half of the circumference. Due to these restrictions there is still a need to develop novel inspection techniques to detect, to size and to map the magnetite piles on the SG tubing. To enable monitoring of the growth of these magnetite deposits and piles on SG tubing during consecutive years, the data of the low frequency inspections over the years need to be compared.

Experimental methods

The presented work is conducted in the NDT-research laboratory at VTT Technical research centre of Finland. The experiments were conducted with two different eddy current techniques, either with a single bobbin probe in a tube or two similar bobbin probes
simultaneously. The two similar probes were in the adjacent parallel tubes, one probe was transmitting and another receiving the eddy current signal. Similar two probe technique was used by Arora et.al. [6] to detect wall loss and grooves on heat exchanger tubes. Later Shatat et.al. [7] have also used the same technique to inspect finned tubes.

In the measurements both absolute and differential technique was used but only the results of the absolute technique are reported. The diameters of the applied probes were 12 mm or 11.5 mm. The fill factor of the probes was 0.85 or 0.78 respectively. The eddy current equipment MS5800 and Magnify 2.0R3 software were used. The applied techniques and parameters are shown in Table 1.

A simple mock-up of the horizontal steam generator tubing was used in the experiments (Fig 2). In the mock-up the free space between the neighbouring tubes is the same than that in the VVER-440 type horizontal steam generator. The free span in horizontal direction is 14 mm and in vertical direction 8 mm. The material of the tubes in the mock-up was Ti-stabilized austenitic steel AISI 316 Ti. The outer diameter of the tubes was 16 mm and wall thickness 1.5 mm. The magnetite material i.e. the flakes used in the measurements, shown in Figures 1-2, origin from the bottom of a horizontal steam generator.

![Figure 2. a) The tubes in a mock-up simulating horizontal VVER-440 S, bobbin probes in two lowest tubes b) the lowest tubes are submerged into the magnetite pile. c) the level of magnetite pile is below the tubes.](image)

In the tests using two-probe technique the transmitting probe and receiving probe were in the adjacent tubes of the mock-up. In the measurement of test series A, the height of the magnetite pile was increased in steps:
- In the first measurement the top of the magnetite pile was below the tubes where the probes were in. The free distance between the tubes and the pile was 10 mm.
- In the second measurement the free distance between the tubes and the pile was 7 mm.
- In the third measurement the magnetite pile touched the lower surface of the tubes.
- In the fourth measurement the tubes were covered by magnetite. The upper surface of the pile was on the same level than the upper surface of the tubes.
- In the last measurement surface of the pile was on the same level than the upper surface of the tube row above. That is the case that the distance of the magnetite pile surface to the surface under the test tube is 40 mm.

In the test series B the width of the magnetite pile was increased in the horizontal direction between two tubes. The height of the pile was kept constant. Tests were also conducted using two-probe technique. The pile extended to the upper surface of the tubes throughout the test series. The width of the pile was controlled by a plastic plate. The tube with transmitting probe was in this embedded tube. The other tube was free of magnetite. Receiving probe was in the free tube. The indication due to magnetite pile was studied.
Thickness of the magnetite layer between these two tubes was changed from 1 to 14 mm (steps: 1, 1.8, 3.4, 4.1, 4.9, 5.8, 7.1, 8.6, 11 and 14 mm). One layer of magnetite flakes, thickness ca. 0.2 mm, on the surface of the tube was measured in addition to the test serie. The layer extended only one fourth of the tube circumference.

In the test series C the magnetite pile located under the unattached test tube and the pile was in contact with the tube all the time. The thickness of the magnetite pile under the tube was varied. The mock-up was not used in these tests, the tube moved upwards with the magnetite pile top level. The tests were done with the single probe technique. The thickness of magnetite layer varied from few flakes up to 40 mm as presented in Table 1.

In the test series D the tests of series A were repeated using the single probe technique. The maximum distance from the lower surface of the tube to the magnetite pile surface below was 10 mm. That is indicated as -10 mm in the results. In the previous test series all distances were measured to the lower surface of the tube.

<table>
<thead>
<tr>
<th>Test</th>
<th>Technique</th>
<th>Probe diam.</th>
<th>Freq.</th>
<th>Gain/ Trans. voltage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Two –probe technique, parallel probes in adjacent tubes, absolute technique</td>
<td>12 mm</td>
<td>12.5, 50, 100 and 200 kHz</td>
<td>60 dB 3 V</td>
<td>The height of the magnetite pile was increased in steps. The distance from the surface under the tube to the magnetite is: -10, -7, 0, 16 and 40 mm</td>
</tr>
<tr>
<td>B</td>
<td>Two-probe technique, parallel probes in adjacent tubes, absolute technique</td>
<td>12 mm</td>
<td>12.5, 50, 100 and 200 kHz</td>
<td>60 dB 3 V</td>
<td>The transmitting probe was in the tube submerged into magnetite pile, receiving probe was in the adjacent tube outside magnetite pile. The thickness of magnetite layer between the tubes was increased up to 14 mm in steps: 0.2, 1, 1.8, 3.4, 4.1, 4.9, 5.8, 7.1, 8.6, 11 and 14 mm.</td>
</tr>
<tr>
<td>C</td>
<td>Single probe technique, absolute technique</td>
<td>11.5 mm</td>
<td>10 kHz 25 kHz</td>
<td>48 dB 2 V</td>
<td>Tube with a probe is loosely on the magnetite pile. The thickness of magnetite pile under the test tube is increased with the steps: few flakes, 1, 2, 5, 6, 8, 11, 15, 20, 25, 30, 35 and 40 mm.</td>
</tr>
<tr>
<td>D</td>
<td>Single probe technique absolute technique</td>
<td>12 mm</td>
<td>12.5, 25 and 50 kHz</td>
<td>48 dB 2 V</td>
<td>Same test as in the series A, with steps: -7, -5, -3, 0, 8, 16, 24 and 40 mm</td>
</tr>
</tbody>
</table>

Results

Tests results of the measurements of two eddy current techniques are presented in the following.

Results of the two probe technique

The results of test series A are given in Figure 3. The amplitude of the eddy current indication due to the magnetic pile is given as a function of the distance between the upper
surface of magnetite pile and the lower surface of the tested tubes i.e. the two tubes which the probes were synchronously pulled through. The magnetite indication could not be distinguished from the noise when the free distance between the tubes and the top of magnetite pile was 10 mm (amplitude 0 V in the graph). When the free distance was 7 mm, the existence of the pile was detected. When the pile was touching the lower surface of the tubes i.e. the distance between the pile and the lower surface of the tubes was 0 mm, the amplitude of the pile indication was roughly half of the maximum pile indication. The amplitudes of the indications due to magnetite pile were increasing when the height of the pile was growing. The magnitude of the amplitude is depending on the applied eddy current frequency.

![Figure 3](image)

**Figure 3.** Test series A: Two–probe technique was applied. The amplitude of the magnetite pile indication versus the distance between the upper level of the pile and the lower surface of the tubes with the probes. The positive distance indicates that the surface of the magnetite pile is above the lower surface of the tube, the tube is embedded in the magnetite. Respectively the negative distance indicates the surface of the magnetite pile is below the lower surface of the tube.

The results of test series B are given in Figure 4. The amplitude of the magnetite indication is given as a function of the thickness of the magnetite layer between two adjacent tubes at the same height. The thickness of the magnetite (in the horizontal direction) was controlled by plastic plates. The trend of the curve is rising. However, the slope of the amplitude versus thickness graph is decreasing strongly when the thickness of the magnetite layer was exceeding 1 mm. The best sensitivity was again achieved, when the eddy current frequency was quite low, 12.5 or 50 kHz.

![Figure 4](image)

**Figure 4.** Test series B: The amplitude of the magnetite pile indication as a function of the thickness of the magnetite layer between the two adjacent tubes where the transmitting and receiving bobbin probes located. Two–probe technique was applied.

Tests series A and B were conducted with the two-probe technique. During the tests it was learned that if the two-probe technique is used, it is very important that the transmitter and receiver probes are located exactly parallel in the same cross-section.
perpendicular to the axis of the two tubes. Any deviation from the proper location will generate an indication which has the same phase angle as the magnetite indication. With the applied probe configuration it is not possible to tell whether the indication is due to a magnetite pile or due to the location error of the transmitter and receiver probes. The proper probe location has to be assured i.e. with intelligent push-pullers.

Results of a single probe technique

The amplitudes of the magnetite pile indications, in test series C with single-probe eddy current technique, are presented in Figure 5 as a function of magnetite pile thickness. If the eddy current frequency was 10 kHz, the amplitude of the magnetite indication was increasing up to the pile thickness of 10 mm. After that the signal saturated and the increase in the amplitude was not significant. When the 25 kHz eddy current frequency was used, the eddy current signal started to saturate when the thickness of the magnetite layer exceeded 8 mm.

![Figure 5. Tests Series C. The amplitude of the magnetite indication as a function of the thickness of magnetite pile under the test tube. Tested with a single probe. The increase in the amplitude was greater with inspection frequency of 10 kHz. The amplitude of the indications due to a 1.3 mm through-wall hole was 0.9 V (10 kHz). The diameter of the bobbin probe applied was 11.5 mm.](image)

The results for test Series D are presented in the Figure 6. The amplitude of the magnetite pile indication increases when the height of the magnetite pile grows. The test setup is similar to that of the test series A. The increase in the amplitude of the magnetite indication is similar in both tests. In test series D, the amplitude increases up to pile level of 24 mm with all applied test frequencies. The amplitude of the magnetite pile indication is not only strongly dependent on the thickness of the magnetite pile but also on the total volume of it.
Figure 6. Test series D. Test with a single-probe. The amplitude of the magnetite pile indication versus the distance between the upper level of the pile and the lower surface of the tubes where the probes are located. The positive distance indicates that the surface of the magnetite pile is above the lower surface of the tube. Respectively the negative distance indicates the upper surface of the magnetite pile is below the lower surface of the tube. Amplitude of the indication due to a 1.3 mm through-wall hole was 1.0 V (12.5 kHz).

Discussion

The results of the conducted tests show that the sensitivity in magnetite detection is greater when the lower, 10-50 kHz, inspection frequency is used. The amplitude of the magnetite indication increases when the thickness of the magnetite pile under the test tube increases up to the point of saturation.

Two-probe technique can be applied to map the extension of the magnetite piles. However the synchronisation of the movement of the two probes could cause a problem. The single probe techniques are more attractive because standard push-pullers can be applied for example in in-service inspections. In the case of single probe techniques special probes shall be applied.

To be able to detect the magnetite deposits on the outer surface of the tube, the eddy current frequency has to be low enough to be able to penetrate the tube wall. To be able to detect and to measure the existence of the magnetite piles between the tubes, the magnetic field generated by eddy current probe has to extend further into the magnetite pile. The results of this study showed that the thickness of the layer of magnetite flakes between the SG tubes can be measured with low eddy current frequencies i.e. 10, 12.5 and 25 kHz if the extension of the pile is known. If the magnetite deposit or the magnetite pile is unsymmetrically around the tube the measurement is more challenging.

Conclusion

This study is a summary of the work done for magnetite detection studies as part of the Finnish Research Programme on Nuclear Power Plant Safety SAFIR. In this work the task was to further develop and test a technique capable to size the magnetite piles within the SG tubing. The measurements were conducted in four test series using eddy current method and bobbin probes. The measurements were conducted with either a single probe technique or a novel two-probe technique. In two-probe technique two similar probes were located in the adjacent parallel tubes. One probe was transmitting and another was receiving the eddy
current signal. The tests were conducted with absolute technique and using several frequencies, between 10 and 200 kHz.

The results of two-probe technique showed that the existence of the pile was detected when the free distance between magnetite pile surface and the tube surface was 7 mm. If the distance between the pile and the surface of the tubes was 0 mm, the amplitude of the pile indication was roughly half of the maximum pile indication. The amplitudes of the indications due to magnetite pile were increasing when the height of the pile was growing. Also the amplitude of the magnetite indication increases if the thickness of the magnetite layer is growing. However, the slope of the amplitude versus thickness is decreasing strongly when the thickness of the magnetite layer was exceeding 1 mm. The magnitude of the amplitude is depending on the applied eddy current frequency. The best sensitivity in both test series with two-probe technique was achieved, when the eddy current frequency was quite low, 12.5 or 50 kHz.

The measurements with single-probe eddy current technique showed that the amplitude of the magnetite indication was increasing, when the thickness of the magnetite layer under the test tube was increasing up to 10 mm with the frequency of 10 kHz or 8 mm with the frequency of 25 kHz. After that the signal saturated and the increase in the amplitude was not significant. Also the amplitude of the magnetite pile indication increases when the height of the magnetite pile grows. The amplitude increases up to pile level of 24 mm with all applied test frequencies with a single probe technique.

The results of studied eddy current techniques showed that the extension of the magnetite pile can be mapped with both studied techniques. Thus, the single probe technique is found more reliable. Therefore the research work will continue with an improved single probe technique. The development of the single probe technique includes also modelling.

References