Locating Magnetite on the Steam Generator Tubes with Eddy Current

Tarja JÄPPINEN ¹, Kari LAHDENPERÄ ¹, Sanna ALA-KLEME ²

¹ VTT Technical Research Centre of Finland, Espoo, Finland
tarja.jappinen@vtt.fi, kari.lahdenpera@vtt.fi
² Fortum Power and Heat Oy, Loviisa Power Plant, Finland; sanna.ala-kleme@fortum.com

Abstract
The magnetite deposition on the secondary circuit of the steam generator tubing is considered a problem, because in many cases the growing defects are located at the same place as the magnetite deposits. For this reason it is more and more important to locate and size the piles of magnetite on the tubing. The steam generator tubes are generally inspected by eddy current methods. During the in-service inspection the size of the magnetite deposit is not determined, only the notification of its existence is given in the inspection report.

In this study experiments were conducted by using eddy current techniques and ordinary bobbin probes to size the thickness of magnetite piles on the test tubes. Tubes were simulating the horizontal steam generator tubes. Results of low frequency tests are shown.

Keywords: Magnetite deposit, sludge pile, eddy current, bobbin probe, steam generator tube

1 Introduction
Steam generators (SG) are a part of primary circuit of the pressurized water reactor (PWR). Walls of the steam generator tubing are a part of the pressure boundary of the primary water circuit and deterioration of SG tubing can restrict the lifetime of the VVER-reactor. The integrity of the SG tubes is important and it is imperative to have careful, regular well-planned inspections. One of the main inspection methods of steam generator tubes has been eddy current method (ET). It is a method with high inspection speed. Eddy current method is sensitive to inner surface (ID) and outer surface (OD) defects like cracks, pits, wastages and wearing.

One of the concerns in the field of steam generator tubing is magnetite deposits accumulating on the secondary side of the tube. Material of the deposits or sludge is magnetic and it is composed mainly of magnetite. In many cases the corrosion induced defects are nucleating and growing on OD surfaces of the tubes under the magnetite deposit. Although the deposits have high importance, the deposits indications detected in in-service-inspections are not analysed and reported in details. The improvement of the eddy current analysis to detect and to size the magnetite deposits on the SG tubing is important to gain the knowledge of the crack formation and growth.

In this presentation the results of deposit measurements are given. The measurements were conducted using eddy current method. The results of different ET techniques (frequencies) in sizing the thickness of deposits on the outer surface of the SG tube are given. The indication of the tube supporting plate was also studied.
2 The magnetite on SG tubing in Loviisa nuclear power plant

The nuclear power plants (NPP) in Loviisa have two VVER-440 type reactors with horizontal steam generators. The SG tubing is regularly inspected by eddy current method to monitor the condition of the SG tubing. Magnetic deposits have been detected with the applied eddy current. These deposits have been detected by using absolute method and low inspection frequency (25 kHz). Because the analysis of recorded eddy current is not automatic the more close analysis on the deposit indications is time-consuming.

The magnetite flakes from the steam generator in Loviisa are shown in the Figure 1. The iron oxide in the secondary water forms magnetite layers on the SG tubes. Thick enough magnetite layers i.e. deposits peel from the surfaces of the tubes and fall on the tube supporting plates (Fig. 2) or on the bottom of the horizontal steam generator and build up magnetite piles.

![Figure 1. Magnetite flakes.](image1)

In the Figures 2a and 2b, the areas where the magnetite depositions have been detected in the eddy current inspections, are presented. In the Figure 2 the hot side of the SG is presented. Eddy current inspections have revealed deposit formation on the tube supporting plates (Fig. 3a) and also on the free span regions between the tube supporting plates (Fig. 3b).

![Figure 2. Magnetite deposits on the hot side in the Loviisa NPP’s steam generator. a) 3D view and b) top view.](image2)
There are several reasons to be interested in the magnetite deposits on the VVER steam generators. One is the fact that the growing defects are often nucleating under the magnetite deposits. Other reported reason is inter granular attack (IGA) associated with stress corrosion cracking (SCC) from the secondary side. This corrosion process is characterized by axial cracks on the places with sludge from the secondary side. Pitting corrosion was found on the same places as IGA/SCC, but it is characterized with the higher volume of degradation and not so deep as first one. The progression rate of pitting is slower and it is easier to detect volumetric pits than cracks. In the regions of sludge there have also been indications of the thinning of the tubes [1].

![Image of depositions on TSP](image)

Figure 3. Images of the depositions on the TSP in VVER steam generator in Loviisa.

Tube support plate blockage, e.g. when magnetite deposit block the crevices between the plates and the tubes, can increase the vibration of the tubes and lead to development of cracks. TSP blockage also decreases the water rate circulation in SG [2].

3 Eddy Current Examination of the SG tubing

Eddy current inspection and monitoring is aiming to detect and characterize the degradation of the steam generator tubes. Bobbing probes have been a standard tool for ET inspection of the steam generator tubes for decades. Bobbing probes are sufficiently reliable and give repeatable results in detecting and sizing volumetric defects. The drawback of the bobbing probes is the inability to detect the circumferential cracks. The bobbin probes are sensitive to axial cracks at straight tube sections. Tube sections with more complex geometries generate large geometric indications. This reduces the probability to detect defects with bobbin probes.

3.1 Defects in horizontal steam generator

Steam generators tubes are affected by several degradation mechanisms. Considering morphology, the defect may be classified as volumetric or planar. More closely the defects could be classified as cracks and volumetric defects such as loss of material (wear and wastage) or hole-like damage (pitting) [1, 3]. This classification is important from the analytical point of view, because the most suitable method for evaluation of tube structural integrity depends on the type of the defects. The wear appears when tube support structures make contact with the vibrating tube. Wear defects are found in negligible extent in VVER steam generators [1].
3.2 Detection of magnetite and TSP blockage

Besides defects the ET inspection data of steam generator tubing includes also additional information of the SG. The data of an absolute eddy current probe has also information of tube wall thickness changes. The changes in the wall thickness change the level and the phase angle of the ET signal. The magnetite piled on the outer surface of the tube is also generating changes in the level and phase angle of the ET signal. The dot presenting the EC signal moves from the original location, if the magnetite has been depositing on the tube. By comparing the data of the low frequency inspections over the years it is possible to predict the magnetite growth on SG tubes.

Corredera et al. describe a method to assess TSP blockage of SG tubing. In this method the ET indication of the TSP with blockage is used [4]. The TSP signal is modelled and correlated with measured ET signal to assess the blockage level. The method is based on the quantitative level of blockage. It has been used to assess the condition of quatrefoil TSP:s in vertical SG’s.

Châtellier et al. describe another method to assess TSP blockage on the vertical SG. The method calculates a ratio where the blockage evaluation from eddy current signals is based on the difference in amplitude of the signal between the upper and lower sides of the tube support plate [2]. In this method it is supposed that the other side of the TSP is clean and the other is blocked. The method is based on the asymmetry of the tube support plate indication when the magnetite deposit is only on the other side of the support plate.

4 Experimental methods

The conducted experiments were aiming to illuminate the effect of the magnetite piles outside the tube surface on the eddy current signal. The experiments were conducted with two eddy current frequencies that were supposed to be optimal for the magnetite detection.

In the literature several mock-up structures used for detection of magnetite or sludge piles have been reported [5, 6]. The experiments described in this article were conducted by a simple mock-up of the horizontal steam generator. The mock-up consists of the stainless steel tubes, magnetite flakes and steel ring simulating the TSP. Steel tubes were Ti-stabilized stainless steel AISI 316 Ti, outer diameter 16 mm and wall thickness 1.5 mm. Eddy current measurements were carried out with a single 11.5 mm bobbin probe. Both absolute and differential methods were used simultaneously. The ET frequencies were 10 and 25 kHz. The fill factor of the bobbin probe was 0.78. The eddy current equipment Zetec MS5800 and Magnify 2.0R3 software were used.

<table>
<thead>
<tr>
<th>Test</th>
<th>Frequency</th>
<th>Gain</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite layer thickness detection</td>
<td>10 and 25</td>
<td>48 dB</td>
<td>the amount of magnetite under the test tube: few flakes, 1, 2, 5, 6, 8, 11, 15, 20, 25, 30, 35 and 40 mm</td>
</tr>
<tr>
<td>detection (abs. channel)</td>
<td>kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetite detection with TSP</td>
<td>10 kHz</td>
<td>48 dB</td>
<td>TSP and tube attached to the magnetite</td>
</tr>
<tr>
<td>(abs. and diff. channel)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The magnetite applied in the tests located under the tube and in contact with the tube as shown in Figure 4. The thickness of magnetite layer varied from few flakes up to 40 mm as presented in Table 1.

![Figure 4. Test tube on the magnetite layer.](image)

### 4.1 Penetration of the eddy current

For the electromagnetic plane waves the penetration depth ($\delta$) of eddy currents induced in conductive specimen is calculated using the equation 1 [7].

To be able to detect the magnetite deposit, the ET frequency has to be low enough to penetrate the tube wall. To further measure the thickness of magnetite deposits outside the tube the eddy currents has to penetrate also magnetite deposit on the outer surface of the tube.

$$\delta = \frac{1}{\pi \mu_0 \mu_r f \sigma}$$

(1)

where

- $\delta$ = penetration depth [mm]
- $\mu_0$ = magnetic permeability of free space
- $\mu_r$ = relative magnetic permeability
- $f$ = frequency
- $\sigma$ = conductivity of the material

The nominal penetration ($\delta$) depths are 4.18 mm and 2.65 mm when eddy current frequencies are 10 and 25 kHz respectively and the material is AISI 316, acid-proof stainless steel.
5 Results

The results of the conducted test are given in Figures 5 and 6. It can be seen that the sensitivity in magnetite detection is greater when the lower 10 kHz inspection frequency was used. The strip charts of the absolute channel are presented in Figure 5. The amplitude of the ET signal increases with growing thickness of the magnetite pile under the test tube. The difference in the amplitude between 15 mm and 20 mm piles is not significant.

![Figure 5. The script chart presentation of ET signals due to magnetite piles of different thickness. Up to 15 mm the vertical amplitude of the ET signal grows with the increasing thickness of magnetite pile. The applied ET frequencies were 10 kHz and 25 kHz. Magnetite pile was locating under the tube.](image)

The amplitude of the eddy current signal is presented in Figure 6 as a function of magnetite pile thickness. With the 10 kHz frequency, the amplitude grows when the thickness of the magnetite layer under the test tube was increasing up to 10 mm. After that the signal saturated and the increase in the amplitude was not significant. When the 25 kHz ET frequency was used, the ET signal started to saturate when the thickness of the magnetite layer exceeded 8 mm.

The magnetite pile under the test tube consists of loose particles. The variation in the amplitude of the eddy current signal on thicker layers was varying when the tube was manually pressed against on the magnetite pile. Due to loading, the magnetite flakes piled tighter than usual which had an effect to the amplitude of the ET signal.
Figure 6. The amplitude of ET signal as a function of the thickness of magnetite layer under the test tube. The increase in the amplitude was greater with inspection frequency 10 kHz. The amplitude of a 1.3 mm through wall hole was 0.9 V and the 10% OD groove 2.15 V.

Figure 7. Indication of the TSP and magnetite. Magnetite under the test tube and TSP a) on both sides of TSP and b) only on the other side of TSP.

A clear indication can be seen of the magnetite on the TSP on both in absolute channel and in differential channel (Figure 7.). In differential channel the amplitude of the indication due to magnetite deposit was low due to gradual increase of the EC signal. The phase angles of the indications due to the TSP and due to the magnetite deposit pile were different (Figure 8.).
5.1 Discussion

The results of the study showed that the thickness of the magnetite pile can be measured up to 10 mm if the ET test frequency is 10 kHz and if the geometry and material of the pile is known. The distance of the adjacent tubes in VVER-400 steam generator is either 8 mm or 14 mm. The next step in the studies is to measure the thickness of magnetite pile between the SG tubes.

In the applied test setup the TSP mock-up was movable and it was possible to measure the effect of magnetite blockage on ET signal. The test showed that the TSP blockage can be easily detected when the ET absolute method is applied. Differential method gives signal from the magnetite and TSP in different phase.

The results of these tests are encouraging. Development of the method to measure the thickness of the magnetite pile will be actively continued. In the next phase two probes will be applied simultaneously.

6 Conclusions

In this work the aim was to measure the actual thickness of the magnetite pile on the SG tube. The results of the tests are encouraging. It seems that the pile thickness can be measured, if the range of pile thickness is from 1 mm to 10 mm and if the geometry and material of the pile is known.

The effect of magnetite was clearly visible in strip chart presentation of ET data. However more work has be done to have more reliable measurements. This study will continue. The goal of the further studies is to have a method to measure the magnetite pile between two tubes and to see if the space between the tubes is fully deposited.

Figure 8. Magnetite on TSP, absolute and differential channels. ET frequency was 10 kHz.
References


