Development of Scale Measurement Technologies for Steam Generator Tubing

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Abstract
Steam generator (S/G) is one of the major components of nuclear power plant and consists of tube bundles which primary water heated by nuclear fuel passes through. Therefore, steam generator tubes are the pressure boundary between primary side and secondary side, which makes them critical for nuclear safety. Tube integrity should be maintained with periodic inspection with eddy current testing. As the operating time of nuclear power plant increases, not only damage mechanisms but also scaled deposits on steam generator tubes are known to be problematic causing tube support flow hole blockage and heat fouling. Recent experiences in Korean nuclear power plants revealed that these conditions can cause water level oscillation, degrading thermal performance of steam generators. The ability to assess the extent and location of scaled deposits on tubes became essential for management and maintenance of steam generator and eddy current bobbin data can be utilized to measure scaled deposit. In this paper, tube mock-up with various thickness of scaled deposit has been set up to provide information about the overall deposit condition of steam generator tubes, providing essential tool for steam generator management and maintenance to predict and prevent future damages. Also, methodology to automatically measure scale thickness on tubes has been developed and applied to field data to estimate overall scale amount.

Keywords: Scaled deposit, deposit mapping, eddy current data analysis, steam generator

1. Introduction

Over the past years, several cases of steam generator problems associated with the presence of secondary side deposits have been reported in domestic nuclear power plants especially with alloy 600 high temperature mill annealed (HTMA) and alloy 600 thermally treated (TT) tube materials. Accumulation of corrosion products from secondary side affects the efficiency of steam generators. Also, continuous deposit build-up on outer side of steam generator tubes can cause altered steam flow and flow induced vibration resulting in denting and/or tube cracking, which makes safety of nuclear power plant at risk. Therefore, it is important to measure scaled deposits of steam generator tubes and understand its distribution to take an appropriate action such as chemical cleaning at the right time to maintain steam generator’s integrity and proper performance. Steam generator is inspected periodically with eddy current testing method and eddy current bobbin coil data can be utilized to measure scaled deposits.

There was a domestic research activity for 3 dimensional visualization of steam generator tube deposit\(^[1]\) and commercial product to 3 dimensionally profile steam generator tube scale is available\(^[2]\), but these are just for visualization and do not include quantification of deposit by measuring deposit thickness.

In this paper, a method to automatically measure the thickness of scaled deposit on steam generator tubes using bobbin coil data has been developed. Based on the scaled deposit thickness information measured by the developed method, it is possible to estimate overall deposit amounts in the steam generator as well as to visualize them 3 dimensionally. This numerical and graphical information will provide a good understanding of current conditions within the steam generator and a comprehensive view of the distribution patterns of secondary side deposits in the steam generator. Plant operators can also use them to develop the appropriate maintenance plan, allowing the optimization of cleaning processes.
2. Scaled deposit mock-ups

2.1 Composition of scaled deposits

To build scaled deposit mock-ups for thickness measurement, it is necessary to understand chemical composition of actual deposits. According to chemical analysis report of steam generator secondary side sludge, more than 90% of sludge is composed of magnetite(Fe$_3$O$_4$) for all steam generators[3]. Table 1 shows basic information of chemical composition from steam generator secondary side sludge for domestic steam generators of nuclear power plants.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Magnetite composition of sludge</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>93.6%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>94.2%</td>
<td>Magnetite(Fe$_3$O$_4$)</td>
</tr>
<tr>
<td>D</td>
<td>97.7%</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>92%</td>
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</table>

2.2 Mock-up design and manufacture

Deposit thickness is measured using eddy current bobbin coil data. Eddy current inspection is non-destructive testing and it needs reference standard to compare with actual test object. As usual, eddy current inspection for steam generators is performed to detect tube defects such as wall loss or crack and reference standard tubes with various sizes of defect of interest are used. In this research, our concern is deposit thickness so it is justifiable to design standard tubes with various deposit thickness. Figure 1 shows deposit standard design and magnetite powder (Fe$_3$O$_4$) of 90% purity is used to simulate deposit[4]. Because problems associated with scaled deposit are related to steam generators with alloy 600 HTMA tubes and alloy 600 TT tubes, the deposit standards are manufactured for both tube materials with same tube diameter and thickness with actual steam generator tubes(Figure 2).

![Figure 1. Deposit standard drawing](image-url)
2.3 Eddy current data analysis of mock-up standard

Using deposit standards described above, eddy current data have been acquired with the same type of bobbin probes, same frequencies and same coil configuration used in the field inspection to observe eddy current signal response in accordance with deposit thickness change. For deposit thickness measurement, low frequency absolute channel of bobbin coil data shall be used. Because deposit thickness measurement should be applied to the history inspection data already acquired without this kind of deposit standard, the same type of calibration standard for inspection has been used with deposit standard as common reference point for comparison during data acquisition. The calibration standard used for inspection is designated by American Society of Mechanical Engineering (ASME) code [5] and is usually referred as ASME standard. 20% flat bottom hole of ASME standard is used for voltage setup to correlate signal voltage to deposit thickness and is set to 4 volts in low frequency absolute channel which is 20kHz. Signal phase is set to tube end signal goes horizontal so that deposit signal goes vertical. Table 2-a and b shows average voltage values of 3 times of acquisition for each deposit patch point of the standards. From the average values of table 2-a and b, the relationship between voltage and deposit thickness can be obtained as figure 3. Figure 4 presents an example of eddy current data acquired using deposit standard. In the long strip chart for 20kHz absolute channel, it can be easily noticed that there is a vertical peaks per each deposit patch location.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>0.75</th>
<th>1.25</th>
<th>1.38</th>
<th>3.4</th>
<th>4.3</th>
<th>5.25</th>
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<td>1</td>
<td>10.75</td>
<td>18.61</td>
<td>22.90</td>
<td>34.66</td>
<td>38.44</td>
<td>40.41</td>
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<tr>
<td>2</td>
<td>11.44</td>
<td>19.39</td>
<td>23.69</td>
<td>36.31</td>
<td>40.07</td>
<td>42.25</td>
</tr>
<tr>
<td>3</td>
<td>11.47</td>
<td>19.70</td>
<td>23.60</td>
<td>36.18</td>
<td>40.28</td>
<td>43.17</td>
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<tr>
<td>Average</td>
<td>11.22</td>
<td>19.23</td>
<td>23.40</td>
<td>35.72</td>
<td>39.60</td>
<td>41.94</td>
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Table 2-a. Voltage vs. deposit thickness: Alloy 600 TT
Table 2-b. Voltage vs. deposit thickness: Alloy 600 HTMA

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>0.52</th>
<th>1.35</th>
<th>1.50</th>
<th>3.00</th>
<th>4.50</th>
<th>5.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17.65</td>
<td>26.24</td>
<td>28.01</td>
<td>39.66</td>
<td>45.79</td>
<td>49.61</td>
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<tr>
<td>2</td>
<td>17.56</td>
<td>23.90</td>
<td>27.80</td>
<td>42.43</td>
<td>45.50</td>
<td>49.29</td>
</tr>
<tr>
<td>3</td>
<td>17.32</td>
<td>25.43</td>
<td>27.25</td>
<td>37.58</td>
<td>45.16</td>
<td>48.89</td>
</tr>
<tr>
<td>Average</td>
<td>17.51</td>
<td>25.19</td>
<td>27.69</td>
<td>39.89</td>
<td>45.48</td>
<td>47.26</td>
</tr>
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</table>

Figure 3. Voltage vs. deposit thickness curve

Figure 4. Example of eddy current signal for deposit standard
3. Automated deposit thickness measurement program

Eddy current inspection data consists of thousands of tube data per steam generator every outage and it is necessary to automate deposit thickness measurement to handle such a huge amount of data. Therefore, an automated deposit thickness measurement program has been developed in C#. Program interface is implemented as in figure 4, and algorithm to detect scaled deposit and measure its thickness is described in figure 5 as flow chart.

![Automated deposit detection and measurement algorithm](image)

3.1 Phase and voltage set-up

Eddy current data is basically similar to the set of points with (X, Y) coordinate on complex plane as shown in figure 6. Left long strip chart indicates vertical values and right long strip chart indicates horizontal values of tube data. The X-Y plane referred as “Lissajous” is similar to complex plane displaying series of horizontal and vertical values for the data in the expanded charts below lissajous. Data can be rotated 0 to 360 degrees and magnified/demagnified in certain purposes. In 20 kHz bobbin absolute channel, the signal of interest which is deposit signal is preferred to be set vertically upward close to 90° for thickness measurement purpose, which can be achieved if tube end signal is set to horizontal[6]. After setting phase, the magnitude of signal is set to 4 volts using 20% flat bottom hole in ASME
standard shown in figure 6 at the same channel. This voltage setting establishes relative signal magnitude reference in voltage, which means the signal’s vector magnitude is expressed as voltage value. The voltage values from deposit signals can be estimated as thickness based on the curves in figure 3.

Figure 6. Setting phase and voltage using ASME 20% flat bottom hole

3.2 Landmark detection

Steam generator has many tube support structures with different types, shapes and materials, and these structures should be detected and eliminated from the measurement range. Tube supports detection and labelling them as landmarks is important because it becomes the primary process to find where to look for deposit thickness measurement. From the steam generator design information, physical location of tube support structures can be obtained. Using this information, tube support landmarking can be conducted with calculating distance between supports signals in actual eddy current tube data based on probe scan speed. Analyst put typical patterns for various tube support signals such as tube ends, tubesheets, tube supports and anti-vibration bars as shown in figure 7. Scanning a tube data from one end to the other end, the program searches and recognizes support patterns, labelling each location as landmark as in figure 8.

3.3 Deposit thickness measurement

After detecting landmarks, actual deposit detection and thickness measurement can be conducted in tube freespan region which has no support structure using voltage vs. thickness measurement curve in figure 3. As signal phase has been set to deposit signal vertically
upward almost 90°, the program finds non deposit location with least vertical transition between landmarks as “null” point first. Scanning tube freespan between supports, vertical transition of eddy current signal from the null point is recognized as deposit and recorded. Figure 8 shows the actual tube data with scaled deposit and figure 9 presents partial sample of thickness measurement results for steam generator inspection data.
4. Future work

Deposit measurement technique described above has been applied to historical field inspection data and measurement results could be obtained as in figure 9. Based on these results, scaled deposit status and distribution shall be presented using 3 dimensional viewer with sectional viewing functions and deposit load estimation. Adding these features, this deposit measurement technique will provide intuitive and comprehensive information about scaled deposit status of steam generator tubes. Furthermore, by performing deposit thickness measurement for historical inspection data and comparing them by outage, it will be a very useful and valuable monitoring tool for steam generator performance.

5. Conclusion

Accumulation of corrosion products from secondary side affects the efficiency of steam generators degrading its performance. Therefore, it is important to measure scaled deposits of steam generator tubes and understand its distribution to keep steam generator’s integrity and proper performance.

In this paper, a method to automatically measure the thickness of scaled deposit on steam generator tubes using bobbin coil data has been developed. Using deposit thickness measurement results produced by the developed technique, it is possible to estimate overall deposit amounts in the steam generator as well as to visualize them 3 dimensionally which will be conducted as future work. Applying this technique, it can be utilized as a powerful
tool for steam generator asset management to provide additional insight into deposit
distribution, severity and trending.

References

5. ASME Boiler and Pressure Vessel Code, Section V, 'Nondestructive Examination'.