EDDY CURRENT SIGNAL ANALYSIS FROM NON-HOMOGENEOUS SLUDGE PILE

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Abstract

Steam generator tubes are the pressure boundary between the primary side and secondary side, which makes them critical for nuclear safety and tube integrity should be maintained with periodic inspection. Among various inspection method, eddy current testing has been applied for steam generator tubes domestically. As the operating time of nuclear power plant increases, not only damage mechanisms such as wear and stress corrosion cracking but also flaw masking signals like sludge and indications from some other inclusion in it has been becoming a challenging issue recently. These indications from other inclusion in the sludge pile tend to misguide eddy current data analysts because they look similar to volumetric indications on top of tubesheet which need to be repaired, in spite that they are not real defects. It seems to need to characterize these flaw-masking indications specifically with experiment and understand what the differences are from the real volumetric indications.

In this paper, a mock-up has been set up with various materials which could be included in steam generator sludge pile to simulate field indications. Through this experiment, it can be noted that titanium inclusion in the sludge pile behaves similar to the volumetric indications due to its electromagnetic characteristics. It is recommended that a chemical component analysis of sludge pile should be performed if volumetric indications are found in the sludge pile on top of tubesheet area to decide whether they are realistic.

1. Introduction

Steam generator tube in nuclear power plant is a pressure boundary between primary side and secondary side, whose integrity is one of the most critical factors to nuclear safety. To assure tube integrity, a periodic inspection with eddy current testing is performed in accordance with proper codes, regulations or guidelines.

Despite diligent attempts by plant operators, engineers and chemists to maintain the purity of plant feedwater and sustain carefully planned chemistry control strategies, impurities are inevitably transported to the secondary side of steam generators in pressurized water reactor (PWR) systems. This transport of impurities through feedwater, drain and condensate systems at PWR is generally slow but progressive process which will usually result in the continual accumulation of unwanted material on the secondary side of steam generators such as deposits and sludge pile on top of tubesheet[1]. As the operating time of nuclear power plant increases, these unwanted materials are accumulated with other inclusion which produces flaw-like signals confusing eddy current data analysts. Recent eddy current inspection data from nuclear power plant in Korea reveals that these flaw-like signals look alike volumetric indications which necessitate tube repair[2]. It is important to differentiate these false signals from real flaw indications so that tubes with no actual flaw would not be repaired based on incorrect information.

To compare and prove the differences between eddy current signals from non-homogeneous sludge pile and those from real volumetric indication, a mock-up has been set up with various materials which could be included in steam generator sludge pile. Experiments are performed to understand the influence of sludge pile on defects and to characterize signal patterns when non-homogeneous inclusions exist in sludge pile.

As a result, it can be noted that sludge pile itself does not mask real defect and titanium inclusion behaves similar to the volumetric indications due to its electromagnetic characteristics. If volumetric -like indications are detected in the field, it is recommended that a chemical component analysis of sludge pile shall be performed to clarify whether they are real defects.

2. Basic Eddy Current Theory

Eddy current inspection uses a coil as a test probe and observes changes of a coil impedance. Coil impedance is affected by electric conductors and proportional to the reciprocal of conductivity. As conductivity increases, the value of test coil impedance decreases. Factors which have an effect on conductivity are test material, temperature, heat treatment, size of grain, hardness and residual stress. Figure 1 shows an impedance plane display and the relationships between impedance and various test parameters such as conductivity(or resistivity), test material thickness, test frequency and fill factor(or lift off)[3, 4].

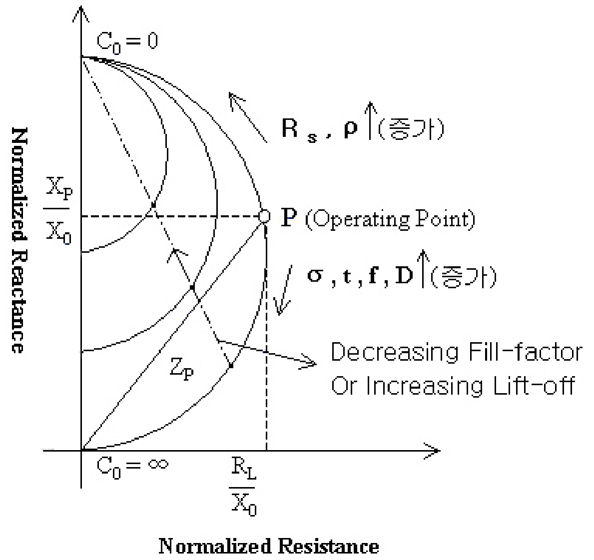

Figure 1: *Impedance plane display*

Figure 2 represents conductivity characteristic of various materials and figure 3 shows values of resistivity and conductivity of various materials. Shadowed materials in figure 3 are materials which are used as steam generator parts such as tubes and tube supports.

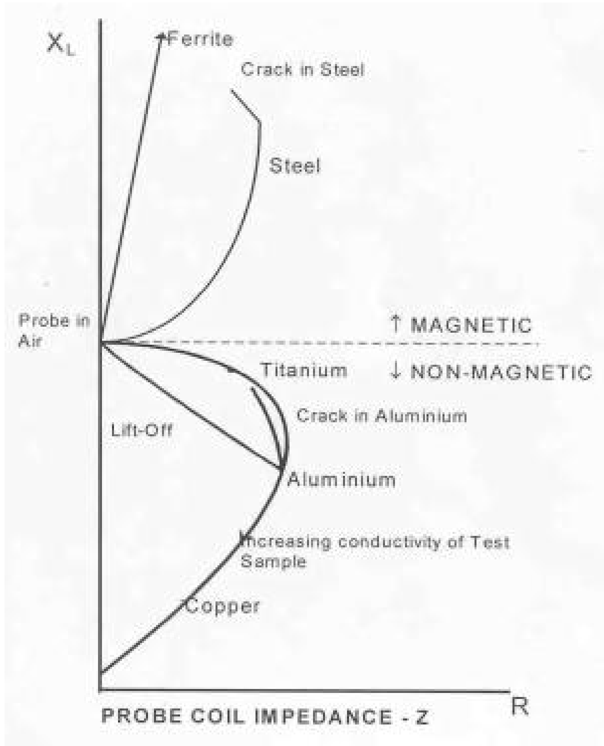

Figure 2: *Conductivity of Various Materials*

MATERIAL	RESISTIVITY MICRO-OHM-CM (μΩcm)	CONDUCTIVITY % IACS
Admiralty Brass	6.90	25.00
Aluminum (99.9)	2.65	64.94
Aluminum 6071-T6	4.10	42.00
Aluminum 7075-T-6	5.30	32.00
Aluminum 2024-T4	5.20	30.00
Aluminum Bronze	12.00	14.00
Copper	1.72	100.00
Copper Nickel 90-10	18.95	9.10
Copper Nickel 70-30	37.00	4.60
Gold	2.35	75.00
Hastelloy-C	130.00	1.30
Inconel 600	100.00	1.72
Lead	20.77	8.30
Magnesium (99%)	4.45	38.60
Monel	48.20	3.60
Sodium	4.20 @ 0°C	41.00
Stainless Steel 304	72.00	3.00
Stainless Steel 316	74.00	2.50
Titanium 99%	48.60	3.55
Tungsten	5.65	30.00
Uranium	≅30.00	5.70
Zirconium	40.00	4.30

Figure 3: *Values of Resistivity and Conductivity for Various Materials*

Inconel 600 is steam generator tube material, stainless steel 304 (SS304) is tube support material and titanium is tube material of secondary side component such as condensers and heat exchangers.

3. Detected Indication Status

Steam generator sludge pile can be removed by lancing. In case tubes are arranged in square pitch, sludge removal is easy and efficient. But in case of triangular pitch like Korean Standard Nuclear Power Plant (KSNP), lancing hardly removes sludge pile.

Table 1: Detection Status of SLG and VOL

Plant / Sludge	Model F (Kori 4)		KSNP (Ulchin 4)			
No. of Tubes	S/G A	1,180	S/G #1	1,435	VOL	43
	S/G B	763				
	S/G C	578	S/G #2	1,001	VOL	7
Avg. Height (inch)	S/G A	1.59	S/G #1	1.18		
	S/G B	1.55				
	S/G C	1.90	S/G #2	0.94		
Max Height (inch)	S/G A	4.35	S/G #1	2.99		
	S/G B	3.71				
	S/G C	4.81	S/G #2	2.03		

Table 1 shows the number of tubes that eddy current sludge signal was detected in recent inspection for Westinghouse Model F steam generator (Kori Unit 4)[5] and a KSNP steam generator (Ulchin Unit 4)[2]. Comparing square-pitched Model F steam generators with tri-pitched KSNP steam generators, Ulchin 4 has lower sludge height than Kori 4 but volumetic-like signals have been found. S/G #1 had 43 VOL indications and S/G #2 had 7. All of these signals are present in sludge zone as shown in figure 4[2].

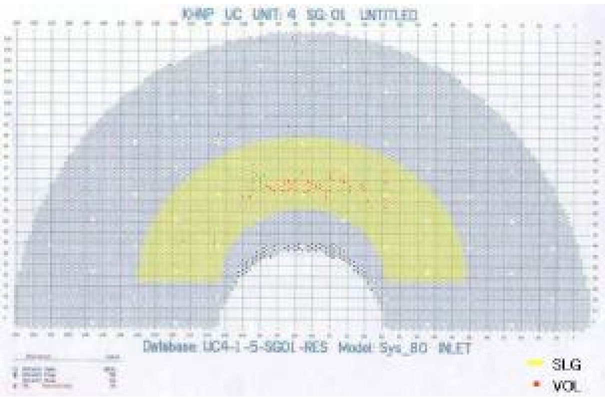

Figure 4*: SLG & VOL Detection Status*

Figure 5 and 7 represents eddy current graphics of these signals tested with +point rotating pancake coil (RPC). Figure 5 is pancake coil response and Figure 6 is +point coil response.

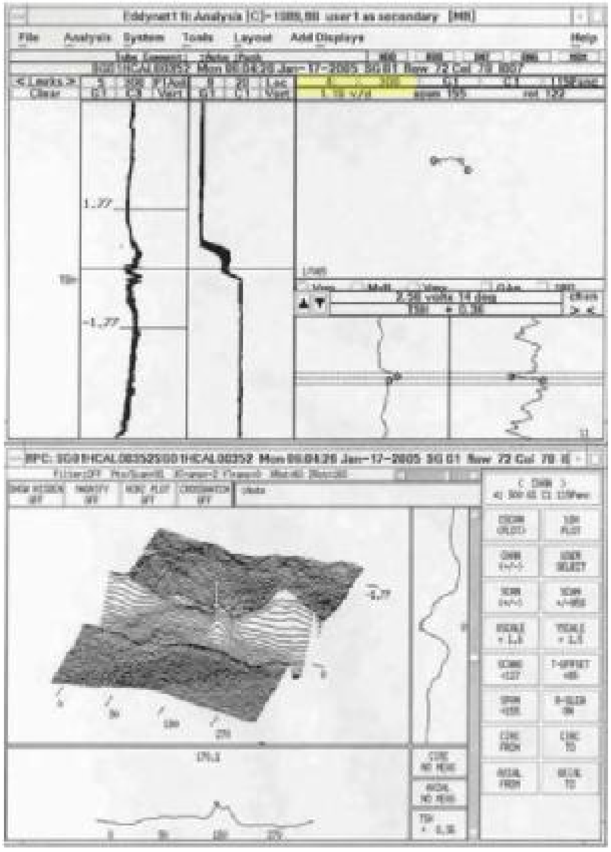

Figure 5*: VOL-like Indication (Pancake)*

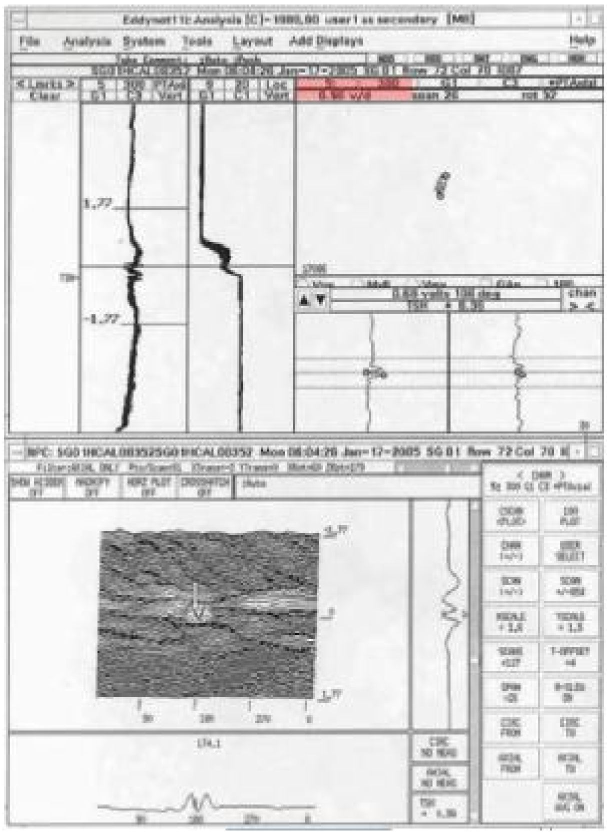

Figure 6*: VOL-like Indication (+-Point)*

Figure 7 shows phase rotation of this indication as test frequency decreases. Note that +point coil shows typical characteristics of volumetric indication in shape and phase rotation but pancake coil does not. It is considered that pancake coil generally does not give correct information at tube expansion transition especially with sludge pile. Also, it seems to be feasible because sometimes real volumetric indications appear near top of tubesheet area due to foreign material.

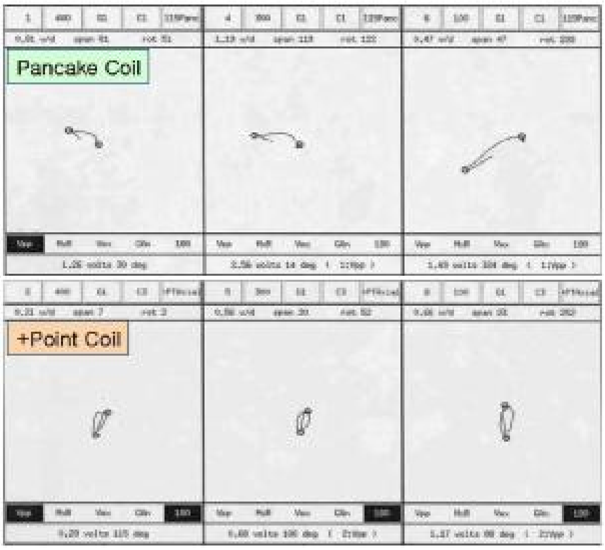

Figure 7*: Phase Rotation of VOL-like Indication*

4. Mock-up Test

To analogize what caused this indication, several susceptible materials from steam generator parts, sludge and deposits are selected and tested with RPC to examine signal characteristics of each material. Test frequencies and signal calibration process was used the same as field inspection. Table 2 shows the results of calibration setup with 40% ID notch to 15°[2].

Table 2: Phase Change of Various Materials per Frequency

Material \ Freq.	400 kHz	300 kHz	100 kHz	10 kHz
Brass	11°	352°	296°	211°
Titanium	7°	346°	277°	181°
Inconel600	3°	342°	278°	175°
Stainless Steel	352°	330°	257°	106°
Carbon Steel	246°	227°	171°	91°
Hard Sludge	220°	202°	150°	81°

Based on the test results above, titanium can be considered to have the closest characteristics to the indication of interest. Therefore, mock-up tests are focused on two things. One is what is the influence of sludge on volumetric defects and the other is what it would be like when sludge has titanium inclusion on volumetric defects. As a test specimen, Inconel 600 HTMA tube with outer diameter of 3/4 inch and thickness of 0.042 inch is used, which has the same material and dimension with KSNP steam generator tubes.

4.1. The Influence of Sludge on Volumetric Defects

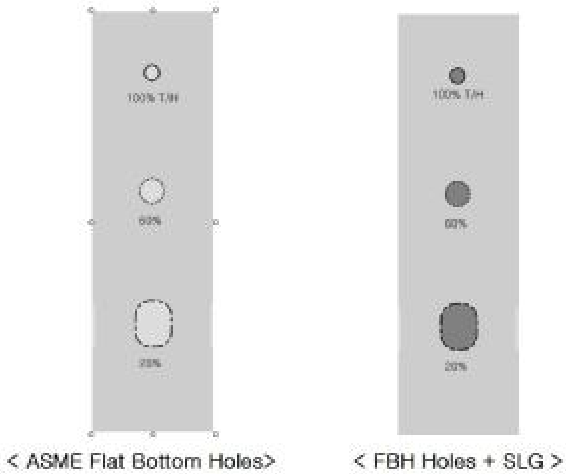

Figure 8*: Sludge on Volumetric Defects*

To ascertain the influence of sludge on volumetric indications, we put sludge from secondary side on 100%, 60% and 20% ASME flat bottom hole(FBH) artificial defects as shown in figure 8. Comparison of eddy current signal response between 100% through wall hole (TWH) itself and 100% TWH with sludge has shown in figure 9 and 10.

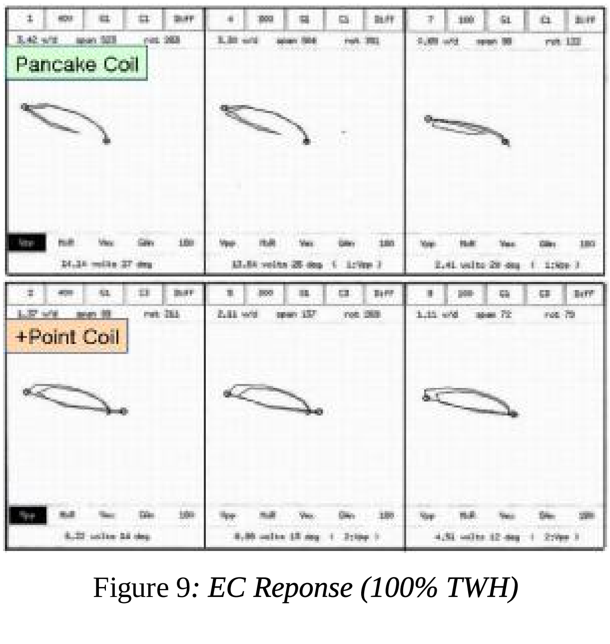

Figure 9*: EC Reponse (100% TWH)*

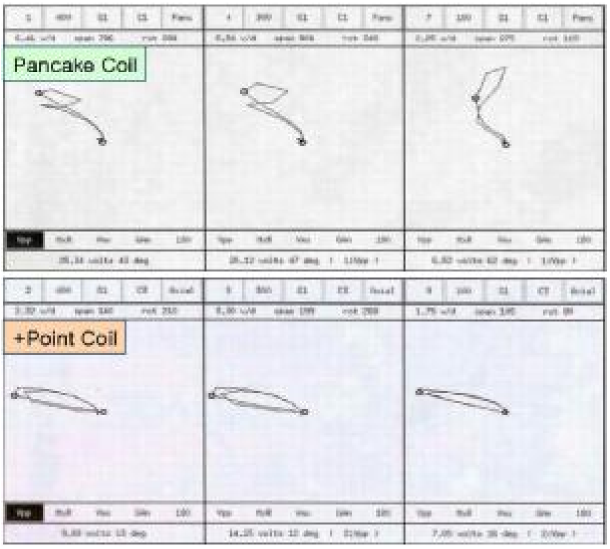

Figure 10*: EC Response (100% + SLG)*

Pancake coil response is distorted a little in signal shape and phase compared with +Point coil response. In other words, +point coil gives more reliable information than pancake coil when there is sludge pile. The same as for 60% FBH and 20% FBH, but basically sludge alone itself does not mask flaw indications so much that it is hard to differentiate from defects.

4.2. The Influence of Non-Homogeneous Sludge on Volumetric Defects

Another mock-up was set up with various shape of titanium with and without sludge as shown in figure 11. On the tube with same nominal size with previous ASME standard, titanium is attached in shape of axial, circumferential and volumetric type using powdered titanium and liquid adhesives.

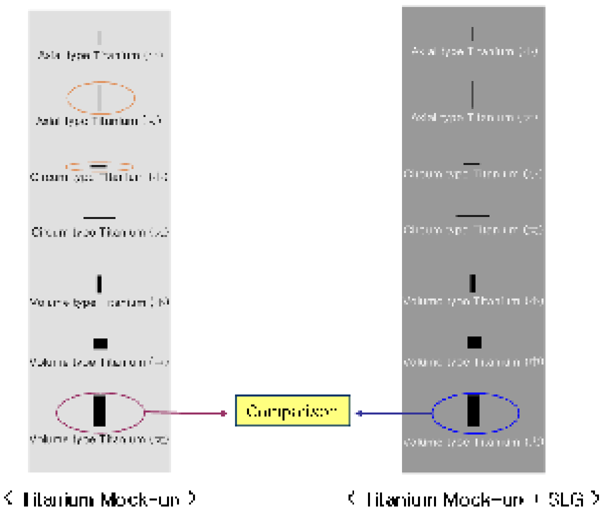

Figure 11*: Non-Homogeneous Sludge on Volumetric Defects*

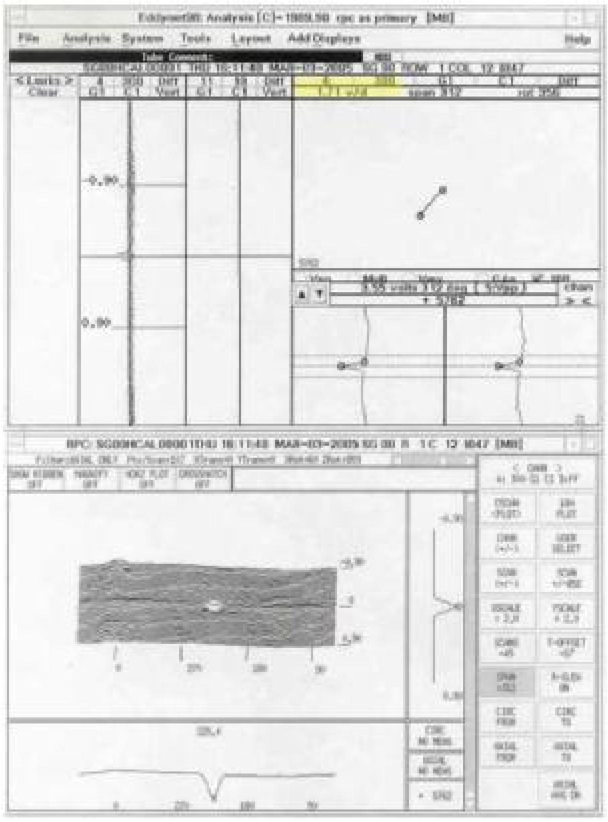

Figure 12*:Volumetric Type Titanium Response (Pancake)*

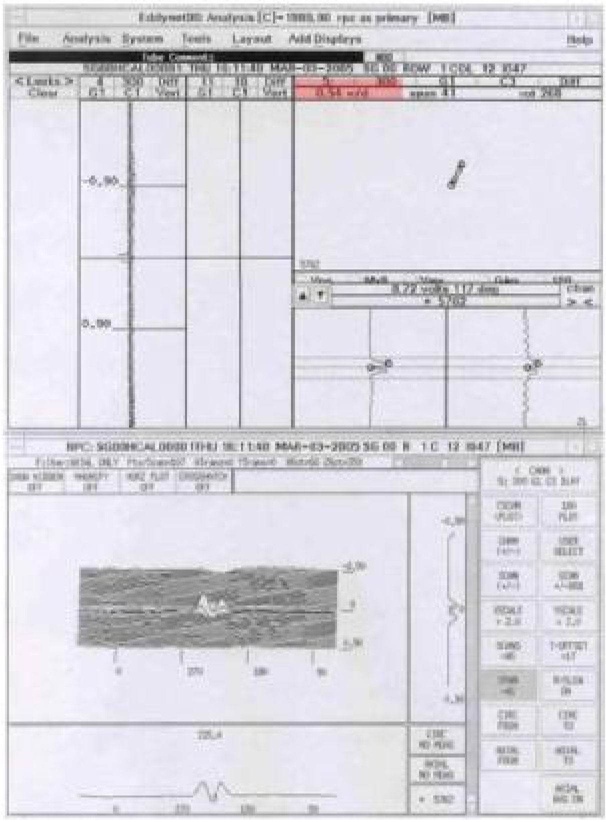

Figure 13*: Volumetric Type Titanium Response (+Point)*

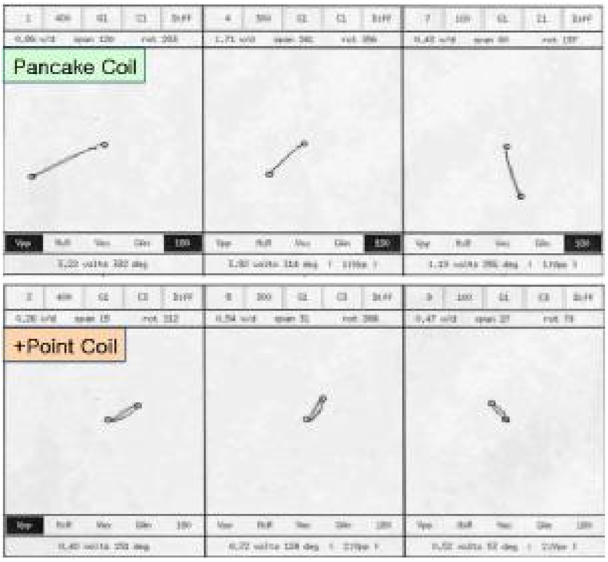

Figure 14: *Phase Rotation of Volumetric Type Titanium*

Figure 12 to 14 represents eddy current signal response for the biggest volumetric type titanium without sludge. Phase rotation in figure 14 shows a little off-phase with values in table 1 which caused by material contact surface variation.

Figure 15 to 17 are EC graphics of volumetric type titanium with sludge. Comparing figure 17 with figure 7 in phase rotation response of pancake coil, they are obviously in phase with each other.

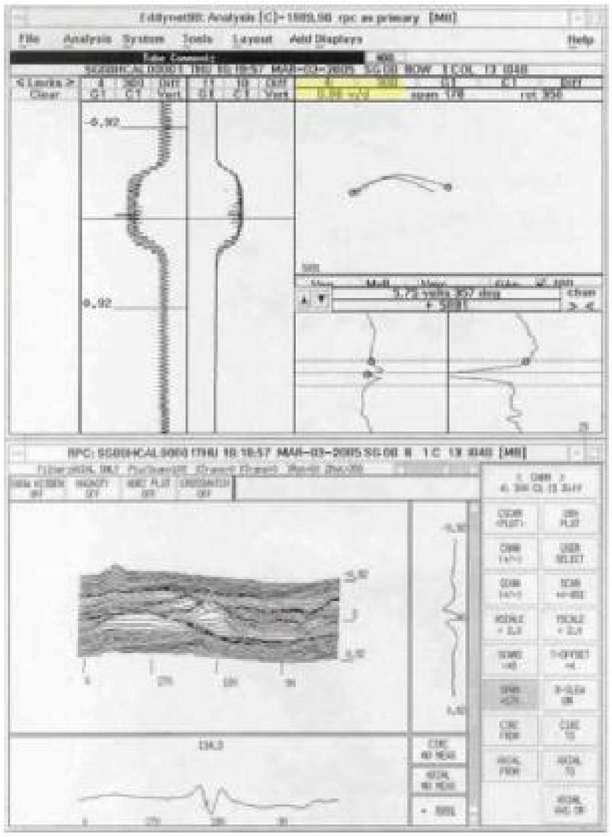

Figure 15*: Volumetric Type Titanium Response with Sludge (Pancake)*

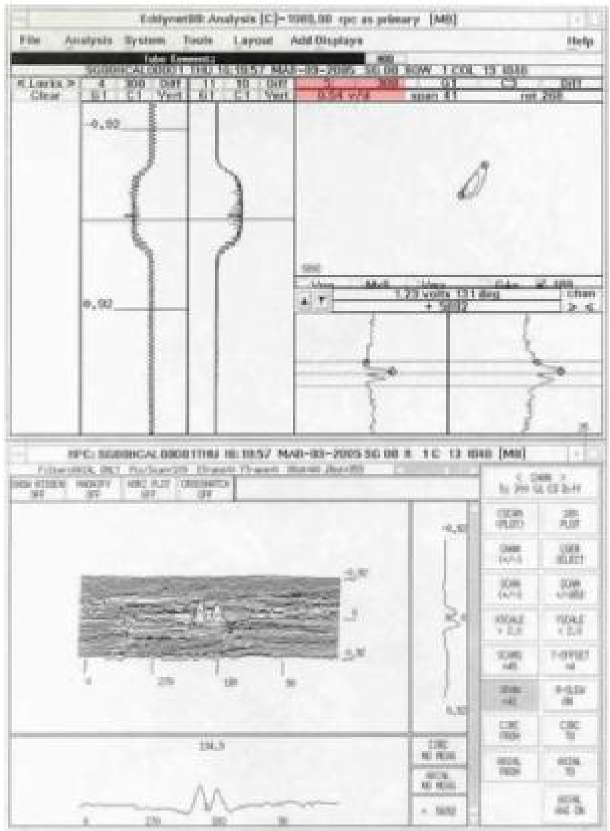

Figure 16*: Volumetric Type Titanium Response with Sludge (+Point)*

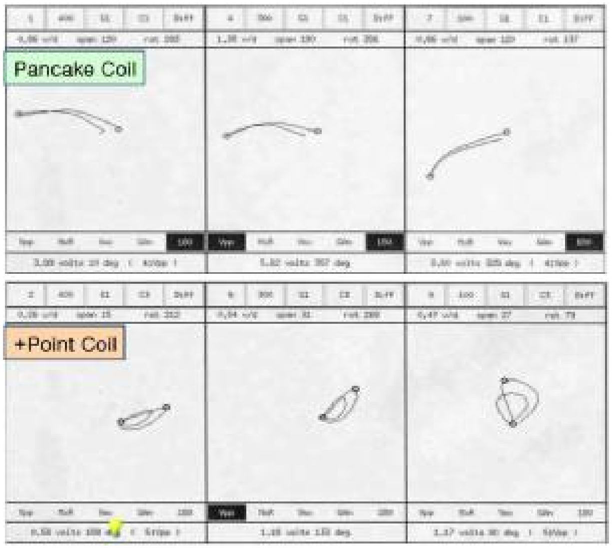

Figure 17*: Phase Rotation of Volumetric Type Titanium with Sludge*

5. Summary and Conclusion

Steam generator tube integrity of nuclear power plant has been maintained by periodic inspection with eddy current testing. During recent inspection, a lot of indications which look similar to volumetric defects were detected near top of tubesheet location in sludge accumulation zone. It did not seem plausible such volumetric defects as many could be developed without any contact with foreign material. In addition, there was no history or trace of foreign material found, these indications should be from something else other than real volumetric defects.

To prove the assumption that the indications of interest are from non-homogeneous inclusion in sludge pile, a mock-up has been set up with materials which could be included in sludge pile. Among various materials tested, titanium showed the most similarity in signal shape and phase rotation behavior with those volumetric-like indications.

Mock-up tests have been performed to look into how much sludge has an influence on volumetric defects with and without non-homogeneous inclusion. Without non-homogeneous inclusion, sludge itself did not have serious influence to differentiate real defect from false or ambiguous ones. With non-homogeneous inclusion with titanium, +Point coil response could be look like volumetric defects, but signal phase rotation of pancake coil proved to be that of titanium inclusion.

Volumetric defect on steam generator tube in nuclear power plant is one of the serious damage mechanisms which necessitate tube repair. Tube repair is such a high cost process that there should not be tube repair by false information.

When this type of indications are encountered in the future, test results of this paper could be a useful reference to decide they are real defects of not.

6. References

[1] EPRI, "Characterization of PWR Steam Generator Deposits", *EPRI TR*-106048, Feb. 1996.

[2] KPS, "The 5th Ulchin Unit 4 Steam Generator Tube Eddy Current Examination – *Final Report*", Mar. 2005.

[3] CGSB, "Advanced Manual for Eddy Current Test Method", *CAN/CGSB*-48.14-M86

[4] Satish S. Udpa and Patrick O. Moore, "Nondestructive Testing Handbook Vol. 5 – Electromagnetic Testing", *ASNT 3rd Edition*, 2004.

[5] KAITEC, "The 14th Kori Unit 4 Steam Generator Tube Eddy Current Examination – *Final Report*", Nov. 2004.