Tube support plate clogging and secondary side deposit: performance evaluation using simulation and site results

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ABSTRACT

Because of tube support plate (TSP) flow hole clogging by corrosion products, the secondary fluid flow through the steam generator can differ (in velocity, pressure, flow rate) from the design basis. Deposits on the freespan of the tubes (length between TSPs) may have similar effects. These differences have a significant effect on the safety and performance of the steam generator [1]. For example, at Cruas Nuclear Power Plant (NPP), the combination of specific features of these steam generators (no tubes in the central area of the tube bundle and no anti vibration rod support for some tubes in this region) and clogging of TSP holes led to an increase in flow velocity which produced excessive vibration and subsequently circumferential fatigue cracking of tubes.

Three techniques are used for deposit estimation: eddy current testing, magnetic flux leakage testing and visual examinations. Here we propose a simulation-based performance evaluation of eddy current and magnetic flux leakage techniques for the measurement of TSP clogging and secondary side deposits. The software used for numerical simulation is Flux3D developed by Cedrat [2]. Simulation results in different configurations are compared to those of measurements on mock-ups. Probes, analysis method and analysis software are proposed for automated evaluation of TSP clogging and secondary side deposits from on-site measurement results.

INTRODUCTION

Tube support plate clogging and tube secondary side deposition [1]

Corrosion products in the secondary loop of nuclear power plants form deposits inside the steam generators. In particular, deposits have been observed on the tubes and inside tube support plate holes; see Figure 1 and Figure 2. Note the nature of clogging in Figure 2 is asymmetrical for the top and bottom of the TSP. This observation is essential to the clogging assessment approach.

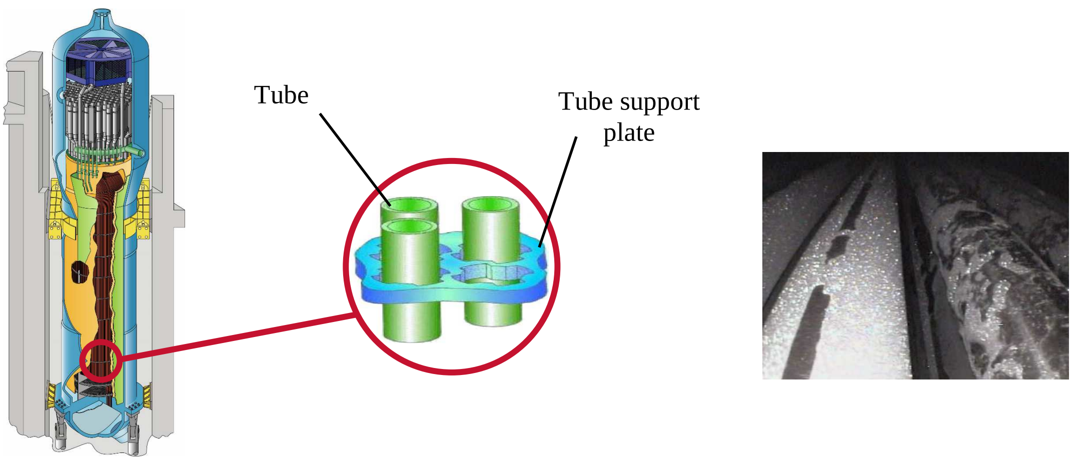


Figure 1 - Left: steam generator cut away. Right: steam generator tube secondary side deposit

Clogging of tube support plate broached holes can induce a velocity increase of the fluid flow. In the case of the tube not being supported by anti vibration bars, excessive vibration and stress on the tube due to fluid structure coupling can occur. These tubes are subject to high cycle fatigue and are likely to develop fatigue cracking. On a larger scale, clogging affects how the tube support plates and tie-rods are subjected to loads from the water-steam flow and local loads can be greater than the design loads. Higher than anticipated stresses can also result from accident or off-design situations, in which the supplementary stresses due to clogging might be a risk factor for safety. Steam generator operational efficiency is also affected by clogging and deposits as noted below:

- deposit on the tubes reduces the heat exchange between primary and secondary sides,
- circulation ratio, an index of the mixing inside the steam generator, is decreased,
- the amount of water available for cooling in the secondary part of the steam generator can be decreased, which reduces the safety margin, in particular there is a risk of water level oscillation for rapid power transients.

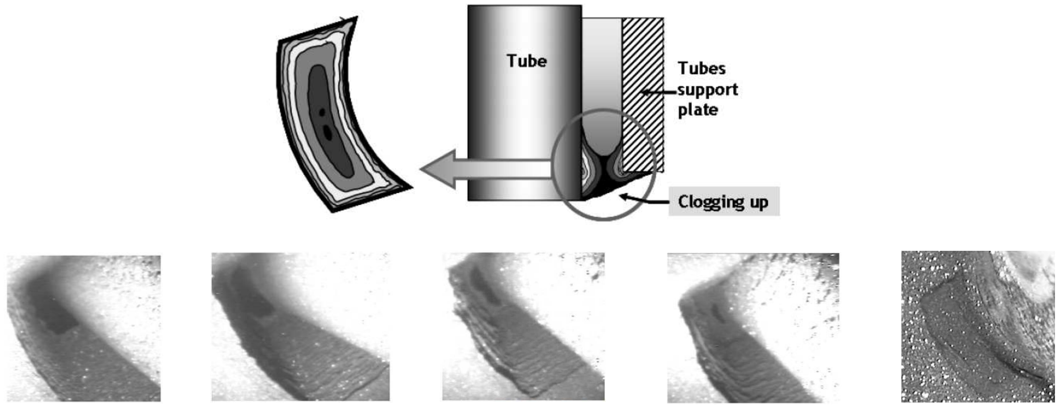


Figure 2 - Top: Tube support plate clogging sketch. Bottom: hole diaphragm clogging, from very small clogging to complete obstruction

Moreover the eddy current examination of steam generator tubes is disturbed by deposits on their external or secondary side, therefore possible defect detection performance might be affected.

For all these reasons NDE techniques are required to monitor the scale and progression of clogging and deposits to take actions such as chemical cleaning. NDE techniques for clogging and deposit estimation also serve the purposes of cleaning efficiency checking.

Industrial solution: probe and software for estimation of clogging % occlusion and deposit

Areva NDE Solutions has developed a specific combined probe in the frame of these requirements. It consists in an eddy current axial sensor (SAX bobbin probe) dedicated to the measurement of free span deposit as well as the usual tube examination, associated to a FLIP sensor (flux leakage technique based) for tube support plate clogging estimation [3]. The probe measurements are exploited using Aida G3, an AREVA signal processing and visualization software. It performs an automated analysis using transfer function between signal and clogging/deposit and delivers graphical representation of clogging/deposit maps on steam generator 2D/3D views (See Figure 3).

AIDA

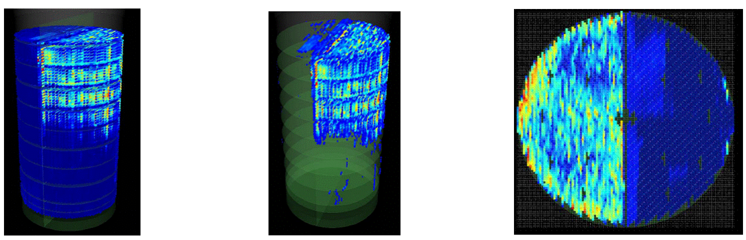


Figure 3 - Left: Aida G3 software logo. Right: 3D and 2D samples of clogging/deposit mapping from probe measurement onto steam generator geometry

A performance evaluation of the industrial solution is in progress in collaboration between EDF and AREVA, involving mock-up measurements, numerical modelling and simulation and site results. This is the work presented in this paper.

SECONDARY SIDE DEPOSIT

Technical approach

The axial probe numerical model that will be used for the performance study is first validated by comparison of finite element simulation results to those of experimental measurements on specific mock-ups. These reference mock-ups have varying characteristics: deposit thickness and deposit mass percentage of magnetite (Fe_3O_4). Magnetite is representative of actual deposits but the electromagnetic properties (electrical conductivity and magnetic permeability) of deposits in steam generators are not known, therefore a theoretical formulation of the magnetic permeability has been used to compute its value from the magnetite composition. This theoretical formulation is challenged in the validation.

The two references tubes that have been manufactured are:

- one tube with deposits of different thickness values, with same composition,
- one tube with deposits of same thickness but with different magnetite mass percentage values,

The deposit is homogeneous along the tube axial direction. In the orthoradial direction the deposit is either homogeneous or only present on half the tube perimeter.

Using the validated numerical model and formulation, the performance of the probe will be evaluated doing a numerical parametric study in order to quantify the influence of parameters such as:

- deposit materiel electrical resistivity,
- tube material,
- deposit configuration,
- deposit density and composition.

Finally the transfer functions obtained by modelling and simulation will be used for estimation of deposit from onsite signals.

Model validation

Finite element modelling and simulation are done using Flux3D software. The geometry of the numerical model is represented in Figure 4. Only half of the tube, probe and deposit are modelled and the deposit is divided in two parts to be able to have deposit on only the half of the tube circumference when the symmetry condition is applied.

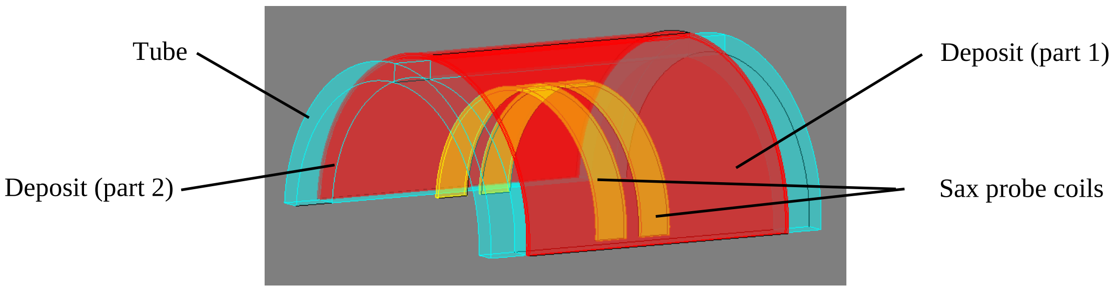


Figure 4 - SAX bobbin probe and tube with deposit numerical model

Simulated signals are compared to measured signals in two cases:

- variable deposit thickness with fixed magnetic relative permeability (magnetite 50% of mass , μ_r=1.08) see Figure 5Figure 6,
- variable deposit magnetic permeability with fixed thickness (0.23mm), see Figure 6.

We observe that the agreement between the simulated and measured signal is quite good, with maximum errors of 12.5% for signal with variable magnetic permeability and 5% for signals with variable thickness. Therefore we can consider that the numerical model and the theoretical formulation for the computation of magnetic permeability are validated.

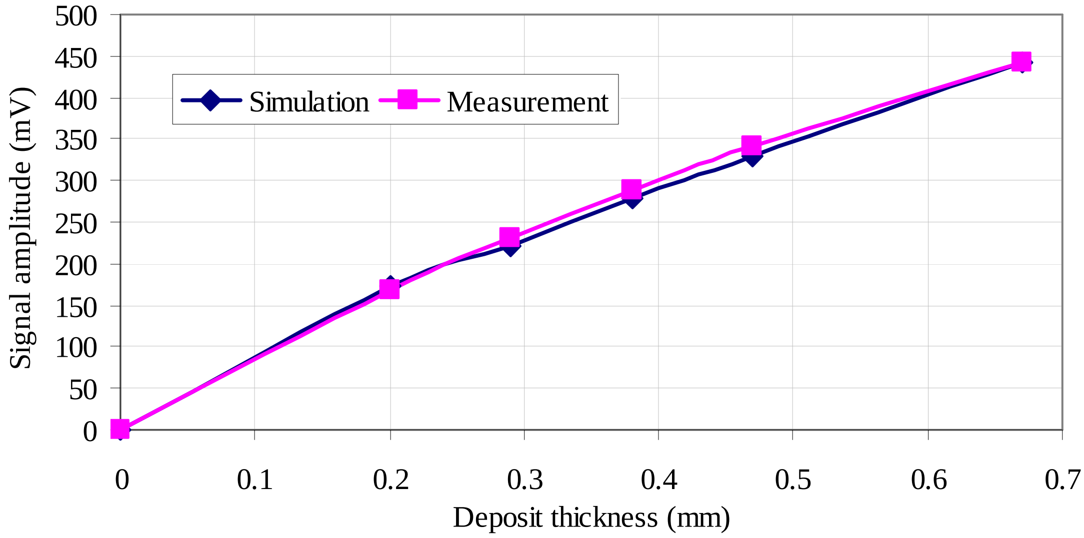


Figure 5 - Effect of the thickness of the deposit on the axial probe signal

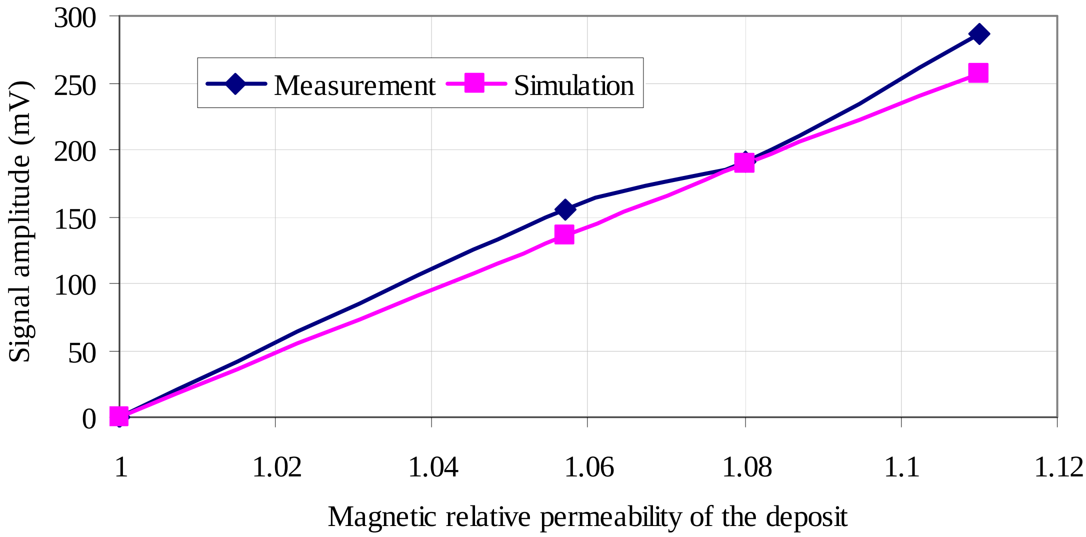


Figure 6 - Effect of the magnetic permeability of the deposit material on the axial probe signal

Parametric study

From the validated numerical model of the probe and tube with deposits, the previously described parametric study leads to the following conclusions:

- There is no influence from the electrical resistivity of the deposit material above $10^{-4}\Omega$.m, as can be seen on Figure 7,
- There is nearly negligible effect of the tube material, with a signal difference smaller than 1.5% between the signal obtained with Inconel 600 and Inconel 690, considering a deposit thickness varying between 0 and 0.67mm, see Figure 8,
- There is a significant effect of the deposit geometry on the probe signal for constant mean deposit thickness. Two geometries have been modelled: 360° deposit and 180° deposit and signals are compared for the same value of mean deposit thickness (see Figure 9). With 180°

homogeneous deposit instead of 360° the deposit thickness is under estimated by around 23% for a maximum thickness of 0.67mm,

- The theoretical formulation of the magnetic relative permeability from the magnetite mass rate in the deposit gives the following values: 1.37 to 1.41 for 88 to 95% magnetite mass percentage.

It must be noted that we have considered no copper in the deposit material. However the presence of copper as well as metal oxides can have an important effect on the signal (in particular the electrical conductivity of the deposit material is changed). Therefore it will be necessary to complete the present results with dedicated experiments and modelling, which includes the manufacturing of specific mock ups with representative deposit material.

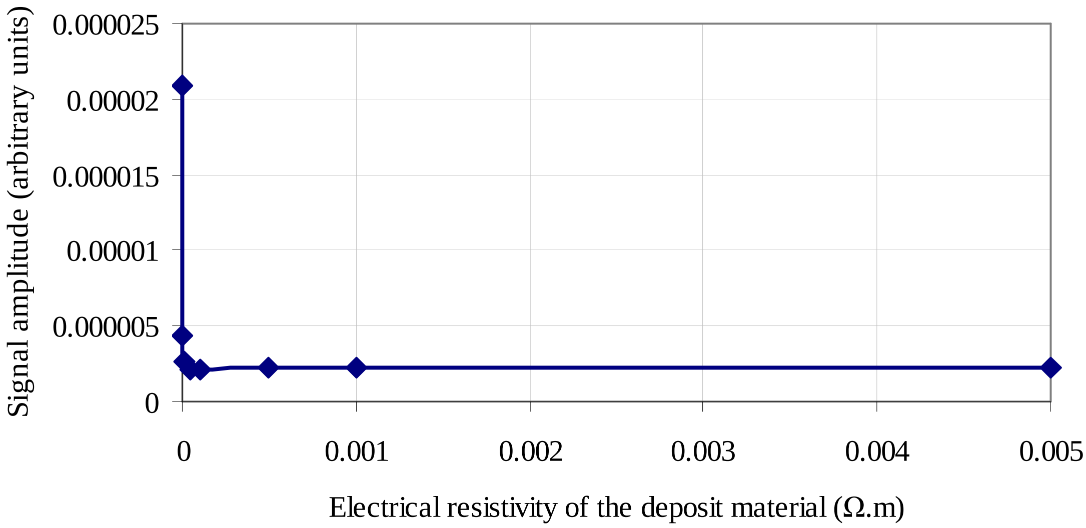


Figure 7 - Influence of electrical resistivity of the deposit material on the axial probe signal (μ_r=1.08)

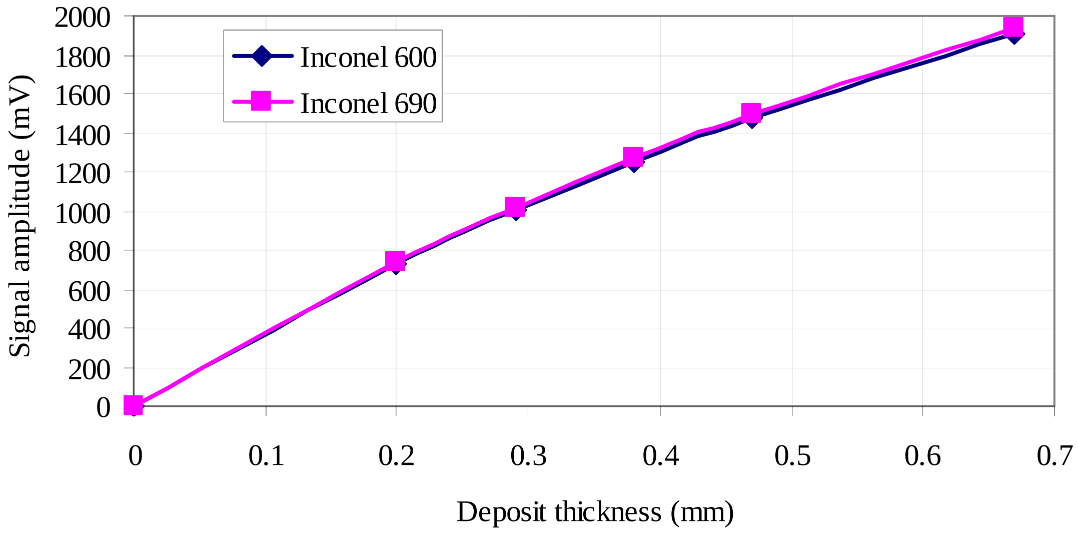


Figure 8 - Influence of tube material on the axial probe signal

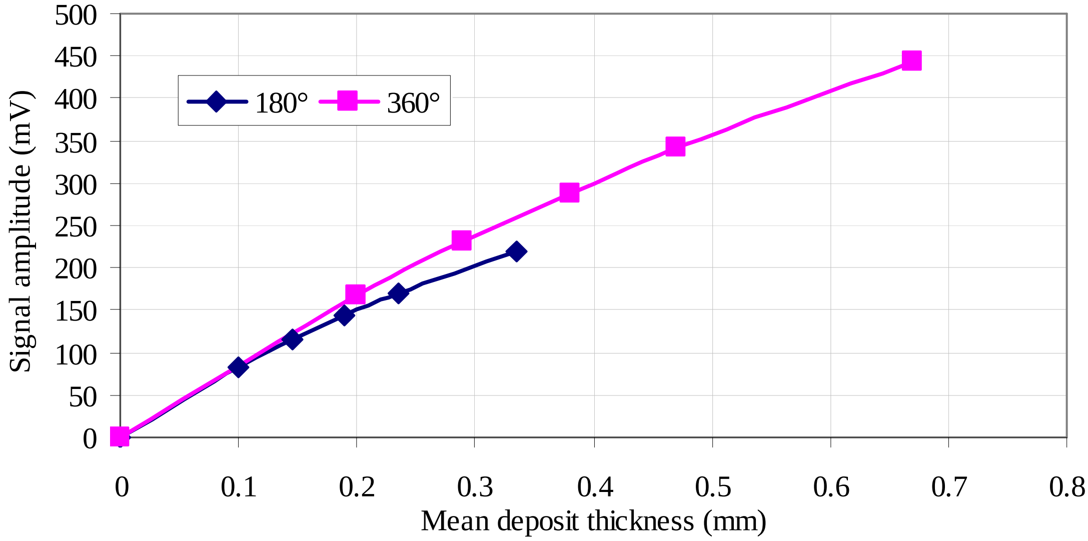


Figure 9 - Deposit geometry effect on the axial probe signal

On-site implementation

Since 2009, the analysis of three EDF steam generator's secondary side have been performed and three more are planned. The tube sizes of the different steam generators concerned are 3/4 and 7/8" and 25 to 50% of the tube bundle has been examined. From the probe signals, Aida G3 software has been used to evaluate the deposit material mass inside the steam generator secondary side. These estimation results are compared to those of EDF reference (mass balance method), see Table 1. We observe a good correlation between the masses estimated by the two methods.

	SG1	SG2	SG3
Areva deposit mapping Estimated deposit material mass (kg)	1104	733	513
EDF reference (kg)	1250	1000 (±30%)	500 (±40%)

Table 1 - Comparison of deposit mass estimate by probe measurement to EDF reference values

TUBE SUPPORT PLATE CLOGGING

Technical approach

A performance evaluation of the two probes, the SAX eddy current bobbin probe and the FLIP flux leakage probe, has been started using finite element software Flux3D. The study is realized under AREVA – EDF collaboration and its program is as follows:

- Step 1 - validation of SAX and FLIP probe numerical models: to perform this validation, Flux3D is used to compute simulated signals corresponding to examination of EDF mock-ups for clogging of tube support plate. The simulated signals are then compared to experimentally measured signals in the same configuration. The clogging of the mock-ups is a homogeneous diaphragm shaped clogging with occlusions of 0-25-50-75-100%, identical in all four holes. It is located at the bottom of the tube support plate holes and its height is 3mm, close to the actual clogging height. Sketches of the mock-up clogging are represented in Figure 10. This kind of clogging is representative of the actual clogging that as been observed during visual examination of steam generators. Mock-ups are made of Inconel 600 for the tube, 410 Stainless Steel-Z10C13 for the tube support plate and a magnetite-glue mix for the clogging material with 95% in mass magnetite and 5g/cm^3 density. These materials are representative of the actual steam generator materials. The geometry is of the 68/19 steam generator type with 3/4” tube diameter.

- Step 2 - evaluate the influence of model parameters on real deposit and clogging configurations using finite element simulation with the previously validated probe models. The clogging and deposit shapes are defined by variable geometric and material parameters. Then a parametric study is realized to evaluate and quantify the influence of each parameter: different sets of parameter values are introduced in the numerical model and related features are extracted from the simulated signals. This parameter-feature mapping can then be used to evaluate the parameter values from onsite measurements.
- Step 3 - predict signals from the defined clogging and deposit configurations, that is to say from representative sets of value of the different parameters.

Considering the results obtained at these different steps, the performances of SAX and FLIP probes for clogging examination will be compared.

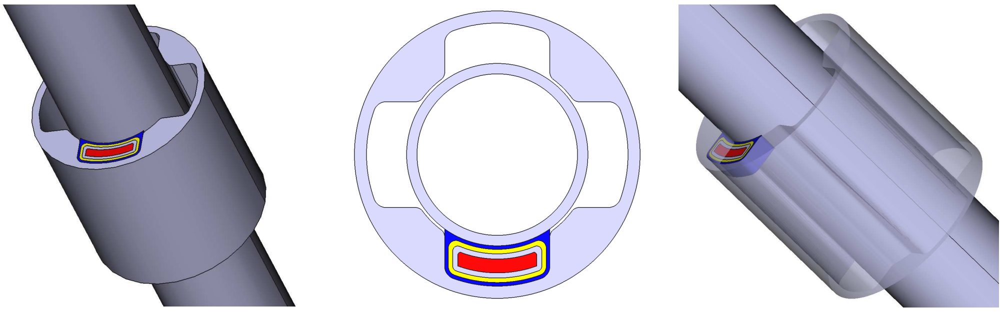
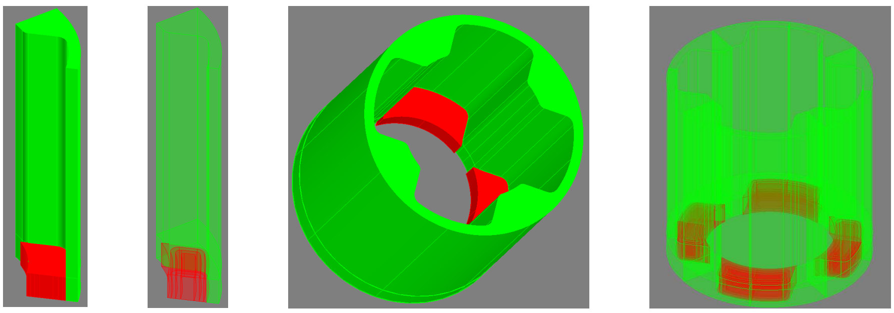


Figure 10 - Clogging configuration of the mock-up numerical models. The tube is centered in the support plate. The plate diameter has been reduced with no effect on the results. Blue, yellow, grey and red clogging volumes correspond to the different clogging occlusion values (blue: 25%, + yellow: 50%, +grey: 75%, +red: 100%). Here clogging is drawn only in one hole but it is present in all four holes.

The current state of advancement is step 1 - validation of the FLIP probe model, is detailed in the next paragraph.

FLIP probe model validation

The numerical model of the mock-ups used for the FLIP probe validation does not include the tube because the tube's relative magnetic permeability is very close to one therefore the magnetic field is not influenced by the tube. Moreover, thanks to symmetry, only one eighth of the geometry is modelled. Images of the tube support plate and clogging volumes are presented in Figure 11.



(a) (b) (c) (d)

Figure 11 - Flux3D numerical model of the mock-up, in red the cloggin volumes, in green the tube support plate. (a) and (b), 1/8th of the actual geometry used for the computation, (c) and (d) full geometry when the symmetry conditions are applied

The magnetic permeability of the mock-up materials (tube support plate material and clogging material) are not known therefore the model validation is two-fold:

1. establish that the simulated signal is similar to the experimentally measured signal,
2. find the values of tube support plate and clogging material's magnetic permeabilities that make the simulated and experimental signals fit.

The best fit of simulated and measured signals are shown in Figure 12 for clogging occlusion values of 25-50-75-100%. The agreement between the signals is excellent then the numerical model of FLIP probe is validated. The corresponding relative magnetic permeabilities are in the range 2.5-2.75 for the clogging material and between 700 and 1000 for the tube support plate material. This last range of values is the one found in the literature (matweb.com) for the material (410 Stainless Steel – Z10C13), and we observe that within this range the permeability value has very little effect (≤1%) on the simulated signal.

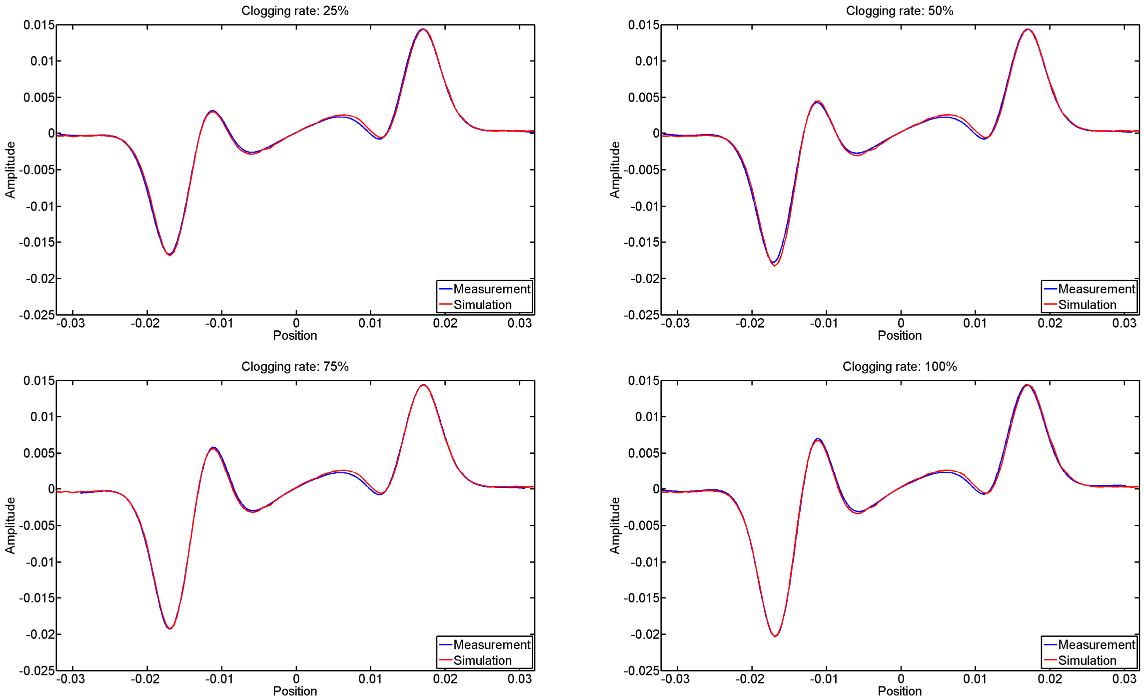


Figure 12 – Best fit of measurement and simulated signals for clogging % occlusions 25-50-75-100%

Transfer function

From signals obtained on configurations with known clogging % occlusions and material properties, a transfer function between the clogging % occlusion and one specific feature of the signal can be defined. This feature is the amplitude ratio of the clogged side signal to the un-clogged side signal. The amplitudes and support plate segments are shown in Figure 13. The transfer function is used to estimate the clogging % occlusion from experimental signal where the amplitude ratio of the measured signal is computed and the corresponding clogging % occlusion is read by applying the transfer function. The transfer function is either obtained with experimental measurements on the clogging mock-up, as shown in Figure 14, or using simulation result.

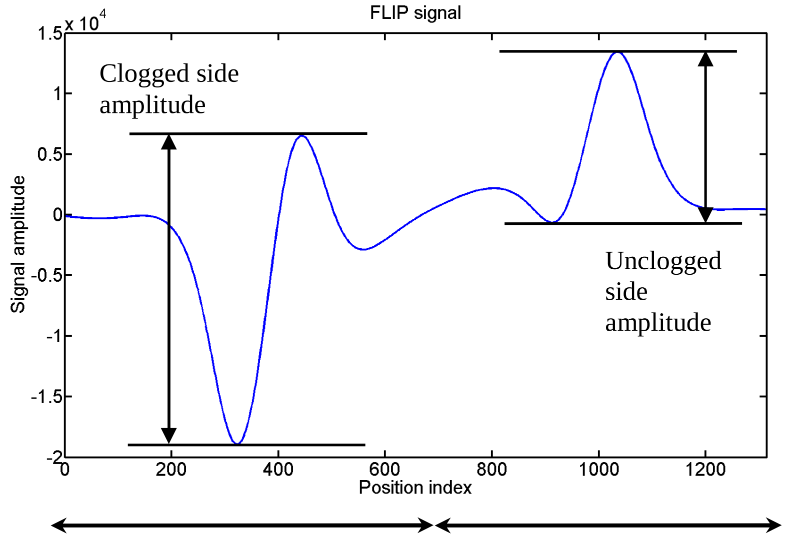


Figure 13 - FLIP signal from clogged and unclogged TSP sides

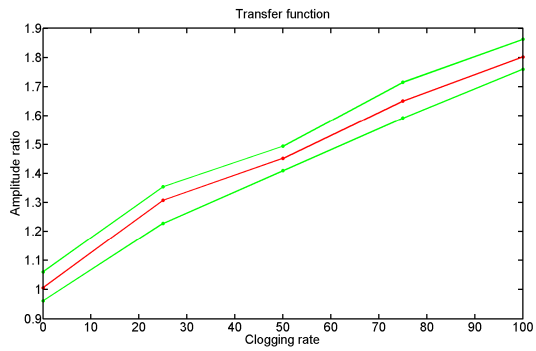


Figure 14 - Transfer function obtained with the EDF clogging mock-up. In red the mean transfer function, in green the maximum and minimum transfer functions for the different acquisitions

CONCLUSION

We have presented here the challenges of modelling and estimating secondary side deposits on tubes and clogging of the tube support plate inside nuclear power plant steam generators. The industrial solution developed by Areva NDE Solutions and applied in the field with the collaboration of EDF Ceidre has been introduced and the current state of its performance evaluation shown.

This performance evaluation relies on comparison of mock-up experimental results to those obtained using finite element numerical modelling and simulation. This allowed validation of the numerical models and software package. Using this validated models the influent parameters are identified by relevant simulation and the results are used to fine tune transfer functions. These updated transfer functions will ultimately be introduced in the Aida G3 processing and visualization software to evaluate and display the deposit and clogging state of the examined steam generator.

The comparison of results obtained by the industrial solution for deposit estimation to actual measurement of deposit mass inside steam generators gave very positive results

REFERENCES

1) Bodineau H and Sollier T, "Tube support plate clogging of french PWR steam generators", Eurosafe Forum, Paris, 3-4 November, 2008

2) http://www.cedrat.com/

3) Piriou M, Glass SW, "Steam Generator Secondary Side Deposit NDE Method for Support Plate Clogging", The 24th KAIF/KNS Annual Conference, March 2009, Seoul, Korea.