INTEREST OF MODEL-DRIVEN STUDIES OF FOULING PHENOMENA IN STEAM GENERATORS OF NUCLEAR POWER PLANTS

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Abstract. Pressurized water reactor steam generators (PWR SGs) are large components whose main function is to cool the fission reactor by extracting the thermal power conveyed by the primary coolant, and thus to produce steam for the turbine-generator. Fouling phenomena may occur in the SG when iron oxide particles carried in the secondary feedwater get unavoidably deposited inside the SG structure, and specifically in two main regions: on the 3,600 U-tube outer walls, and on the quadrifoil sections of the plates that support the U-tubes. They may reduce its cooling efficiency and impact its dynamic behaviour, thus leading to possible safety issues.

Methods based on local inspections of the SG have been designed and are already in use. They produce estimators of the local fouling rate, during the yearly outage of the plant for refuelling and maintenance.

A new method to assess a global estimator of the fouling rate is presented. This method is based on a 1D physical model of the SG that reproduces the complex dynamics of the two-phase flow phenomena inside the SG. The model was developed in the Modelica language.

This model is used to compute response curves of the SG characteristics to a particular transient that challenges the dynamics of the SG, when affected by fouling. The estimator is obtained by comparing the computed response curves to real response curves measured on-site.

The method is still under validation. However, first results show that it is able to give global estimators that are consistent with local ones.

This new method is expected to improve the monitoring of possible SG sludge fouling phenomena by producing fouling rate estimators with better accuracy, with a quarterly periodicity while the plant is in operation.

1 INTRODUCTION : STAKES AND ISSUES

Steam generators (SGs) are key components for the operation of pressurized water reactors: these huge heat exchangers (typically 20 m in height and 4 m in diameter) serve as a barrier between the primary system fluid which is highly radioactive (as it is heated by the nuclear fission in the reactor vessel) and the water-steam secondary system which is “normal” (i.e. not radioactive).

The main function for SGs is to transform the heat from the primary coolant water into steam feeding the turbines.

Current PWR units have 3 or 4 SGs : the secondary system feedwater is heated by the primary coolant water into steam, through 3,600 tubes (see Fig. 1). The U-shaped tubes are about 1 inch in diameter, and are held by 8 support plates (meant to prevent excessive vibration due to turbulent flow inside the riser).

A huge component like a SG must work within given operation limits to achieve satisfactory thermal performance and acceptable lifetime: although chemistry conditions are carefully monitored, fouling will unavoidably occur with time, thus affecting the SG performance.

Fouling deposits are found on the U-tube outer wall and on the tube support plate: fouling deposits on the U-tube outer wall impact the heat exchange capacity, and tube support plate fouling will lead to reduction of flow passage in the quadfrifoil sections. Such gradual drifts of the SG behaviour are very small per operation cycle, but may in the end lead to significant impact after decades of plant operation: thus they have to be monitored to help making the adequate maintenance strategies (such as chemical cleaning times).

Monitoring potential fouling situations is an interesting aid to operation and maintenance strategies. This paper presents possible monitoring capabilities based on modelling the static and dynamic behaviour of SGs.

So far, fouling monitoring has been performed with methods used during outages (outages are periods occurring every 12-18 months, during which the plant is shutdown for periodic examination and maintenance). Non destructive evaluation (NDE) techniques such as eddy current measurements or camera inspections allow inspection on a sampling of fouling locations.

It would be of significant improvement to also provide fouling estimators on the global scale of the SG, during normal operation (i.e. between two outages). Having these on-line fouling indicators would help making preventive maintenance decisions, namely chemical cleaning strategies to be performed during the next outage.

To that end, a model-based simulation of SG behaviour, both static and dynamic, was developed.

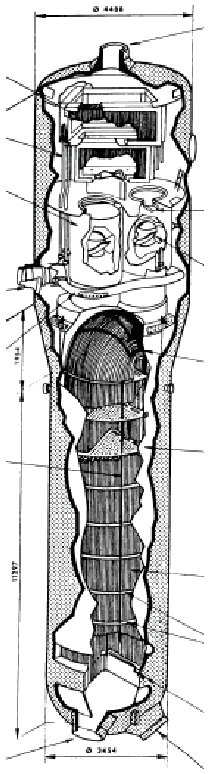

Figure 1. 51B-type steam generator of the 3-loop PWRs

2 STEAM GENERATOR PHYSICAL BEHAVIOR

The role of the steam generator is to transfer heat from the primary loop to the secondary loop of the plant. The steam generator works as a countercurrent flow heat exchanger: the hot primary fluid coming from the reactor vessel flows inside thousands of U-shaped tubes and releases heat to the secondary fluid. On the secondary side, feedwater enters into a ring located towards the top of the tank, and flows down to the bottom along the downcomer. At the bottom, it enters through a flow distribution plate into the riser, where primary/secondary loop heat exchange takes place. Water is heated up to boiling and becomes a 2-phase emulsion. At the top of the riser, the ratio between the total flow and the steam flow, called the circulation ratio, is between 4 and 5 at full nominal power. The emulsion continues flowing through a first set of phase separators. The liquid separated from the emulsion is mixed with the incoming feedwater to go back along the downcomer into the riser for another round of boiling. The higher quality steam goes through a second set of separators. It leaves the steam generator to go to the steam turbine with a vapor quality higher than 99,75 %.

3 POSSIBLE FOULING PHENOMENA IN SGs

Secondary system feedwater carries oxide particles, mainly resulting from iron corrosion and oxidization of other large components such as the MSR (moisture separator reheater), the condenser, the feedwater reheater stages, etc.: magnetite is then preferentially trapped in the SG, on the U-tube outer walls and in the quadrifoil passages of the tube support plates.

Sludge buildup eventually leads to mass flow decrease through the plates, resulting in higher void fraction inside the riser.

4 A MODEL-BASED METHODOLOGY AIMED AT MONITORING SG FOULING PHENOMENA

EDF R&D has developed an innovative method in order to estimate the fouling rate of each SG.

The principle is to build a 1D physical model of the SG. This model is used to process real operation data of a reference power transient that shows the alteration in dynamic behavior of the SG due to sludge fouling. The result of the model computations is a global estimator of the SG sludge fouling. Here, global means that the whole SG is considered, as opposed to the local methods based on local measurements or visual inspections of a sample of U-tubes.

The main steps of the method are:

- a 1D physical model of the SG is built;
- a power transient that challenges the dynamic response of the SG is sought: this transient exists in the form of a periodic testing of the control rods, namely a 60% power derate in 20 minutes (EP RGL 4);
- on site measurement data are recorded with the plant data historian: the SG specific data (temperature, pressure, flow rates) at the inlets and outlets of both primary and secondary sides of the SG are extracted during the above mentioned periodic test;
- a parametric study on the fouling rate is made by feeding the characteristics of the EP RGL 4 transient into the model;
- the response curves depending on the fouling rate are compared to the measured data: this analysis is aimed at finding the curve parameters that best characterize the dynamic response of the fouled SG;
- the best fitted curve gives the most probable estimator.

From the physical point of view, fouling shall decrease the circulation ratio because the flow inside the riser is restricted by the obstructed quadrifoil flow sections.

Consequently, a dynamic SG model was developed, as described in the next section. A dynamic model is needed because the fouling rate is reflected by the delayed response of the SG behavior to a decrease in the primary thermal power.

5 DESCRIPTION OF THE MODEL

The model has 3 main parts: the steam generator itself, the boundary conditions and the steam generator control system.

The model developed and hereafter presented is a 51B type, typical of early 900 MW PWRs, equipping twelve 3-loop units of EDF’s 58 unit fleet.

5.1 Model of the steam generator

The challenge is to produce the simplest model as possible that is precise enough to account for the influence of sludge fouling on the overall behaviour of the steam generator.

The difficult part is the complex physical phenomena that occur within the riser. Temperature and pressure distribution in the plane section perpendicular to the main flow direction is not constant: the heat flux produced by the U-tubes decreases as the primary fluid gets cooler, so that the temperature of the emulsion is higher on the side of the riser where the primary fluid enters the U-tubes, called the hot leg, than on the other side where the primary fluid leaves the riser, called the cold leg. This phenomenon can be captured by different precision grade models, going from simple 1D mono-axial models that neglect the dissymmetry between the hot and the cold leg, to full 3D CFD models, that are very detailed, but CPU-time consuming.

Modeling choices must also be made to account for the pressure losses distribution along the downcomer, in the section going from the downcomer to the flow distribution plate at the bottom of the riser, through the support plate holes inside the riser and through the water/steam separators.

The following choices were made:

- The dissymmetry between the hot and cold legs is taken into account, but there is no heat conduction between them. Each leg is modelled as a distributed tube with a wall for heat conduction between the primary and secondary fluid, and proper correlations to account for water vaporization at the wall: Mac Adams for 1-phase flow, Gungor-Chen and GRETH for all 2-phase flow regimes. So the flow is considered as homogeneous in each leg. More precise 2-phase flow description such as the Zuber and Findlay drift-flux correlations are not used here. These correlations take into account phase slip and non uniform velocity and void fraction distribution across the tube. Each tube is divided into sections, that represent the volumes between 2 consecutive support plates. The singular pressure loss due to the holes is captured by an additional pressure loss coefficient that depends upon the fouling rate. These coefficients are estimated from pressure loss measurements between the bottom and the top of the riser.

- The downcomer is modelled as two simple adiabatic tubes, where the pressure difference between the inlet and outlet is mainly due to gravity. Heat transfer between the riser and the downcomer, and between the downcomer and the outside is neglected.
- The separators are modelled as a sequence of pressure losses and a 2-phase water/steam cavity with water level. The water level is controlled by the SG level control system, in order to ensure its stability over the transients.

5.2 The boundary conditions

The objective is to reproduce the thermo-hydraulic conditions of the transient at the boundary of the steam generator that is used to characterize the support plate sludge fouling.

On the primary side, the boundary conditions are the fluid pressure, mass flow and specific enthalpy at the inlet of the U-tubes. On the secondary side, the boundary conditions are the feedwater pressure at the inlet of the downcomer, and the vapor pressure at the outlet of the separators.

The decrease in primary power is obtained with a ramp imposed on the fluid specific enthalpy.

The mass flow profile at the inlet of the downcomer is obtained with a control valve. The position of the valve is given by the control system, in order to follow the mass flow profile measured on site.

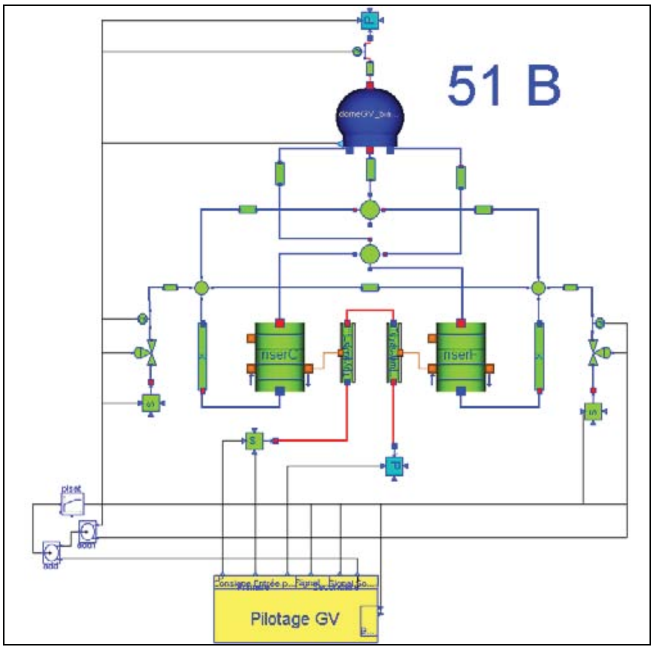

Figure 2. Model of the 51B-type steam generators

The model was developed by interconnecting components from a Modelica power plant library developed at EDF (see Figure 2).

6 PRELIMINARY RESULTS

Parametric studies were done using Dymola. They show that the EP RGL 4 transient is fully adequate to characterize the fouling rate. Moreover, first inter-comparisons with local fouling estimators are positive so far.

As an example, Figure 3 shows the results of one parametric study that can be used to identify response curve parameters: response of water level with time is shown during and after a typical EP RGL4 transient, with various fouling rates.

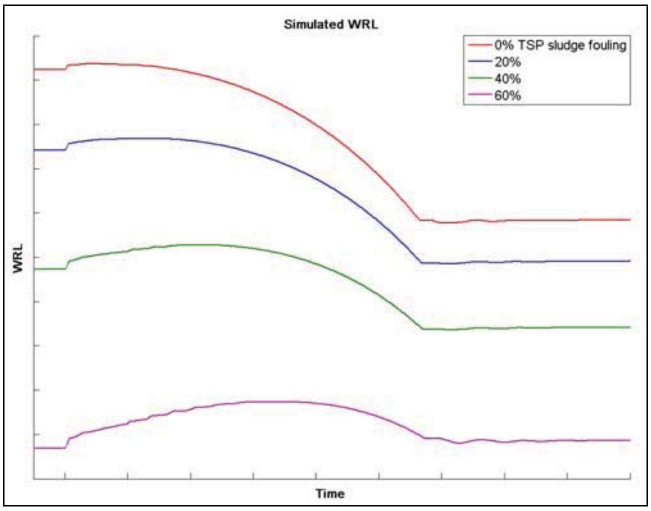

Figure 3. Response curves for four simulated fouling rates

7 CONCLUSIONS

A 1D physical model of the SG of a 900 MWe pressurized water reactor has been presented.

By feeding the process data of a reference power transient into the model, it is possible to compute a new estimator of the tube support plate sludge fouling ratio.

Other methods based on eddy current and visual inspections give local ratios every year, during the plant outage for refuelling and maintenance.

This novel method gives a global estimator that can be automatically updated every three months during each periodic power transient test. Therefore, a better monitoring of the SG fouling may be obtained.

First results show that the new method gives a global estimator that is coherent with the local estimators. Further validation and improvements are under way.

The model will be improved by using better heat exchange correlations, and a mesh model more adapted to the different boiling regimes in the riser.

In addition, the model will be adapted to investigate 1300 MWe units. Future work may also include the modelling of secondary systems with their 3 or 4 SGs and feedwater pumps, depending on the number of plant primary loops.

8 ACKNOWLEDGEMENTS

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