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EDF Steam Generators Fleet: In-operation Monitoring of TSP Blockage and Tube Fouling

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ABSTRACT

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been affected by Steam Generators (SG) Tube Support Plates (TSP) blockage and U-tubes external surface fouling with iron oxides deposits due to corrosion of secondary-side components. These issues have been tackled by a global maintenance strategy of chemical cleanings and a method for in-operation monitoring of fouling and TSP blockage has been developed and is implemented since mid 2009. This monitoring is aimed at giving information for SG maintenance planning as regards non destructive examinations and chemical cleaning.

This paper will first remind of the physical reasons of fouling and TSP blockage and identify the resulting stakes regarding safety and availability along with the action levers available to control both phenomena.

Then details will be given on how in-operation monitoring of fouling and TSP blockage is carried out, using measurements of Wide Range water Level (WRL) and SG steam pressure during thermally stabilized periods. Information will also be given on how those data are analyzed and shared as well at a local as at a corporate level to participate in the planning of SG inspection and maintenance operations.

Finally, possible refinements will be discussed, notably regarding the issue of WRL measurements reliability and the possibility to use the analysis of SG dynamic behavior during power transients to assess the TSP blockage ratio.

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investigated by EDF:

1. SG pressure can have quite large variations during one operating cycle (notably after a plant trip) and from one cycle to the other and generally pressure tends to decrease on a long term basis. How can such variations be explained? What are the solutions to moderate/stop the pressure loss?

2. On some of the SG models operated by EDF, hard curative Chemical Cleaning of the U-tubes didn't bring any pressure rise (although NDE showed that the deposit has been removed from the tubes and although such chemical cleaning brought significant pressure rise on other SG models). How can that be explained?

3. What would be the impact on the SG pressure of a degradation of the performances of the upper internals (primary and secondary moisture separators)? Do models exist to explain/predict such a degradation? Would it be interesting to clean the upper internals?

4. EDF currently has some issues regarding Wide-Range Level measurement reliability (drop after outage, possibly due to invasive maintenance actions on WRL sensors). Do other utilities have the same kind of issue? How can the drops be explained?

1. INTRODUCTION

EDF operates 58 Pressurized Water Reactors in France. , Q WKH PLG ¶V VRPH RI W been affected by Steam Generators (SG) Tube Support Plates (TSP) blockage and U-tubes external surface fouling with iron oxides deposits due to corrosion of secondary-side components.

This paper will first remind of the physical reasons of fouling and TSP blockage and identify the resulting stakes regarding safety and availability along with the action levers available to control both phenomena.

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1.1 Physical reasons of tube fouling and TSP blockage

High-pressure re-heater in the secondary side of French PWRs are the main contributors to the Flow Accelerated Corrosion (FAC) phenomenon that puts iron in the Feed-Water (FW) either as particles or as dissolved species. That is due to temperature, pressure and flow conditions over the carbon-steel tubes bundle surface. The transport of corrosion products towards SGs may cause problems as the iron accumulates and settles mainly as magnetite (Fe_3O_4) in the SG.

Depending on the location where the iron oxides settle, magnetite trapped into the trifoil or quatrefoil broach HG KROHV RI WKH 76´ LV FDOOHG ³blockage´ whereas the one covering the inverted U-WXEHV RXWHU ZDOO´ LV FDOOHG ³fouling

Figure 1: TSP blockage and tube fouling

TSP blockage and tube fouling are also correlated with other secondary water chemistry issues that have been widely discussed in reference [5].

1.2 Safety and availability consequences of TSP blockage and tube fouling

The consequences of TSP blockage are safety issues whereas fouling causes rather a performance issue. Reference [2] gives an overview of the safety issues related to blockage.

1.2.1 Safety issues

1.2.1.1 Water level oscillations

TSP blockage induces changes in pressure loss distribution that can cause SG level, pressure and temperature oscillations and variations of the related primary parameters. It reduces safety margins for the Excessive Increase in Secondary Steam Flow transient. A solution is to reduce the power of affected PWRs. This lever is also efficient for the issues listed below.

1.2.1.2 Hydraulic loads applied on tie-rods and TSP

TSP blockage increases the loads on TSP and the strains on both TSPs and tie-rods. It reduces mechanical criterion margins for the secondary side depressurization transient (steam line break).

1.2.1.3 Tube vibration behavior

Considering French SG design, significant TSP blockage implies higher flow velocity in the center of the tube bundle, as well as higher void fraction in the U-bend. It increases the dynamic loads applied to some tubes (non-supported small-radius U-tubes in the center of the SG), which may cause a tube failure by fluidelastic instability in normal operating conditions.

1.2.1.4 Water mass in the secondary system

TSP blockage decreases the water mass available for cooling in the secondary system. This is due to a significantly more important evaporation in the riser because of thermal-hydraulics flow changes in clogged SGs. It reduces safety margins for the Loss of Normal Feed water Flow as an example of transient. For instance the water inventory in a 51B type 900 MWe SG with a 65% blocked higher TSP is something about 10% (4) less than in a clean one.

1.2.2 Availability issues

1.2.2.1 Potential electric output losses

Tube fouling adds a thermal resistance to the primary-to-secondary-side heat exchange. For a given primary nominal state point, saturated temperature and hence steam pressure just above the tubes bundle decreases as deposit thickness increases. When the pressure is so low that steam turbine inlet control valves do not laminate anymore (fully opened), electric output is lost.

1.3 Action levers

1.3.1 pH increase and change of secondary side components

1RW DOO (')¶V UHDFWRUV DUH DIIHFWHG WR WKH VDPH H Feed-water pH is indeed the main lever to limit FAC. Above pH 9.6 the phenomenon appears PXFK OHVV DFXWH 6R (')¶V VWUDWHJ\ LV WR a minimal to reach that pH for the secondary-side FW. However, materials that compose secondary-side major components (condenser, heaters, ...) do not allow to increase pH without inducing corrosion issues. Hence the replacement of those equipments is scheduled in the next fifteen years. This strategy causes however a complex problem because removing brass, for example, in the secondary components implies a lower biocide efficiency on hot water releases. So as a first step, the low-pH sites (about 9.2) can be moved to an intermediate pH (about 9.4) with still a bit of brass in the equipment material compounds before reaching high pH (9.6) in a near future. Those pH are obtained using Ammonia water, but Morpholine (or more recently Ethanolamine) is more and more used.

As high-pressure FW reheaters have to be changed, chromium rate of the steel used is carefully chosen to minimize sensitivity to FAC.

1.3.2 Chemical Cleaning

Those two levers are long-term and preventive ones. In case of a rather advanced fouling or blockage state, restoring safety and efficiency of the SGs is achieved through Chemical Cleanings (CC) of the U-tubes. State-of-the-art mechanical high-pressure water cleanings have always proved to be much less effective than CCs. When an advanced state has been reached by some SGs an "curative" CC has been carried out with RQ SURFHVVHV DYDLODEOH ZRUOGZLGH (')¶V VWUDWHJ\ LV QR WKH 6*V IOHHW- SUHYHQWLYH ³&RIW´ industrial CC R I WKH DGDS processes (available now or in a near future).

1.4 Need for in-operation monitoring of TSP blockage and tube fouling

)LQDOO\ LGHQWLILHG DV WKH FDXVH RI WKH WKUHH 6* WXE February 2004, Cruas Unit 4 in November 2005 and February 2006), TSP blockage led to plan 9 unplanned SG CCs in 2007-2008. The standard measurement mean of blockage has firstly been camera inspection on a sample of TSP broached holes (eventually complemented by eddy current measurements) during outage but it has several limitations: not all TSPs are accessible for inspection and the frequency of the measurement is quite low (at most every outage, rather every other outage actually).

As a consequence, monitoring more precisely and more often TSP blockage but also fouling indicators was decided in early 2009. The aim of this monitoring strategy is to detect as early as possible a degradation of thermohydraulic performances of the SG (due to blockage and/or fouling) and to give additional information to people in charge of SG maintenance planning as regards inspection and cleaning.

In order to be proactive about SGs that do not have fouling or clogging issues today, the strategy is to apply the same standard tool and monitoring method to the whole (')¶V 6* IOHHW 7KLV Z thus allow anticipating long and mid-term SG state and maintenance actions.

2. ³,1 23(5$7,21´ 0 21,7RING OF TSP BLOCKAGE AND TUBE FOULING

At the end of the 24-hour full-power thermally stabilized period[1] preceding the monthly neutron flux core mapping, specific data are collected to compute two indicators characterizing WKH 6*V¶ EORFNDJH DQG IRXOLQJ VWDWH

2.1 Indicator for TSP blockage state: the Wide-Range Levels

Even though WRL sensors have not been designed to measure blockage state, applying %HUQRXOOL¶V HTXDWLRQ to differential pressure between steam drum and the lower WRL pressure tap shows that the higher the blockage the higher the WRL:

- blockage increases the flow resistance through the TSPs
- the total flowrate (Q_{FW}+Q_R) through tube bundle decreases
- since the feed-water flowrate (Q_{FW}) remains constant (equal to the steam flowrate Q_S), the recirculation flowrate (Q_R) decreases
- the pressure drop within the downcomer (where Q_R flows) decreases
- pressure at the bottom of downcomer (point F) increases
- WRL measurement increases (although the actual SG water level always remains the same, thanks to regulation)

[1] Blockage state can also be assessed thanks to the analysis of SG dynamic behavior during power transients. See section 4.

Figure 2: recirculating and WRL measurement within the SG

2.2 Indicator for tube fouling state: the SG drum pressure

As explained in section 1.2.2.1, the effect of tube fouling on SG performance is more direct: tube fouling increases the thermal resistance of the tubes and hence the pressure of the steam delivered by the SG is lower.

So the higher the tube fouling, the lower the pressure within the SG steam drum.

But to take into account differences in the thermal-hydraulic state point between measurement periods, a correction LV DSSOLHG WR WKH steam drum pressure 3UDZ value[2]:

where :

- T_{HL} = primary-side hot-leg temperature
- T_{CL} = primary-side cold-leg temperature
- T_{FW} = secondary-side feed-water temperature
- Q_{FW} = secondary-side feed-water flow-rate
- Q_{BD} = secondary-side blow-down flow-rate

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[2] :5/ YDOXH GRHVQ¶W QHHG to be corrected, since WRL GRHVQ¶W YDU\ around the nominal state-point.

- a, b, c ,d, e = linear correction factors to nominal reference state-point (provided by the SG manufacturer)

Data used to compute the corrected steam drum pressure have to be collected with much more precise sensors than the standard ones used for plant operation (especially for the primary-side temperatures which have the strongest effect on the corrected pressure). Most of them are actually already to be collected for the monthly periodic test (called “BIL”) to fix primary nominal thermal power and readjust the power control and reactor protection.

In addition to the WRL and the corrected steam drum pressure, other complementary data are also collected to help further analysis:

- steam turbine inlet control valve position
- SG tube plugging rate[3]
- mass of suspended and dissolved iron and copper species (accumulated since last measurement and since beginning of cycle)

2.3 Monitoring thresholds

WRL, corrected pressure (along with complementary data) are collected at least quarterly for each plant and are compared to three threshold values, each of them associated with specific actions :

- Crossing threshold 1 leads to a strengthening of the monitoring. Data are collected monthly, instead of quarterly in a standard situation.
- Crossing threshold 2 leads to considering an adaptation of the SG maintenance program. A camera inspection can be planned or anticipated to confirm the actual cleanness state of the SG and later a chemical cleaning, if necessary.
- Threshold 3 corresponds to the limits of the safety studies (with extra margin). It can not be crossed without complementary justifications or compensating actions (power limitation for instance).

This four-class segmentation is based on INPO Advanced Process n°9-13 concepts.

These thresholds have been designed so as to have at least 3 years between the crossing of two thresholds (with the standard evolution rates observed on our fleet for WRL and steam pressures).

[3] Although tube plugging has a direct effect on SG pressure, pressure correction does not include tube plugging rate because the corrected pressure value is compared to limits that correspond to the combination of both tube plugging and fouling (see section 2.3 for the principles of this comparison to limits).

3. ANALYSIS AND SHARING OF THE MONITORING DATA

3.1 First level analysis

All the data mentioned above are collected by the NPP test sections (with some help from the chemists and the automation sections for some measurements). A normalized tool (Excel spreadsheet) has E H H Q V X S S O L H G W R (')¶V 1 3 3 V, which automatically computes the blockage and fouling indicators and compares them to the monitoring thresholds:

Figure 3: example of the output of the monitoring tool

The NPP local teams are responsible for the first-level analysis of the records, that basically consists in making sure that the proper actions are undertaken (see section 2.3) when a threshold is crossed. These analyses are shared, discussed and validated with the corporate-level engineering department and historicized in specific paperwork.

Moreover, at the end of each cycle, the NPP local teams write a report reviewing all the records of the cycle, trying to explain odd behaviors and to identify the lessons that can be learned from these results. Such a report supposes a cross contribution from several specialties (test section, chemists, automation, engineering).

3.2 Data base and second-level analysis

Collecting data, computing and analyzing indicators at plant level is a way to involve local teams in the monitoring strategy and thus to improve data quality. But in order to make the most of fleet effect and to allow corporate-level departments (R&D, Basic Design, National Engineering, etc.) to share expertise and to build the global picture essential for the planning of maintenance operations, all monitoring data are historicized in one single corporate-level database.

All this information is used by the National Engineering Departement to carry out second-level analyses:

- Support to local teams in case of odd behaviors of the indicators (search for correlation with operating events: power transients, trouble with the SG blow-down system, change in plant chemistry, etc.)
- Global view of the fleet (at least twice a year) :

Figure 4: example of fleet global view

This kind of chart is used as a communication tool toward the Safety Authority.

- Global statistics for the fleet: although the global monitoring strategy has been implemented since mid 2009, data-historian are available to rebuild histories of blockage and fouling indicators for all the units of the fleet over a couple of decades. It enables to compute long-term trends, like for instance the average pressure loss trend for EDF SGs affected by tube fouling: 100 mbar/year (150 mbar/year for the most affected, 50 mbar/year for the least affected)
- Assessment of the efficiency of Chemical Cleanings

Figure 5: example of the effect of a Chemical Cleaning on WRLs

4. CONCLUSION, LIMITS AND PROSPECTS

The in-operation monitoring of WRLs and SG pressures has been successfully part of the global strategy to plan mainteQDQFH SURJUDP RQ (')¶V 1300 MW fleet since mid-2009. Waiting for future IHHGEDFN (')¶V 1XFOHDU 2SHUDWLRQ 'LYLVLRQ LV DOVR Y exchange with other companies, authorities, institutes and agencies that would like to use, refine RU UHGHYHORS VXFK DQ ³RQOLQH´ PRQLWRULQJ VWUDWHJ\

The information gathered by the first years of monitoring has notably raised some issues that are currently under investigation:

- Some issues regarding WRL measurement reliability (drop after outage, possibly due to invasive maintenance actions on WRL sensors)

Figure 6: example of WRL drop

- Chemical cleanings have had a positive effect on the pressures of one specific type of SGs (average pressure rise of 1,5 bars) but no visible effect on the pressures of other types of SGs (although televisual inspections performed for these tube bundle after chemical cleaning showed that tube fouling was correctly removed). Note also that those cleanings have had a positive effect on the TSP blockage level of all the SGs. One major design difference between these two types of SGs regards the primary moisture separators (3 « big » separators for the first type, 16 or 18 « smaller » separators for the other types).
- Some units experience non-monotonic evolutions of SG pressure, notably after chemical cleaning and plant trip.

Figure 6: example of non-monotonic evolutions of SG pressure

Recent R&D work dealing with magnetite deposit modeling (see reference [4]) could help understand such evolutions.

More generally, EDF is currently working for a better comprehension of those phenomena and would be happy to share more information in those fields.

%HVLGHV QH[W GHYHORSPHQWV IRU ('))¶V 6* in operation monitoring strategy are:

- Define the monitoring thresholds mentioned in section 2.3 for the newest SG models LQVWDOOHG RQ ('))¶V SRZHU SODQWV DQG SRVVLEO\ UH account evolutions in safety studies or new information on blockage and fouling phenomena.
- Implement a new monitoring method developed by EDF R&D based on the analysis of 6*¶V G\QDPLF :5/ UHVSRQVH during a standard power transient (see references [1] and [3]). This method derives from the observation that WRL response during a specific standard power WUDQVLHQW SHUIRUPHG HYHU\ PRQWKV WR V DIIHFWHG E\ WKH 6*¶V EORFNDJH VWDWH

Figure 7: effect of TSP blockage on SG WRL dynamic response

A model has been developed to compute, for various TSP blockage ratios, the theoretical WRL response to the power transient. Comparing the actual response of a SG to the theoretical responses enables to assess its blockage ratio.

This new method has the advantages of being fully non-invasive, being free from WRL sensors' calibration on sensibility and increasing accuracy.

5. REFERENCES

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