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Steam Generator Internals Design Review Part I: Bundle Wrapper Studies / Status and Perspective

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ABSTRACT

EDF, in association with the designer and manufacturer Framatome, has performed a design review of the structural internal parts of PWR steam generators (SG). This review allowed an examination and analysis of available design, fabrication and operating transient data. French and international experience was examined. In particular, degradations of the bundle wrappers observed in 1994 in the Blayais nuclear power plant SG (wrapper drop, cracking in the wrapper around the blocks) led to: an inspection program (televisual examinations and measurements) of the wrapper supporting devices in French SGs, as well as analysis of the operating transients previously experienced by the SGs, followed by specific studies and test programs, aimed at improving understanding of the potential risks and planning ahead for remedies, and defining a maintenance strategy and policy for SGs in service.

1. INTRODUCTION

1.1. Background

In 1994, during the 10-year inspection of Blayais unit 3, a drop of the tube bundle wrapper on steam generator No.1 (SG1) prevented access via the handholes of tube sheet lancing tools. It was revealed that the bundle wrapper had dropped by 20 mm. On SG2, the same phenomenon had occurred, but to a lesser degree, involving a drop of approximately 5 mm.

In 1995, during the following outage, televisual examinations and measurements of all 6 wrapper support systems (support blocks, wrapper restraint keys, hold-down blocks: see Figure 1) were performed, revealing pronounced degradation of the support blocks and, in particular, cracking in the bundle wrappers of Blayais 3 SG1 and SG2 (see Figure 2).

From 1995 to 1998 televisual examinations and measurements of all wrapper support systems were performed on all french SG.

These examinations revealed limited degradations for 3 more Sgs. Nevertheless, it was taken into account that these degradations could affect all SGs, regardless of the model or the time duration during which it has been in operation.

1.2. Studies undertaken to understand and master the phenomenon

Immediately after the initial observation of these degradations in 1994 at Blayais 3, EDF and the designer and manufacturer Framatome launched a major work program. These wide-reaching actions were aimed at understanding the phenomena, determining whether it was a generic problem, analyzing its impact in terms of safety, designing and developing both preventive and remedial monitoring and repair tools, and defining a monitoring and maintenance program that could be implemented for SG wrapper support devices at EDF nuclear power plants.

Integrating other degradations of SG internals observed and mastered, such as the tube support plates (Cf. paper D 04/1 SMIRT 14 LYON August 1997) , a design review of the structural internal parts of SG's already in service or due to enter service in France was conducted. To date, all of these studies and actions have had positive outcomes:

- The main results of these studies regarding the identification of the root causes and consequences of bundle wrapper degradation, together with the nationwide actions implemented, are detailed in §3.
- An analysis of the safety consequences of a drop of the bundle wrapper from its nominal position to the secondary side of the tube sheet is presented in the second part of this paper (Ref. [1]: paper D4-A3-FR).
- A conservative multi-year monitoring strategy and preventive maintenance policy was defined. This program has been implemented since 1998, and its approach and methodology are detailed in §4.

The detailed report of this experience feedback of the televisual examinations and measurements conducted since 1995 and the maintenance follow-up of EDF SGs are presented in §2.

The third part of this paper (Ref. [2]: paper D4-A2-FR) presents the systematic and specific monitoring and maintenance tools, together with the specific repair resources developed to implement this monitoring and maintenance policy.

In addition, within the scope of research and development efforts, different SGs have been instrumented to monitor the movements of the bundle wrapper in order to confirm the loadings resulting from theoretical calculations and to gain a better understanding of the degradation kinetics. These resources are covered in the third section (Ref. [2]).

2. MAIN OPERATING EXPERIENCE FEEDBACK

2.1. Objectives of inspections and test programs carried out since 1994

The inspection strategy consisted in:

- knowing initial state of the different supports and the position of the bundle wrapper at a given time (zero point, as reference);
- a follow-up by long-term monitoring in order to detect any changes.

Two types of inspections were performed:

- altimetric controls to determine the position of the bottom of the wrapper.
- televisual inspections and measurements to determine the support condition, and the state of the support block and hold-down block welds.

The inspection program was implemented at all concerned or potentially concerned SGs, to determine the «zero point», involving 150 SGs. This program was conducted between 1995 and 1996.

Most of the SGs inspected as part of the zero point program underwent additional altimetric inspections in 1997. SGs with observed or suspected degradations following the zero point inspection were also subject to additional televisual inspections in 1997.

As of 1998 and the launch of the monitoring strategy and maintenance policy, only SGs that met certain criteria defined by the studies (see §3) underwent televisual inspections and measurements. This resulted in the inspection of 30 SGs.

2.2. Results of the inspections at end 1998

Following the zero-point inspections, three 900 MW SGs met the support block damage and/or bundle wrapper drop criteria. These were Blayais 2 SG1 (with no wrapper drop) and Blayais 3 SG1 and SG2 (with limited wrapper drop): see Figures 1 and 2. Two wrapper additional support devices were installed on these SGs in 1995 (SG1) and 1996 (SG2), respectively.

All the inspections from 1994 to 1998 for the 5 SGs with degradation have shown no evolution or very slow evolution of the degradation. The characterisation of the cracks on the affected support block were made using a specific tool, also allowing ultrasonic measurement of the crack (OCMF tool, Cf. Part 3 : Ref. [2]).

Although there was practically no risk of a loose part to be created, a clamp (Cf description : Ref [2]) was fitted on the support blocks to immobilize it.

3. MAIN OBJECTIVES OF THE DESIGN REVIEW: STUDY RESULTS, ROOT CAUSES AND DEGRADATION SCENARIOS :

The extensive program conducted from 1995 to 1998 comprised three main phases:

3.1. Definition Of The Reference Base: Design, Fabrication And Safety

In order that the design review is exhaustive, operating experience in foreign plants was taken into account.

A status of SG design and fabrication has been determined starting from the original license. As far as the wrapper and supporting system is concerned, evolution status did not permit the identification of degradation root causes with led to our decision to initiate detailed studies.

Internals components, degradations of wich could affect safety functions of the steam generator, were looked for. Processes by which such degradations could occur were analysed and sensitive zones concerned were identified. Lastly, an analysis of the real or potential harmfulness of the degradations was performed.

These safety studies taking into account sudden or gradual wrapper drop produced positive results. These points are analyzed in detail in the second part of this paper (Cf.: Ref [1]).

3.2. Identification of degradation root causes and scenario

The analysis of real or potential degradation modes, their root causes, the resulting plausible degradation scenarios and their impact on the life-cycle of the equipment concerned were extensively examined through:

- A precise determination of the condition of each support block weld seam on each EDF SG in service by means of zero point televisual examinations, carried out as of 1995 (Cf. §2);

- Analysis of data generated by instrumentation installed on the Blayais SGs between 1994 and 1996, allowing study of the wrapper deplacement and of the vibration behavior as well as the evaluation of the risks of cracking around the support blocks of all SG models;

- A nationwide survey of transients experienced since the outset in order to determine the loadings induced on the supports of each EDF SG.

Vibration analysis of all SG models

The analysis of the signals transmitted by the axial and radial instruments on one of the Blayais SGs made it possible to monitor the movements of the wrapper during several complete operating cycles. This revealed vibration phenomena at the bottom of the bundle wrapper that is very likely related to the vortex shedding of the feedwater downstream the support blocks.

An evaluation of the vibration facing bundle wrappers on each type of SG was conducted on the basis of the excitation rate and the modal analysis of each type of wrapper.

Endurance testing on a mock-up of a bundle wrapper support device and risk analysis of vibration fatigue cracking of all wrapper types for each SG model

Tests were carried out by EDF's Laboratories Department (GDL), using either blocks from a removed SG, or mock-ups of wrapper support systems (bundle wrapper, support block and hold-down blocks – see Figure 3). The aim was to determine the conditions which result in vibration fatigue cracking and propagation and to identify the degradation time sequence and type.

These tests allowed evaluation of the endurance limit of the support block weld seams and comparison of the test amplitude with the amplitude measured on site using instruments. In addition, destructive testing of the mock-ups made it possible to define the support block degradation time sequence and scenarios.

In light of these results, together with those from the vibration analysis of each SG model, a study of the risk of vibration fatigue cracking was conducted on a comparative basis by numerical analysis (SYSTUS modeling). The results made it possible to rank SG types in order of risk and, more significantly, to distinguish two groups of SG:

- SG those with low vibration stress in the support block weld seams, and zero or residual cracking risk;
- SG those with high vibration stress in the support block weld seams, for which the potential risk of cracking could not be excluded.

Experience feedback corroborates this ranking, since the only SGs affected belong to the second group. However, vibration instrumentation has been installed on different SG models in order to confirm this point.

Analysis and identification of stress – nationwide survey of transients

The analysis of experience feedback and the readings from instrumentation devices fitted on the Blayais SGs revealed significant axial movement of the bundle wrapper associated with certain operating situations, which were subsequently identified as being liable to cause notable stress on the SG bundle wrapper support blocks.

In particular, these analyses confirmed both the phenomenon of differential expansion that is inhibited during the Auxiliary Feedwater Supply (AFS) cooling transients, and the consistency between shift amplitudes applied on the support blocks and the theoretical amplitudes defined during the initial studies performed in 1994 to explain the first degradations on Blayais 3 SG1 and SG2.

Thanks to transients analysis including associated shift measurements and taking into account of supporting device stiffness, an estimation of loading induced on the blocks has been performed. A list of the most penalizing transients has thus been obtained. These aspects were traced and identified in the past history of SG's showing support block degradations. They led to the definition of specifications for a nationwide survey in order to identify which SG of the whole French Fleet has known such loading.

With regard to the root causes and degradation scenarios of the support block weld seams, followed by the drop of the steam generator bundle wrapper, the following conclusions may be drawn:

The design review studies revealed that the cause of the problem was a vibration condition at the bottom of the wrapper and a plastic deformation of support blocks due to some operating transients that induce additional loadings on blocks by thermal expansion.

3.3. Identification of Preventive and Corrective Actions

In light of the above factors, the following measures to combat both real and potential degradations were implemented :

- Justifying to keep in place the support blocks or to perform a repair if a criterion is met. This specific criterion, depending on support block rupture margin, was defined for each SG following the televisual examinations and measurements of EDF SGs performed in 1995 and 1996 (Cf.§2).

- Identifying and monitoring precursor degradation phenomena for each SG (marking of support block edges, witness of a vibration state, which is also determined and monitored by systematic televisual inspections of certain SGs since 1995 – Cf. §2 and §3.1.), together with operating transients experienced by the SG and resulting in additional loadings on the support block weld seams, determined for each EDF SG on the basis of the nationwide survey (Cf. §3.1.).

- Limiting certain operating situations found to induce progressive plastic deformation of the support blocks (Cf. §3.2).

- Defining a bundle wrapper monitoring and maintenance policy for SGs to coordinate the implementation of preventive modifications and repairs if necessary (Cf. §4).

4. PREVENTIVE MAINTENANCE POLICY TO COUNTER SG BUNDLE WRAPPER DEGRADATIONS

4.1. General

The maintenance policy was defined with a particularly conservative approach in order to take into account the different plausible degradation scenarios described in §3. This uses:

- Criteria to survey vibration phenomena (marking on edges of the blocks) and blocks plastic deformation (experienced transients), and the exact determination of a risk factor assessed for each SG (support block rupture margin).
- Specific monitoring tools and maintenance tools which were developed specifically for this purpose. These resources are described in detail in the third section of this paper (Ref. [2]).

4.2. The Approach Selected

For each SG involved, it is necessary to regularly check the position of the bundle wrapper in relation to the zero-point and/or to check the condition of its support blocks.

The altimetric change in position of the bundle wrapper and/or the degree of degradation of the support blocks determine whether monitoring tools and repairs should be implemented.

Should the number of non-degraded support blocks become insufficient to support the weight of the bundle wrapper for the SG type in question under all circumstances and to ensure the hold-down function, additional wrapper support devices must be fitted to the upper shell of the SG (Cf. Ref. [2]).

This measure is taken to avoid the risk of a gradual or sudden drop of the bundle wrapper. It should be emphasized that this is essentially an economic risk, since this phenomenon does not jeopardize plant safety (Cf. Ref. [1]), but would necessitate replacement of the SG.

If wrapper cracking appears in the corners of the bonds between the support block and the bundle wrapper, or if tearing is observed on the block weld seams, a clamp must be fitted to provide additional mechanical support for the support block. Furthermore, depending on the nature of the crack, and in light of experience feedback on crack development, it may be necessary to halt its propagation (by perforating the crack tip). These measures are taken to prevent the separation of a support block and/or a piece of wrapper sheet metal, which would result in a loose part and an opening in the wrapper, with possible harmful consequences for the tube bundle.

Three families of SG have been defined according to their susceptibility to vibration fatigue cracking and/or to gradual deformation of their bundle wrapper support blocks. The criteria for defining these families, which are based on cross-referenced experience feedback, the physical features of each SG, and the condition of their support blocks, are defined in §3.3 and reiterated below:

- the «marking» of a support block, corresponding to a potential vibration phenomenon;
- the specific criterion defined for each SG, allowing for a wrapper drop margin,
- the experience of the SG in terms of loads that could result in plastic deformation of the

support block weld seams, based on the nationwide survey of transients.

SGs belonging to the first family are subject to systematic inspections during each refueling outage, regardless of the SG model or operating hours. The monitoring and maintenance procedures during refueling outages and the application frequencies differ according to the SG family concerned. The SG classification in families is called into question at the occasion of each outage.

5. GENERAL ORIENTATIONS AND CONCLUSIONS REGARDING THE INTERNALS DESIGN REVIEW AND BUNDLE WRAPPER DEGRADATION

The safety issues and root causes of support device degradations on SG bundle wrappers were evaluated through several different studies conducted within the scope of the SG internals design review.

These challenges are today under control, and the operation of equipment that is potentially concerned does not jeopardize plant safety and availability, thanks to the measures implemented, in particular the specific monitoring strategy and preventive maintenance policy detailed above.

Within the scope of R&D efforts, different SG models have been instrumented to monitor the movements of the bundle wrapper to get a better understanding of the degradation kinetics. In addition, tests using mock-ups are under way to determine more precisely the role played by vibration and plastic deformation phenomena. Depending on the results of this research, the present monitoring program will either be strengthened or reduced.

Furthermore, from the extensive experience and expertise acquired through these actions, FRAMATOME and EDF have been able to review the design and fabrication of replacement SGs. Thanks to the improvements of the in-service inspectability and fabrication which were so introduced, longer life duration of these steam generators is expected with great confidence.

REFERENCES:

[1] Poudroux, G., Bouamoud, K., Gauchet, J.P., Petit M. and Munoz, F., «SG design internals review, part 2 'Wrapper drop safety studies'», D4-A4-FR, *SMIRT 15,* Seoul, Korea, 1999.

[2] Munoz, F; Gauchet, J.P., Stindel, M., Dabere, C. and Pradel, A., «SG design internals review, part 3 'Corrective and preventive maintenance and in-service surveillance of wrapper', D4-A2-FR, *SMIRT 15,* Seoul, Korea, 1999.

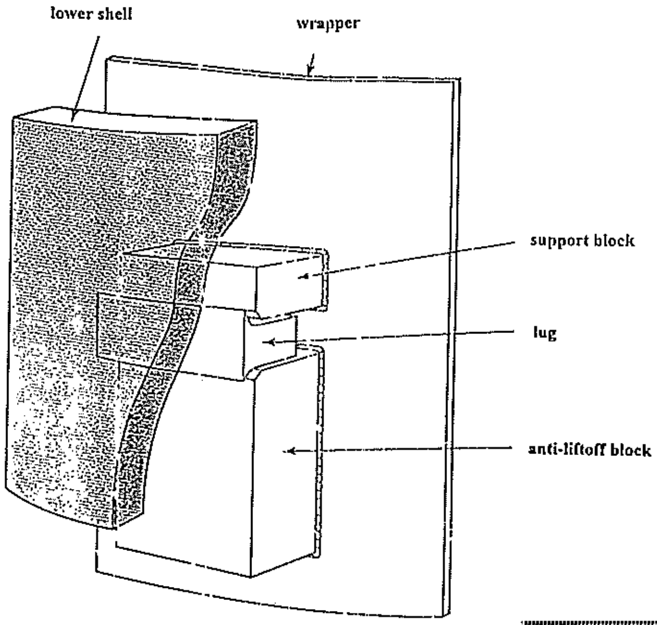

Fig. 1 : detailled view of support system for tube bundle wrapper

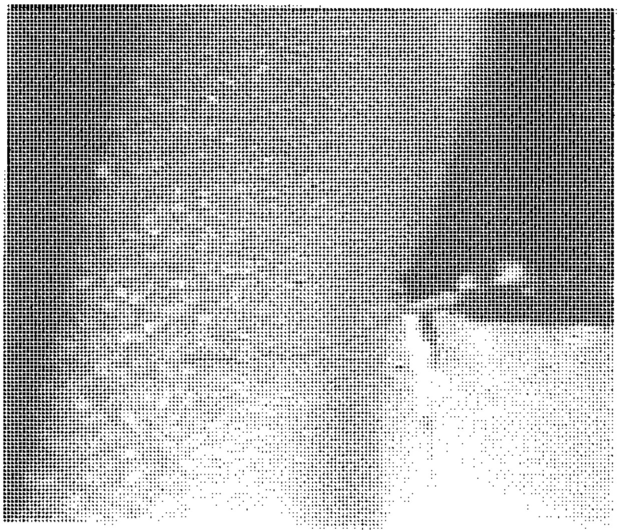

Fig. 2 : illus:ration of cracking in the tube bundle wrapper of Blayais 3 SG 2

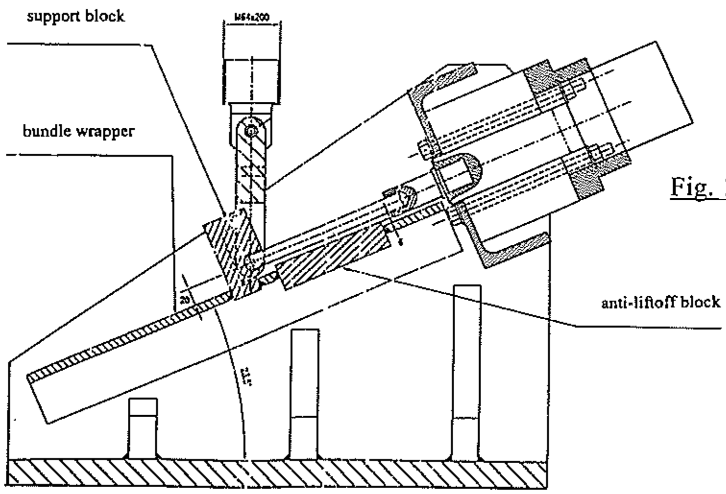

Fig. 3 : endurance testing on a mock-up of wrapper support system