Fast-track development of a TOFD inspection procedure for forged Steam Generator channel heads

Y. Forestier¹, C. Herault¹, P. Brun², L. De Roumilly¹, E. Martin¹

¹: EDF-CEIDRE, 2 rue Ampère, 93206 Saint-Denis Cedex, France
²: Framatome – 4, rue Thomas Dumorey, 71109 Chalon sur Saône Cedex, France

Abstract
This paper presents the work performed in order to develop, validate and apply a TOFD (Time of Flight Diffraction) inspection procedure on-site, all of these steps were completed in a few weeks’ time.

This inspection was a consequence of the discovery of a carbon macro-segregation issue in steam generator channel heads (SG primary side) that could potentially have affected the mechanical properties of the material for SGs in several Nuclear Power Plants (NPP). The SGs are thick carbon steel spherically forged components, for which no in-service inspection had ever been performed. The inspection aimed at detecting postulated planar defects in the outer half of the channel heads.

The project deadline was that the first Pressurised Water Reactors (PWR) were scheduled for outage 1 month later. Therefore, an innovative approach was chosen and several actions were performed in parallel in order to reduce the development duration, most of these actions involved a joint EDF-Framatome team:

- A wide selection of probes, probe holders and scanning equipment were tested;
- The capacity of this equipment was assessed on full-size mockups;
- Testblocks containing narrow electrical discharge machined (EDM) notches were manufactured;
- Computations with the CIVA UT software were also used to complement the experimental data.
- Finally, the inspection procedure was finalized and personnel training was carried out.

This also included customization of existing scanning equipment, in order to be adapted to the geometry of the real component and to deal with some obstacles welded onto the scanning surface.

The first inspection and all the subsequent ones were performed successfully, requiring only minor adjustments to the procedure along the way. None of the inspected steam generators were found to contain the targeted defects.
1. Foreword:

This study starts with the discovery of a carbon macro-segregation issue in a number of steam generator channel heads, installed in some of EDF’s nuclear power units. The SGs are large ferritic low-alloyed steel components, with a general spherical shape, thicknesses generally between 140 and 220 mm, and clad internally with austenitic stainless steel. Some areas of the steam generators, as a result of the manufacturing process (forging), end up with a higher than average carbon content; i.e. positive macro-segregation.

An extensive series of measurements were performed to measure the carbon content on-site, for which the measurement method was qualified. Then it was possible to assess the updated mechanical properties of the components, which could be used as input data for fracture analysis, during both normal plant operating conditions and worst-case transient situations.

This in turn could reduce the acceptable postulated defect size, in relation with a lower resistance to crack propagation (fracture toughness).

For each channel head, the area of concern was the central part of the forging, (see Fig.1), between the outer surface and the middle of the thickness. This area is normally not inspected in-service and is not optimally designed to allow for good inspectability. The targeted defect size was an elliptical planar defect, radial in orientation, embedded, and perpendicular to the external surface.

![Figure 1. Inspection area (bottom view of a steam generator channel head)](image)

2. Selecting a suitable NDT technique:

As the need to perform a large series of inspections arose, very little time was available to perform the whole inspection and equipment design, as well as the associated technical justifications. So a joint EDF-Framatome team worked in a day-by-day taskforce mode, in order to reduce to a strict minimum any project delay. In EDF power plants, no similar inspections had ever been performed, especially on such a large scale.
At a first glance, a simple compressive wave 0° beam may have seemed like an attractive NDT option, as it is a very simple UT technique to implement and analyze. However, it has some major drawbacks, such as a potentially low signal/noise ratio, as well as limited sizing capacity for defects perpendicular to the scanning surface.

Thus, Time of Flight Diffraction (TOFD) technique was very quickly agreed by the project team as being the most adequate NDT technique for its better detection and sizing capacities, and also the ease of recording TOFD data for subsequent analysis. Other key factors contributing to this choice were the material (low-alloyed ferritic steel with limited structural noise), the simple geometry (essentially a large radius hemi-spherical pressure vessel) and the existence of several experienced TOFD equipment manufacturers.

3. Project dual approach:

In order to deal with the lack of project time: using off-the-shelf devices was the preferred option for any of the following aspects:

- NDT equipment;
- UT testblocks (performance assessment and calibration blocks);
- Manipulators;
- Full-size mockups;
- Training facilities.

In parallel of this, custom-made inspection solutions were also progressively procured or manufactured for each of the former aspects, in order to optimise the final inspection procedure:

- Fourteen TOFD probe couples were assessed on the same testblocks in order to find the best compromise in terms of sensitivity, coverage in depth, signal-to-noise ratio and procurement time. Several frequencies and crystal sizes were compared, and in the end, two couples of probes were selected. The final Probe Center Separations (PCS) and beam angles were selected in order to cover the whole inspection thickness: two complementary pairs of compressive wave beams (PCS80/CW 60° and PCS180/CW 45°). This choice was verified by a combination of measurements on testblocks as well as CIVA UT software computations.

- The UT generator was a Zetec © Topaz, combined to a manipulator also provided by Zetec. The latter initially contained parts obtained by 3D-printing in polymer material for maximum reactivity (the first equipment evaluations were performed within a couple of weeks after the project started). The critical manipulator parts were, however, subsequently changed to machined aluminium (which has higher mechanical resistance), in order to anticipate possible wear generated by repeated inspections on the field.

- Full-size SG mock-ups were available in two facilities, including a 1450 MWe unclad SG channel head at EDF Lab - Les Renardières and a thin 900 MWe SG template at the CETIC in Châlon sur Saône (joint AREVA-EDF training facility).
These two mock-ups were used in order:

- To assess the robustness and ease of use of all scanning equipment and probe holders;
- To suitably train and qualify the personnel that would subsequently perform the in-service inspections (ISI).

4. **Inspection performance assessment:**

The performance assessment (detection, signal/noise ratio, coverage and sizing) was done using a combination of experimental data and numerical NDT simulation (using the CIVA UT software).

A series of specific testblocks containing wire-machined planar defects were procured. The main hurdle to overcome was obtaining TOFD responses to defects with semi-elliptical defect edges, representative of the targeted defect. These required more advanced manufacturing techniques, so the first testblocks to be machined contained only rectangular-shaped notches (see Fig. 2).

**Figure 2. Experimental B-Scan of a testblock containing several rectangular notches**

The straight-to-elliptical-edge gain transfer was then assessed separately, using CIVA UT computations (see Fig. 3).
Figure 3. CIVA UT computation of the response for an embedded elliptical defect

A compressive-to-shear mode conversion signal can be seen below the primary diffraction arc.

However, in a second project phase, testblocks containing notches with a semi-elliptical diffracting edge were also procured, in order to confirm the computed results.

5. Writing an inspection procedure:

As for all inspections in operating NPP, it was of paramount importance that the inspection duration (during which personnel is exposed to radiation) be controlled, so the scanning and increment steps needed to be optimized. These settings were adjusted based on CIVA UT computations, which allowed to determine the TOFD procedure’s sensitivity at any depth and to ensure that the diffraction arcs produced by the targeted defect would be easy to detect and measure.

The gain transfer between planar notches and side-drilled holes (SDH) was assessed during the procedure trials so that standard forged calibration blocks containing SDH, and already used extensively on the field, may also be used for the SG channel head inspections. This also allowed to perform several inspections on different power plants in parallel, without the need to duplicate complex testblocks.

The targeted defect was identified using flowchart-based decision, with a focus on the presence of two superimposed diffraction arcs with a significant measured length, and phase opposition between the two diffraction signals.

The primary scanning pattern was made up of successive circumferential scans with wheel encoding, from the centre of the component towards the larger diameters. For recordable TOFD indications, additional circumferential scans at intermediate positions and/or radial scans were to be performed in order to confirm the possible presence of a planar defect, and estimate its length and height. As the scanning was performed manually by an operator, the prototype manipulator was modified to improve its robustness and the ease of all scanning movements.

The procedure was released by a level 3 TOFD expert and validated by an EDF expert board a few days before the beginning of the first inspection.
6. **Personnel training:**  
The TOFD analysis was performed by TOFD level 2 certified personnel (according to ISO 9712) from several service-providing companies; level 3 certified experts were also present off-site to validate non-conformance records as well as the final inspection reports.  
Series of two-day training sessions were organized at the CETIC facility. The training programme included a presentation of the TOFD equipment and scanner, presentation of the component and inspection environment and practical training to the key points of the inspection procedure including inspection records.  
Noteworthy is the fact that the bottom of the steam generator is located only 1-1.5 m above the ground (see Fig.4). Combined with the radiation and temperature issues, the training thus needed to focus on being able to perform the procedure steps sequentially and as efficiently as possible.

![Image](image_url)

*Figure 4. Prototype (training) TOFD manipulator on a full-size mockup*

7. **In-Service Inspection results:**  
The first ISI was carried out in June 2016 during a programmed reactor outage, less than six weeks after the project had started. Subsequent reactors were then inspected between June 2016 and April 2017. The typical inspection duration was 1-2 days for the acquisition and 1 additional day for analysis on each steam generator.  
After the first successful inspection, more duplicate TOFD equipment and manipulators were procured, and in addition several inspection teams were trained. This allowed for up to 3 inspections in parallel in different power stations. This was an important factor for EDF, as the NDT results were sometimes the last step of the technical justifications required to allow the restart of the reactors.
The operational feedback from the first inspections was used to further improve the inspection procedure; in particular a decision flowchart was added to the inspection procedure in order to facilitate the recording and analysis process on-site.

No TOFD indication corresponding to the targeted defect (i.e. dual diffraction arcs with associated phase inversion) was found in any of the SG end covers. Thus, no need for follow-up inspections is foreseen.

**Conclusions:**

The joint EDF-Framatome task-force succeeded in going through all the various project steps (inspection specification, NDT equipment procurement, TOFD inspection procedure, and personnel training) in less than a month. This was also made possible thanks to the active cooperation of a panel of subcontractors and equipment manufacturers.

The task-force development mode proved to be a crucial factor in the successful development and multi-site deployment. If is foreseen that this will be renewed for future projects, whenever project time is scarce and no off-the-shelf NDT solution is available.

As for the in-service inspections, although the inspection environment was challenging, in terms of access, geometrical constraints, temperature and radiation level, the inspection procedure was found to be easy-to-follow and only minor improvements were required along the way.

This one-shot inspection was performed on a large number of steam generators in France, sometimes in parallel in different power stations. No recordable indication, corresponding to the targeted defect, was found in any of the steam generators, and all reactors were thus allowed to proceed to the restart phase.

This was one of the first instance of large-scale deployment of a TOFD procedure on the EDF installed reactors.