Tube support plate clogging up of French PWR steam generators

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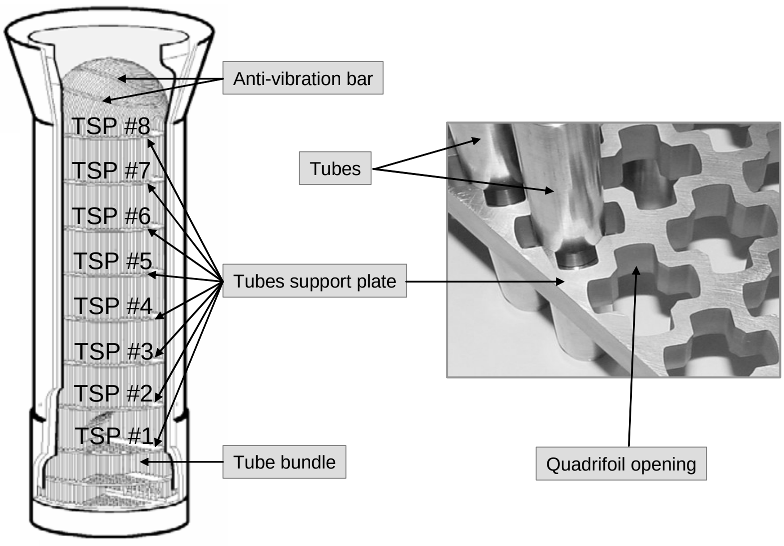
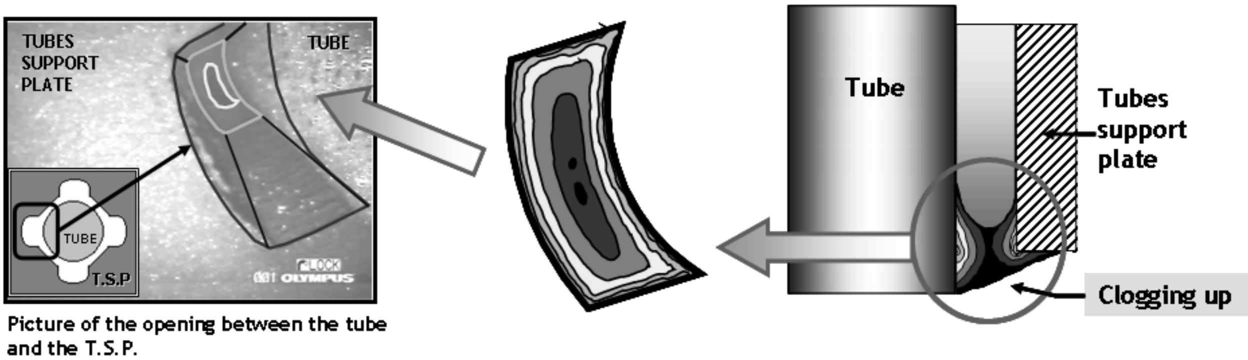
Abstract: Between 2004 and 2006, three primary-to-secondary leaks occurred at the Cruas NPP: unit 1 in February 2004 and unit 4 in November 2005 and February 2006. The three leaks were all the result of a circumferential crack in the tube at the location where the tube passes through the uppermost tube support plate (TSP #8).
In addition to crack causes, this paper describes the main results of the safety assessment carried out by IRSN, such as the increase in stresses on TSPs during transients, the risk of water level oscillations and the water mass reduction.

1 ANOMALIES OBSERVED

Continuous monitoring of primary-to-secondary leaks led to three shutdowns at the Cruas NPP: unit 1 in February 2004 and unit 4 in November 2005 and February 2006. Analyses carried out by EDF, further to the last two events, resulted in them being attributed to high cycle fatigue of steam generator tubes due to flow-induced vibration.
The results of in situ examination initiated by the Cruas NPP operator showed that the flow holes of the uppermost Tube Support Plates (TSPs) were partially or completely blocked by corrosion products. This phenomenon is referred to in this paper as TSP “clogging-up” and it was considered potentially generic for EDF NPP fleet. For the Cruas leakages, it was established that the association of TSP clogging-up and the specificity of the Cruas steam generator (central area in the tube bundle where no tubes are installed) were responsible for a significant increase in the velocity of the secondary fluid in the tube bundle central area. The high velocity of the fluid in this region increases the risk of fluidelastic instability for the tubes. Based on this preliminary analysis, EDF has implemented preventive measures (stabilizing and plugging of tubes in the central area of the tube bundle deemed sensitive to high cycle fatigue risk).



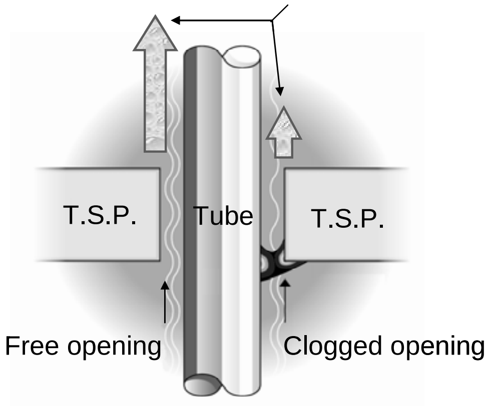
Pic. # 1: Location of the TSP and presentation of quadrifoil openings



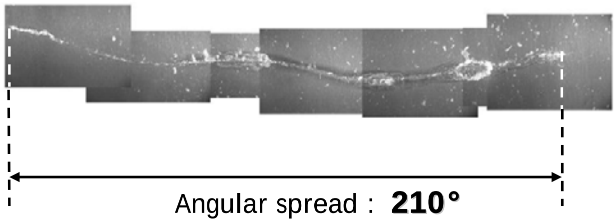
Pic. # 2: Representation of the clogged quadrifoil-shaped holes in the TSPs

2 UNDERSTANDING OF THE PHENOMENON

The phenomenon of cracking due to high cycle fatigue of U-bend tubes not supported by an Anti-Vibration Bar (AVB) was highlighted as early as 1987 (tube rupture in the NORTH ANNA 1 plant) and 1991 (MIHAMA). The tubes which leaked at Cruas were all located in raw 8 and were not supported by AVB by design. They were not considered sensitive to high cycle fatigue. A new fact caused the leakages observed on the Cruas units: the heavy build-up of deposits on the secondary side of the steam generator which changed the flow conditions in the center of the tube bundle. The deposits reduced or blocked water/steam flow through the quadrifoil-shaped holes in TSPs, forcing more water and steam into the center of the tube bundle, which caused the excessive vibration of the tubes near the center of the tube bundle. This excessive vibration due to fluid-elastic instability resulted in fatigue cracking of the tube.

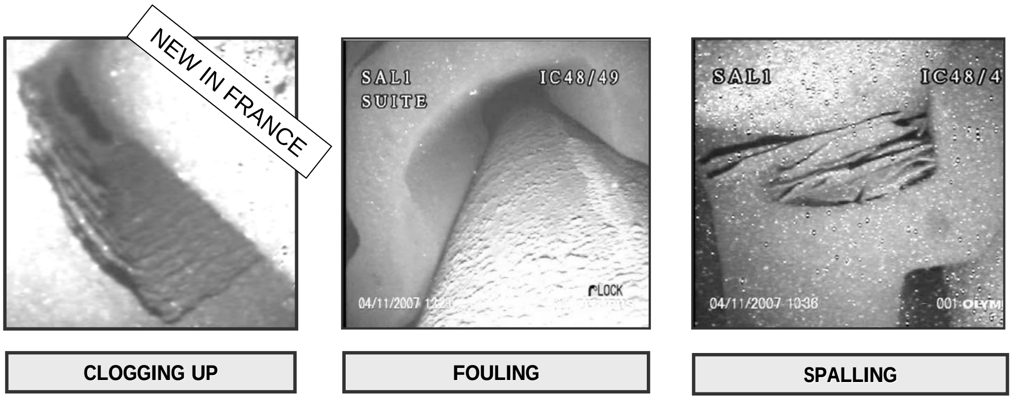


Pic. # 3: Representation of the water-steam flow through the quadrifoil holes



Pic. # 4: Crack of tube L008 C047 (Cruas NPP - Unit 4 - S.G. # 2)

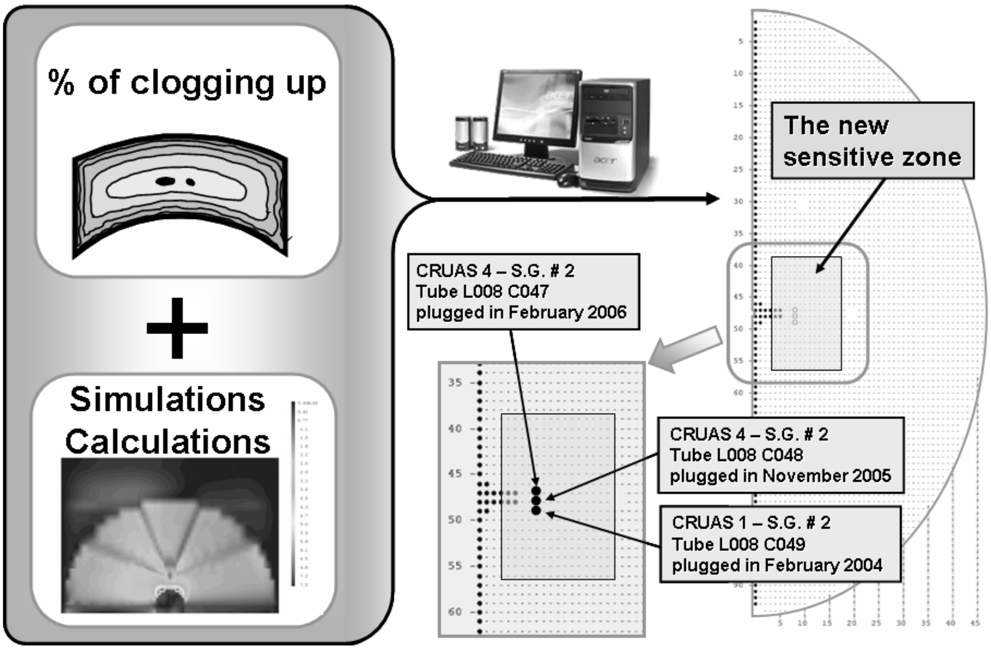
Deposits had already been observed in steam generators on numerous occasions both in France and abroad, for example deposits of metal oxides corresponding to corrosion products (sludge) on the tube sheet. Other deposits had been observed on the external surface of the tubes – called fouling – one of the consequences of which is decreased heat exchange performance in the steam generator. In the case described above, the deposits are located in the quadrifoil-shaped holes in TSPs – known as clogging. Foreign reactors have also experienced this type of deposit but maintenance programs implemented in France were not able to detect it.



Pic. # 5: Difference between clogging up, fouling and spalling

3 INITIAL MEASURES

A specificity of the steam generators on the Cruas units is that they have a tubeless area in the central part. This area thus constitutes an easy path for the secondary system water. Moreover, due to its thermal-hydraulic effects, TSP clogging further increases the flow rate in this area and thus the vibration amplitude of the tubes (small U-bends) not supported by AVB. It is in this area that the previously mentioned tube cracking was observed. EDF then decided to take preventive action by plugging and stabilizing 58 tubes surrounding this area so that their potential degradation would not cause any primary-to-secondary leaks harmful to safety. This plugging was carried out for all the steam generators with the same design as Cruas.

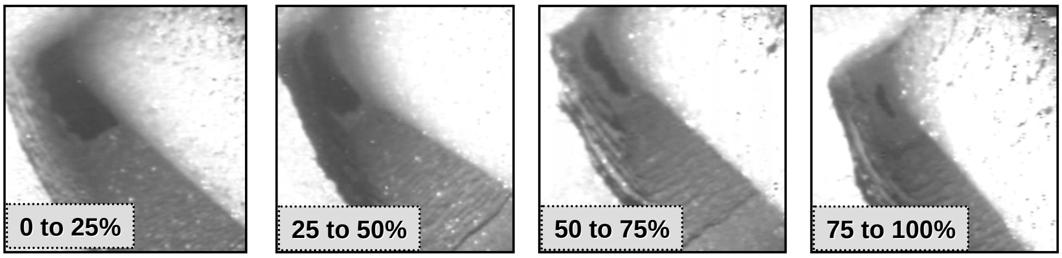


Pic. # 6: Preventive plugging of 58 tubes

At the same time, EDF strengthened the surveillance of tube bundle tightness with more restrictive specifications for continuous monitoring of primary-to-secondary leaks.

4 INVESTIGATIONS

The initial inspections carried out inside the steam generators on the Cruas units showed significant clogging of the highest TSPs: on average, the cross-section of the quadrifoil-shaped holes was reduced by about 70% and some of them were completely blocked up.



Pic. # 7: Different rates of clogging up observed by EDF

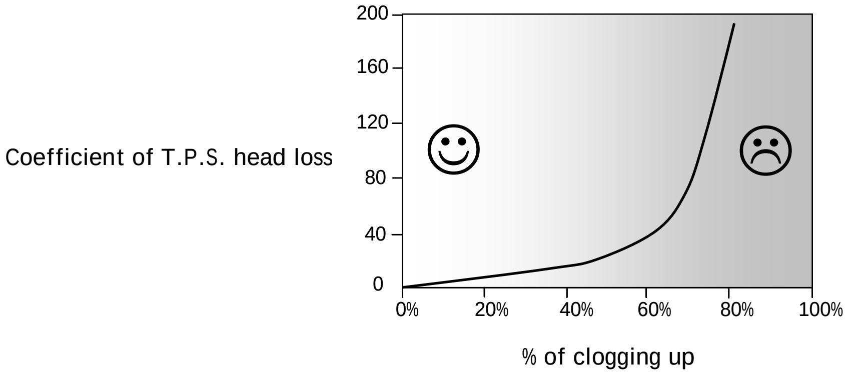
Based on these elements, EDF together with the vendor AREVA conducted numerical analyses simulating the thermal-hydraulic water flow in the secondary system through clogged TSPs so as to characterize the vibration behaviour of the tubes. These studies confirmed that in general terms the tubes with the highest coefficient versus fluid-elastic instability risk were those which experienced degradation, thus consolidating the understanding of the phenomenon and relevance of the initial measures taken (i.e. plugging a central area in the tube bundle).
EDF studied the effect of the chemical conditioning of the secondary system water especially regarding the pH on the deposit build-up on TSPs. The use for certain units of condensers containing copper alloys leads EDF to use a relatively low pH for the water (below 9.6). This results in more corrosion products in the feed train, thereby increasing the probability of TSP clogging-up.
Lastly as recommended by IRSN, EDF assessed the potential consequences of clogging on the management of incidental and accidental situations studied in the plant safety report.

5 EFFECTS ON PLANT SAFETY

In addition to the risk of steam generator tube rupture due to high cycle fatigue, which was the subject of the above-mentioned preventive measures (plugging of certain tubes and strengthened surveillance of primary-to-secondary leaks), clogging-up modifies both the mechanical stresses on the TSPs along with their mounting tie-rods in the SGs and the thermal-hydraulic behaviour of the secondary system in the various incident and accident situations which could affect NPP.

5.1 Behaviour of tube support plates and tie-rods

The clogging-up of TSPs results in greater resistance to water flows than considered at the design stage. Therefore TSPs and tie-rods could be subjected to heavier loads than considered at the design phase for transients.



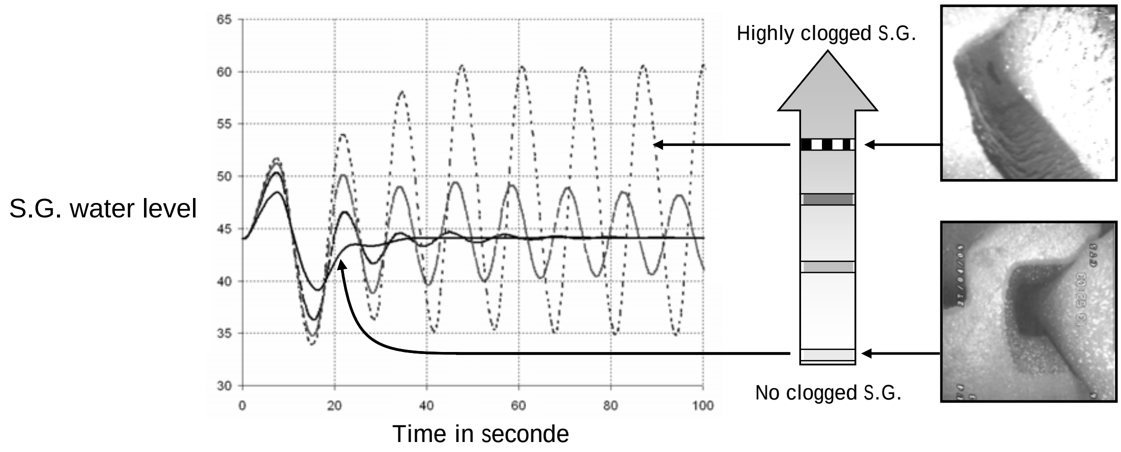
<u>Pic. # 8: Correlation between clogging up % and TSP head losses</u>

The proper behaviour of these components in a clogged configuration should therefore be checked both during normal reactor operations and for incident and accident conditions. The situation where there is the highest stress (i.e. the flow rate crossing the plates is at the maximum) is that of a large steam line break (very low probability event) resulting in complete draining of the steam generator in a very brief lapse of time. Studies have been conducted by EDF on this subject.

IRSN considered essential that EDF should also study cases of higher probability, for example, spurious closing of an isolation valve in the secondary system. During such a spurious closing, removal of steam from the steam generators is suddenly interrupted. During the very brief lapse of time preceding reactor scram, the heat is removed from the reactor by the other steam generators. Steam flow rate is therefore increased in these steam generators, hence the greater stresses placed on the tube support plates and tie-rods. EDF has demonstrated that the stress experienced by these components remains acceptable in the configuration of a high-level clogging-up. After detailed analysis of these studies, IRSN considered that they did not enable the progressive degradation of tube bundle support structures (tube support plates and tie-rods) to be completely ruled out.

5.2 Thermal-hydraulic behaviour of the secondary system

The clogging-up of TSPs decreases the circulation ratio of the steam generator and decreases the mass of water available for cooling in the secondary part of the steam generator, which reduces safety margins for certain accidental situations.
IRSN has also established a risk of water level oscillation by computation in response to a rapid transient such as a 10% power step (see picture #9).



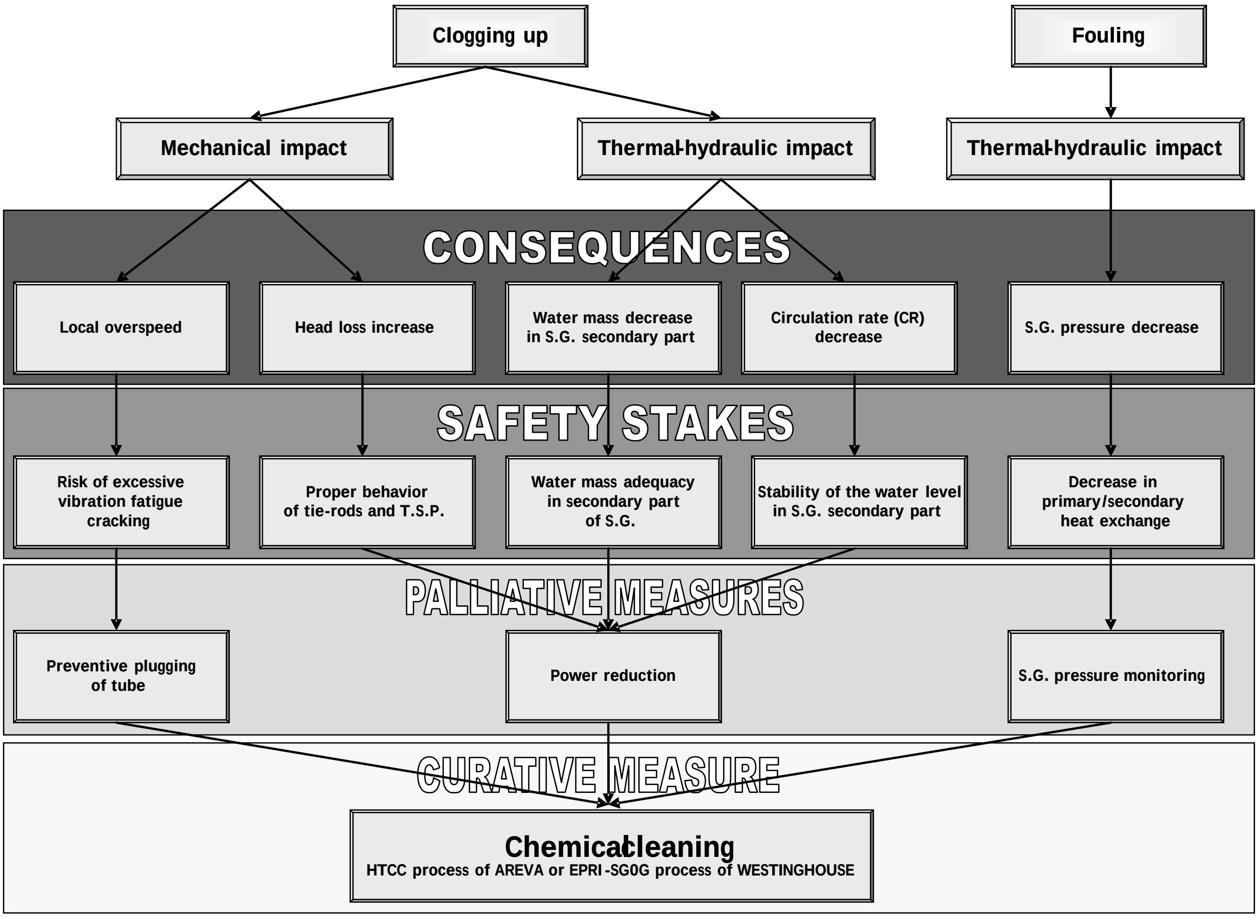
Pic. # 9: Risk of water level oscillation in case of clogged TSP.

EDF has consequently reduced the maximum reactor operating power before the chemical cleaning of units:

- 1 and 4 of Cruas NPP (900 MW) ⇨ Power reduction at 80% of the nominal power,
- 1 of Belleville NPP (1300 MW) ⇨ Power reduction at 93% of the nominal power,
- 1 of Cattenom NPP (1300 MW) ⇨ Power reduction at 93% of the nominal power.

5.3 Synthesis of the effects on plant safety

In brief, according to the nature of the anomaly (fouling or clogging up), the consequences on the plant safety are the following:



Pic. # 10: Effects on plant safety with respect to tube fouling and clogging up

On the basis of its safety analysis of the TSP clogging-up, at the end of 2006, IRSN recommended that the ASN (French Nuclear Safety Authority) should ask EDF to clean the tube support plates in the steam generators in Cruas unit 4 within three months.

6 CLEANING OF TUBE SUPPORT PLATES

Such cleaning can be carried out with different procedures mainly based on chemical cleaning using reduction and sequestering of metal oxides using an appropriate solution. EDF decided to clean the most clogged steam generators in 2007 – units 1 and 4 of Cruas nuclear power plants and unit 2 of Chinon B for the 900 MWe series, and unit 1 in Saint-Alban for the 1300 MWe series. EDF opted at the beginning for an industrial process of chemical cleaning at high temperature. This procedure has been carried out a number of times on steam generators throughout the world as well as on unit 1 of Chinon B in 2003 to eliminate deposits on tubes. However, it is the first time that it has been used to eliminate clogging deposits on tube support plates.

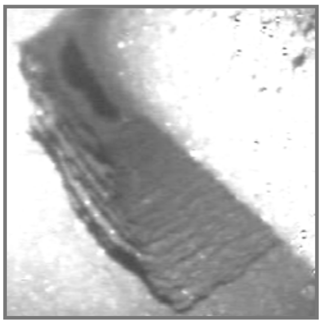
Units cleaned in 2007		Units cleaned in 2008	
NPP	Process used	NPP	Process used
Cruas unit 4	HTCC	Chinon B unit 4	HTCC
Cruas unit 1	HTCC	Saint Alban unit 2	HTCC
Chinon B unit 2	HTCC	Cruas unit 3	EPRI - SGOG
Saint Alban unit 1	HTCC	Cruas unit 2	EPRI - SGOG
		Belleville unit 1	EPRI - SGOG

HTCC: Process at high temperature carried out by Areva,
EPRI-SGOG: Process at low temperature carried out by Westinghouse.

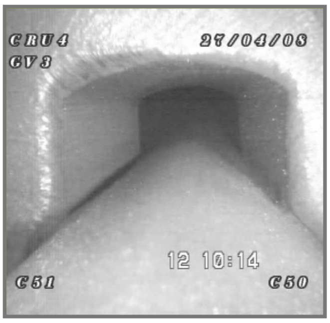
Therefore, IRSN carried out a detailed analysis of the site operation file submitted by EDF concerning both the qualification of the chemical procedure intended to enable deposits to be eliminated without causing any damage to the vessel and operations and inspections planned before the vessel is put back into service after the work.

As this constitutes a significant operation with the reactor core in place, IRSN also assessed the related risks. The analysis carried out by IRSN enabled it to conclude that there was no major hindrance to the cleaning operation.

Given the analyses described above, ASN granted EDF authorization to carry out the chemical cleaning of steam generators on the units listed above in the table. These operations took place in 2007 and 2008. Based on eddy current testing and direct visual examinations, EDF considers that all the chemical cleanings were effective. However, IRSN considers that the operational feedback from both the implementation of the procedure and its impact on the plant should be analysed in details and used to optimize the next chemical cleaning.



BEFORE
CHEMICAL CLEANING



AFTER
CHEMICAL CLEANING

Pic. # 11: View of a quadrifoil-shaped hole before and after chemical cleaning on Cruas unit 4

7 FORTHCOMING ACTIONS

IRSN has recommended that EDF should draw up the precise status of the various standardized plant series versus the clogging-up of steam generators for both 900 MWe and 1300 MWe reactors and present an appropriate strategy for the treatment of this generic issue to ASN. This strategy must take into account the fact that chemical cleaning produces around 1000 m^3 of liquid effluent per unit, which could saturate the treatment system currently used if the number of operations to be carried out proved to be high.

At the request of ASN, IRSN is continuing its analysis, especially focusing on the understanding of the occurrence of steam generator TSP clogging-up and the resulting risk of high cycle fatigue for tubes, the consequences of clogging-up on NPPs for incidental and accidental operations as well as the assessment of the method used by EDF to estimate the rate of clogging-up for the various standardized plant series steam generators equipped with “multi-foil” tube support plates.