IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

5 December 2016

Information Notice

IRSN assessment of the safety of reactors equipped with steam generators whose channel heads contain an abnormally high level of carbon

Following the anomaly detected on the domes of the Flamanville EPR reactor vessel, EDF notified the French Nuclear Safety Authority (ASN) that certain reactor primary coolant channel heads in steam generators manufactured by Creusot Forge (CF) and Japan Casting and Forging Corporation (JCFC) could be affected by positive residual macrosegregations of carbon.

This anomaly meant that EDF had to re-examine the risks of fracture of those steam generators insofar as the mechanical properties of the steel are altered. It should be recalled that the failure of steam generators is not postulated in the reactor safety demonstration, which implies a high level of requirements at the manufacturing stage.

IRSN's examination of the justifications provided by EDF in relation to the steam generator channel heads manufactured at CF has enabled ASN to take a position on restarting the six reactors affected[1]. The maximum carbon contents measured in these channel heads are in the region of 0.3 % compared to the maximum expected value of 0.22 %. The initial inspections of the steam generator channel heads manufactured by JCFC revealed higher carbon content levels of around 0.4 % locally, which has meant that EDF has had to conduct additional studies.

These studies were made available by EDF in October and November 2016; they have been assessed by IRSN, which published its assessment report on 30 November 2016, which is available on its website[2].

The analytical approach adopted by IRSN with a view to assessing this anomaly affecting twelve reactors[3] in operation aimed to obtain a reasonable level of assurance that this anomaly does not call into question the assessment of the risk of fracture of the affected steam generators. To this end, IRSN drew on the initial justifications communicated by EDF[4], as well as its own calculations and the available literature data and research results.

IRSN also reaffirmed its position on the mechanical properties of the steels containing high carbon levels by drawing on the expertise of the Belgian body BEL-V, which is a member of the ETSON network, which comprises IRSN and its European counterparts. It also conducted with ASN a joint mission in Japan to the manufacturer JCFC with a view in particular to better understanding the cause of the excessive carbon levels observed.

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[1] The affected 900 MWe reactors are: Blayais 1, Chinon B1 and B2, Dampierre 2 and 4 and Saint-Laurent-des-Eaux B2.

[2] IRSN Assessment 2016-00369 of 30 November 2016 (in French).

[3] The affected reactors are: Bugey 4, Dampierre 3, Fessenheim 1, Gravelines 2 and 4, Saint-Laurent-des-Eaux B1 and Tricastin 1, 2, 3 and 4 (900 MWe reactors) and Civaux 1 and 2 (1450 MWe reactors).

[4] This initial information will be complemented subsequently, particularly through the results of EDF's steel characterisation programme based on sacrificial parts.

The aim of a fracture mechanics analysis is to justify the absence of failure initiation resulting from a known or postulated crack in the material. Thus, IRSN evaluated the following in particular:

- the extent of the crack in the steel, which are postulated in the file communicated by EDF, taking into account the detection limit of the inspection equipment used during manufacture and during the on-site inspections performed on the steam generator channel heads;
- the loads giving rise to stresses tending to open the postulated cracks, i.e., the thermal shocks that can affect steam generators under all reactor operating conditions (normal, abnormal and accident operation);
- the mechanical properties of the steel, particularly its fracture toughness, which is affected by the steel's carbon content, taking into account the preliminary data provided by EDF for steel with a carbon content of 0.4 %.

Pursuant to ASN's request, the evaluation focused on the 900 MWe reactors only. This evaluation gave rise to the following conclusions.

1. In terms of cracks, EDF transmitted a report of the inspections performed both during manufacture (prior to removal of a metal coating on the inside surface of the channel heads) and on-site as part of the process of treating this anomaly. No cracks were detected during these inspections. IRSN evaluated the inspection techniques used and is of the opinion that they are well suited to detecting cracks of a greater magnitude than those postulated in the EDF study.

2. In terms of the loads giving rise to stresses tending to open the cracks, EDF selected a set of the most serious cold shock transients from the file which lists the situations to be taken into account when justifying the serviceability of the main reactor coolant system to which the steam generators belong. Various reactor coolant break scenarios were thus selected. EDF added to this list by looking for additional transients important to be considered in terms of fracture mechanics analysis of the steam generator channel head, based on the identification of all of the heat sources and heat sinks likely to cause a cold shock or a series of hot shocks and cold shocks. As a result, cold shock scenarios caused by inserting a cold water plug into the channel head of the steam generators were added.

   The approach adopted by EDF to define the cold shocks to be studied is appropriate in principle. However, during its evaluation, IRSN pinpointed transients that had not been identified by EDF and which need to be taken into account when treating the anomaly. Moreover, IRSN identified shortcomings in the characterisation of certain transients, for which more relevant hypotheses are required in terms of the fracture mechanics analysis of the steam generator channel heads.

IRSN did not make any further comments about the exhaustivity and relevance of the characterisation of the scenarios chosen for the cold shock transients affecting steam generators in 900 MWe reactors. In terms of hot shocks, EDF's file did not give rise to any further remarks[5].

In order to limit the extent of the potential thermal shocks, EDF has defined compensatory measures to be implemented during operation, such as limiting to 14 °C/h the cooling speed of the reactor coolant system during reactor shutdown. These compensatory measures are deemed satisfactory by IRSN, which nonetheless recommended that they be flanked by provisions designed, under certain conditions, to:

- reduce the probability of the operator unintentionally restarting a reactor coolant pump;
- limit the discrepancy between the discharge temperature of the cooling system during shutdown and the temperature of the emergency feedwater supply to the steam generators.

Based on its assessment, IRSN recommended that EDF reaffirm its file within a deadline of six months by providing additional justifications for certain situations that could cause cold shocks in the SG channel heads.

3. As regards the mechanical properties of the steel, EDF's study revealed carbon content levels reaching a maximum of 0.39 % on the outside surface and 0.26 % on the inside surface. The first value is based on the measurements made; the second is an estimation using a conservative approach based on the premise that the excess carbon observed is the result of a carbon segregation phenomenon in the ingot used to manufacture the channel heads. Providing the measurements were performed properly and in compliance with the precautionary measures announced by EDF with a view to ensuring their representativeness, a carbon content scenario of a maximum of 0.39 % on the outside surface is acceptable.

   Investigations conducted by IRSN, particularly during its mission to Japan, revealed that the segregation phenomenon hypothesis indeed provides the best explanation for the carbon levels observed. Consequently, the approach chosen by EDF for evaluating the inside surface carbon rate is appropriate and gives rise to a conservative estimation.

   In order to evaluate the fracture toughness of the steel in respect of these carbon content levels, EDF uses a method that is listed in the design and construction rules for the mechanical materials of the nuclear islands of pressurised water reactors (RCC-M). Use of this method appears right in this case and the resulting fracture toughness estimations are conservative both for the outside and inside surfaces.

[5] Cf. IRSN assessment 2016-00275 of 5 August 2016 and 2016-00277 of 11 August 2016, which focus in particular on the characterisation of hot thermal shocks for steam generators whose channel heads show high carbon levels (in French).

The evaluation conducted by IRSN has led it to conclude that there is no risk of fracture for the steam generators manufactured by JCFC and fitted in the 900 MWe reactors covered by the evaluation (with the exception of the Bugey 4, Fessenheim 1 and Tricastin 4 reactors, for which EDF still has to apply its method for analysing the fracture risk), subject to its recommendations and the results of the inspections requested by ASN.