28 June 2017

Note on the assessment of the serviceability of the closure head and lower head of the Flamanville EPR reactor pressure vessel

Context

At the end of 2014, EDF discovered an anomaly regarding the chemical composition of the steel forming the central part of the closure head and lower head of the EPR reactor pressure vessel manufactured by Creusot Forge.[1]

The anomaly is constituted by the presence of carbon in excess of specifications (content locally reaching 0.32% for an expected content of at most 0.22%) in the steel of the hemispherical domes used to manufacture the closure head and lower head of this reactor pressure vessel[2]. High carbon concentrations in a piece lead to a reduction in the toughness properties of the steel, i.e. the ability of the material to withstand crack propagation in presence of a pre-existing flaw.

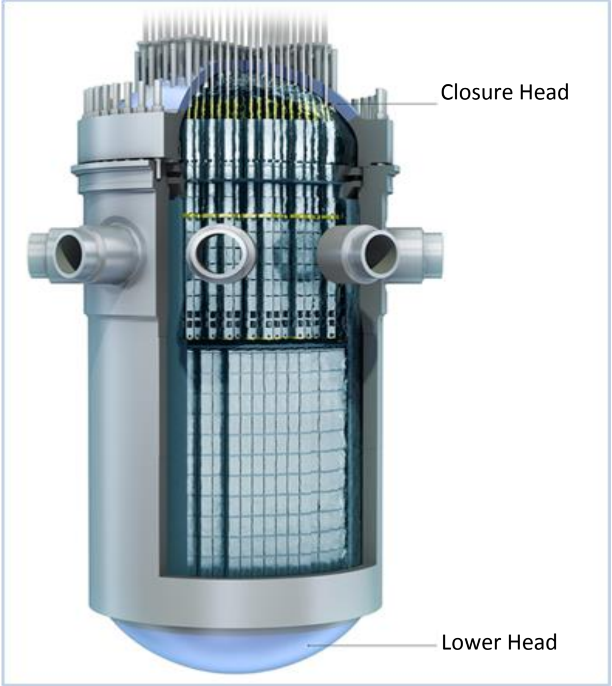

Diagram of the EPR reactor pressure vessel

The large dimensions of the closure head and lower head of the EPR reactor pressure vessel have led to a change in the manufacturing process of the parts, using in particular a higher mass ingot than for the reactor vessels currently in use. The excess carbon in the steel results from the use of a forging technique from a "conventional" ingot, of high tonnage, for which all precautions have not been taken to eliminate the portions with excess carbon (namely the zones with "*residual positive macrosegregation*" or "*segregation zones*" in the ingot): the physical phenomenon of segregation occurs at cooling of the ingot, which does not takes place uniformly. After pouring and solidification of the steel, the large-sized ingots thus comprise macroscopic heterogeneities in their chemical composition, in particular their carbon concentration, which it is important to control the extent and location of.

[1]This anomaly was detected during the technical qualification required under the regulation applicable to nuclear pressure equipment, during mechanical tests carried out on a scale-one replica dome of those of the Flamanville EPR.

[2] A reinforcement of the requirements concerning the prevention of the heterogeneity of parts has been introduced in the regulation applicable to nuclear pressure equipment resulting from the Decree of 12 December 2005.

Demonstration approach regarding the mechanical strength of the closure head and lower head of the EPR reactor pressure vessel

In 2015, Areva NP proposed a demonstration approach of the mechanical strength of the closure head and lower head of the EPR reactor pressure vessel based on an assessment of the risk of fast fracture resulting from normal and accidental operating conditions.

This approach is intended to demonstrate that the risk of fast fracture may be considered as excluded; rupture of the pressure vessel is indeed not considered in the safety demonstration of a pressurized water reactor. The risk of fast facture exists when there is concomitant presence of:

- a flaw in the material whose characteristics (defined by its position, its orientation and its dimensions) make it a prejudicial flaw;
- an insufficiently tough material (term characterising the fracture resistance);
- a large-scale mechanical or thermal loading.

The demonstration approach to the risk of fast fracture proposed by Areva NP is based on:

- the **verification of the absence of prejudicial flaws** in the domes of the Flamanville EPR;
- a **test program** carried out on specimens[3] sampled from domes forged using the same manufacturing process (scale-one replica domes[4]), in order to estimate the mechanical properties (especially toughness) of the high carbon concentration zones;
- the **calculation of the maximum stresses** induced by the pressure and temperature loadings in the domes of the pressure vessel resulting from the normal or accidental operating conditions of the reactor. These calculations are carried out by simulation software for thermohydraulic, thermal et mechanical phenomena;
- the **verification that the minimum toughness of the material is indeed higher** than the determined toughness required to withstand the maximum stresses resulting from the pressure and temperature loading of the reactor pressure vessel.

This approach was examined by IRSN and the Nuclear Pressure Equipment Department (DEP) of ASN, formalized by a joint report, and reviewed by the Advisory Committee for nuclear pressure equipment (GPESPN) on 30 September 2015. Following these reviews, ASN took position and considered acceptable, in principle, the demonstration approach proposed by Areva NP, subject to requests to be taken into account in its implementation. **In the light of the first test results, Areva NP changed its demonstration approach and completed the testing program.**

[3] Samples of material on which the tests are carried out.
[4] Destructive tests are not feasible on the closure head and the lower head of the Flamanville EPR reactor pressure vessel, since they would lead to rendering them unusable. Destructive tests of the program were therefore conducted on three scale-one replica domes, the upper domes originally scheduled for EPR projects in the USA and Great Britain, and the lower dome set for the EPR project in the USA.

At the end of 2016, Areva NP transmitted its analysis of the consequences of the anomaly of the closure head and lower head of the Flamanville EPR reactor pressure vessel. Areva NP concludes that the two components are serviceable without the need for in-service inspections.

Conclusions of the assessment

Areva NP analysis was examined jointly by ASN DEP and IRSN. This assessment is formalized in a joint report that was presented to the GPESPN on 26 and 27 June 2017 in order for the Advisory Committee to give an opinion to ASN, prior to its own position.

The main conclusions of this assessment are as follows:

- checks during manufacturing: ASN DEP and IRSN confirmed, given the results reported by Areva NP, **the absence of detection of prejudicial flaws** (manufacturing controls and additional actions required as a result of the GPESPN of 30/09/2015) and the **consistency between the size of the flaws postulated** in the Areva NP mechanical analysis with the performance levels of these inspections[5];
- characterisation of the material: the presence of residual carbon segregation is at the origin of the modification of the mechanical properties. However, the behaviour observed remains that expected of this type of steel (ferritic steel), used in the manufacturing of all reactor pressure vessels currently in use. The modification of the mechanical properties mainly results in an increase in the transition temperature between the brittle behaviour of the material and its ductile behaviour, of a few tens of degrees. Consequently, the fact that Areva NP adopted a tenacity consistent with the increase in the transition temperature observed at the end of the tests carried out, is satisfactory;
- thermomechanical loadings: the numerous exchanges which took place during the examination of the exhaustiveness of the situations to be considered and their characterization (pressure, temperature, flow) led Areva NP to complete its initial file and consolidate its demonstration. The approach adopted by Areva NP to identify the situations causing the most severe loadings of the reactor pressure vessel domes is considered to be satisfactory, as is the conservative nature of the loads which were deduced from it;
- mechanical analysis of the fast fracture risk: the conclusions of the assessment carried out by ASN DEP and IRSN show that the mechanical properties of the material in the segregation zones are sufficient to preclude the risk of fast fracture. The margins obtained, while being smaller than those obtained for a material free of positive segregation of carbon, are superior to the design criteria.

[5] This is to ensure that the flaws studied are larger than the flaws that could remain in the part after the checks because they are too small to be seen. The larger the flaw, the more likely it is to initiate: studying a larger flaw than those that could remain in the component is a guarantee of safety.

The shortcomings observed in the technical qualification process, the use of a manufacturing process which was unable to rule out risks linked to residual carbon segregation and the reduction of fast fracture risk margins, reflect the fact that the first level of defence in depth[6] is affected.

The Areva NP demonstration approach helps demonstrate the adequacy of the margins but is unable, on its own, to restore all the guarantees that this first level of defence in depth must provide. Therefore Areva NP's justification is not the only way to restore all the guarantees that this first level of defense must provide. **Therefore, the justification approach proposed by Areva NP needs to be complemented by in-service inspections to reinforce the defence in depth overall approach.**

ASN DEP and IRSN consider that in-service inspections planned by EDF for the closure head and lower head of the reactor pressure vessel should be adapted in order to verify the absence of flaw apparition during the operation of the installation, which has been designed by EDF and Areva NP for a period of operation of 60 years. If the feasibility of these inspections appears to have been acquired for the lower head, this remains to be established for the closure head, given the numerous penetrations present for the passage of the control rod drive mechanisms (designed to control the nuclear reaction), the instrumentation of the reactor core and the vent tube.

In conclusion, the serviceability of the EPR reactor vessel domes was justified by Areva NP despite the anomaly observed. However, additional in-service inspections shall be implemented to periodically monitor such equipment during operation of the installation. Failing to develop such inspections for the closure head, it should be replaced within a few years. The possibilities of bringing the pressure vessel into compliance (repair of the closure head and replacement of the lower head of the reactor pressure vessel) were not analysed in the context of this assessment. This item will be examined by ASN in the framework of its decision-making process.

As part of its openness to society, IRSN has set up, in partnership with the National Association of Committees and Local Information Commissions (Anccli), the Local Information Commission (CLI) of Flamanville and the Nuclear Safety Authority (ASN), a technical dialogue on the anomaly in the composition of steel of the EPR reactor vessel in Flamanville, Manche. This technical dialogue aims to provide access to expertise and exchanges on the latter with the members of society. Three meetings were held in December 2015, April 2016 and September 2016, in order to review the issues surrounding the EPR vessel in Flamanville and the justification of their suitability for service. A new meeting will be organized in early July 2017 to present and discuss the technical elements of the instruction and conclusions of the joint ASN DEP and IRSN report.

[6] The principle of *defence in depth* is the fundamental principle for designing nuclear reactors. It involves the implementation of successive levels of defence (intrinsic characteristics, physical provisions and procedures) intended to prevent incidents and accidents and, in the event of failure of prevention, to limit their consequences.