HCTISN REPORT ON THE FLAMANVILLE 3 EPR REACTOR VESSEL ANOMALIES

June 2017

High Committee for Transparency and Information on Nuclear Safety
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INTRODUCTION

On 7 April 2015[1] an anomaly in the composition of the steel in certain zones of the Flamanville[2] EPR reactor vessel was made public by the French nuclear safety regulator, ASN.

This communication follows on from the ASN notification, in late 2014, by the designer and manufacturer of nuclear reactors – AREVA – of the results of mechanical tests performed on a reactor vessel closure head similar to that of the Flamanville EPR reactor, which were below the reference value mentioned in the regulations. The results of these tests, performed at the end of 2014 as part of the technical qualification of the reactor vessel, revealed the presence of a zone with a high carbon concentration located in the central part of the vessel head and leading to lower than expected mechanical properties.

The Flamanville EPR construction site began in 2007. Following a first phase of civil engineering works, the reactor vessel was put in place in January 2014 in the building designed to house it, called the "reactor building".

In order to demonstrate that the characteristics of the steel used for the reactor pressure vessel closure head and bottom head, referred to as the "upper dome" and "lower dome" respectively, are adequate and to demonstrate the strength of the EPR reactor vessel, AREVA initiated a further campaign of in-depth testing in April 2015, on a material representative of the lower and upper domes of the reactor pressure vessel. This approach is currently being examined by ASN, which is drawing on the expertise of its technical support organisation, the French Institute for Radiation Protection and Nuclear Safety (IRSN) and the Advisory Committee for nuclear pressure equipment (GP ESPN)[3].

By virtue of its duty of information, consultation and debate concerning the risks involved in nuclear activities, a plenary meeting of the High Committee for Transparency and Information on Nuclear Safety (HCTISN) on 18 June 2015, decided to set up a monitoring group to oversee the investigation and the performance of the new test campaign proposed by AREVA and to ensure complete public information and transparency on this matter.

[1] ASN press release of 7 April 2015 "Anomalies in the manufacture of the Flamanville EPR reactor vessel", available on the ASN website: https://www.asn.fr/Informer/Actualites/EPR-de-Flamanville-anomalies-de-fabrication-de-la-cuve

[2] The EPR (European Power Reactor) is a 3rd generation nuclear reactor designed in the early 1990s. The Flamanville EPR, with a power of 1650 MW electric, for which the creation authorisation was granted by the decree of 10 April 2007, following approval by ASN, has been under construction since September 2007. Following the civil engineering work, the first large components were introduced in 2014 (reactor pressure vessel, steam generators, etc.) and mechanical installation is currently ongoing.

[3] Advisory Committee reporting to the ASN Director General and comprising experts appointed for their expertise in the field of pressure equipment, including outside the nuclear sector. Its members come from civil society, from university research laboratories, from inspection agencies, from expert appraisal bodies, from the licensees concerned by the subjects dealt with as well as from foreign safety regulators.

This decision taken by HCTISN was reinforced when, on 5 October 2015[4] it was asked by the Minister responsible for nuclear safety to examine the conditions in which the public is informed of the answers to the following three questions:

- *"How did this anomaly occur and why did it come to light nine years after the manufacture of the parts in question?*
- *What are the underlying physical phenomena and what are their safety consequences in the context of the EPR, explained in clearly understandable language?*
- *What steps are taken by AREVA and EDF to ensure public information and the transparency of this test programme on the scale-one replica reactor vessel, in particular with regard to the tests performed and the results obtained, as well as with regard to the analysis of the conformity of the Flamanville 3 EPR reactor vessel with the regulations on nuclear pressure equipment?"*

The group monitoring this dossier, the members of which are listed in the appendix, comprises a member of Parliament, representatives of the local information committees, of environmental protection associations, persons responsible for nuclear activities, trade union organisations, personalities chosen for their scientific competence and representatives of ASN, IRSN and State services.

This oversight group first of all met on three occasions on 27 January 2016, 23 March 2016 and 29 June 2016 in order to go back over the history of manufacture of the EPR reactor vessel and gain a clearer understanding of the implications of the anomaly detected.
ASN presented all the members with a report[5] on the manufacturing history of the reactor vessel and the technical qualification of its domes, on the regulatory context and on the inspections it carried out and requested on the reactor pressure vessel.

Independently of each other, EDF and AREVA also produced two reports on the manufacturing history of the EPR reactor pressure vessel domes. The EDF report more specifically concerns its role in the oversight of the manufacture of the reactor vessel domes. That from AREVA concerns the history of the design, manufacture and justification of the reactor vessel domes.
Finally, AREVA also organised two visits for the members of the oversight group. The first took place on 13 May 2016 in the Areva Technical Centre in Erlangen, Germany. This is where some of the additional tests are carried out to justify the adequacy of the properties of the steel used for the reactor vessel domes. The second visit, on 23 November 2016, was to AREVA's "Creusot Forge" plant, where the two reactor vessel closure head and bottom head domes were forged.
The oversight group then met on four occasions on 5 October 2016, 21 February 2017, 25 April 2017 and 24 May 2017, to compile all the collected information in the

[4] A copy of the request from the Minister dated 5 October 2015 is appended.

[5] Report for the 23 March 2016 meeting of the HCTISN oversight group for the Flamanville 3 reactor pressure vessel anomaly, available on the ASN website: https://www.asn.fr/Informer/Actualites/Historique-des-echanges-avec-Areva-fabrication-de-la-cuve-de-l-EPR-de-Flamanville

form of this present report. The working documents used to draft it are appended and have been made public.
This report only concerns the anomaly in the upper and lower domes of the Flamanville EPR reactor pressure vessel, said anomaly being linked to a higher than expected carbon content in certain zones.

It is an interim report, resulting from the initial work performed by the HCTISN oversight committee and aims to summarise all the information communicated to it and clarify the corresponding chronology, ensuring that it is coherent and comprehensible to the public.

CONTENTS

Acronyms and abbreviations

ASN: French Nuclear Safety Authority

BCCN: ASN's nuclear steam supply system control office (until 2006)

CL: Creusot Loire (now AREVA, Creusot Forge plant)

DEP: ASN's Nuclear Pressure Equipment Department, successor to the BCCN (as of 2006)

DGPR : Directorate General for Risk Prevention of the Ministry of Ecology

EPR: European Pressurized Reactor

ESPN: Nuclear pressure equipment

FA3: Flamanville 3 EPR

FILAB: Chemical analysis laboratory in Dijon

BNI: Basic Nuclear Installation

IRSN: French Institute for Radiation Protection and Nuclear Safety

JSW: The Japan Steel Works Ltd.

LSD: Directional solidification ingot

MWe: Megawatt electric

MSNR: Nuclear safety and radiation protection mission of the DGPR

N4: EDF's French 1450 MWe reactors (Civaux 1 and 2, Chooz B1 and B2)

PTF: Technical manufacturing programme

QT: Technical Qualification

RCC-M: Design and construction rules for mechanical equipment on PWR nuclear islands

Glossary

Ductility: Ability of a material to become elongated, to stretch without breaking.

Bending rupture energy: Ability of a material to absorb energy when deforming under the effect of an impact. The bending rupture energy of a material depends on the temperature. It characterises its impact resistance. The bending rupture energy level is an indicator of the degree of **toughness**. It is expressed in Joules.

Shrinkage: Flaw consisting of a cavity forming in the massive parts of cast metal parts owing to the contraction of the metal as it solidifies.

Toughness: Ability of a material to withstand crack propagation under loading (for example: mechanical loads at pressure and temperature). In the case of a nuclear reactor pressure vessel, this property is in particular important to withstand thermal shocks, for example following the injection of cold water into the reactor coolant system.

Acceptance zones: Zones of the part chosen by convention for sampling of test specimens used for chemical and mechanical characterisation of the material**.**

Macrosegregation zone: Visually observable zone with heterogeneous carbon composition, on an ingot cut into two, by means of a developer (chemical etching). The macrosegregations are different from extremely localised segregations, which can be observed by a microscope with varying degrees of magnification.

1. The issue with the EPR reactor pressure vessel domes

1.1 The EPR

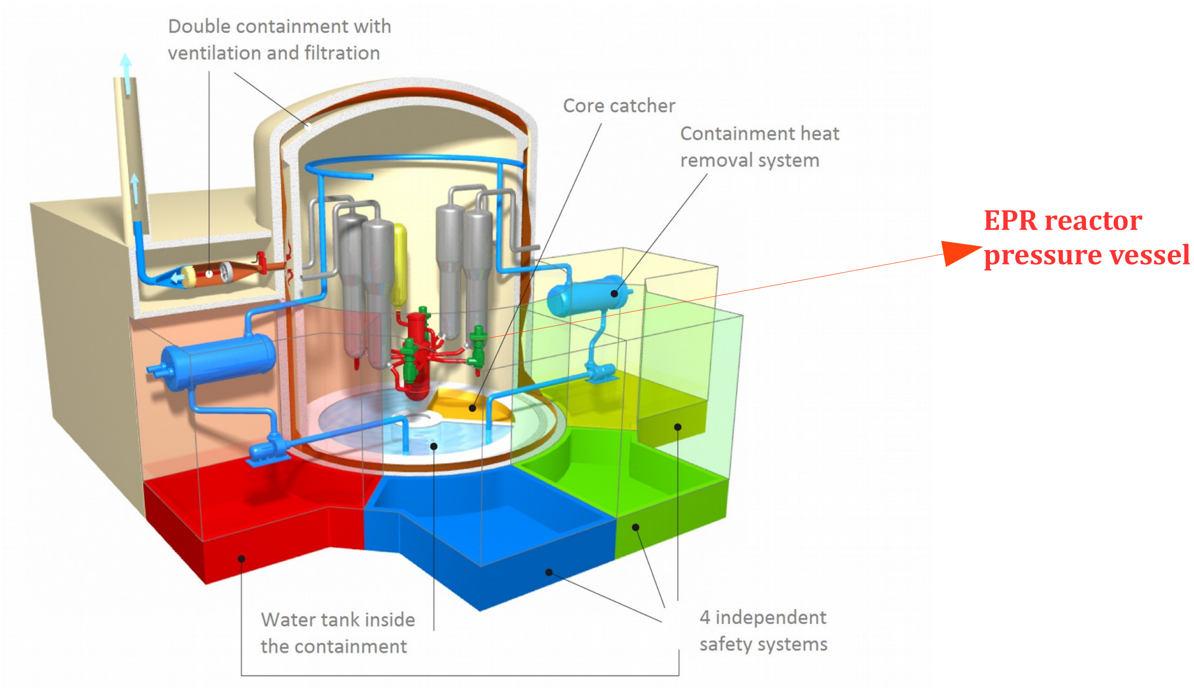
The EPR is presented by the designer and the licensee as an “evolutionary” 3rd generation reactor with regard to the existing pressurised water reactors, incorporating all the experience gained from the previous generations. Its design dates back to the early 1990s and incorporates elements from the French N4 reactors and German Konvoi reactors.

The electrical output of the Flamanville 3 EPR is 1650 MW electric (MWe), which makes it one of the world's most powerful reactors.

According to the designer and the licensee and in accordance with the objectives set by ASN, the main developments in the EPR - by comparison with previous generations - aim to reinforce defence in depth through:

- **a significant increase in the strength of the nuclear island civil engineering enabling it to withstand external hazards of all types;**
- **enhanced prevention of core and spent fuel pool fuel melt accidents by measures to deal with multiple failures liable to affect the installation;**
- **measures to significantly mitigate the radiological consequences of a severe accident, notably the installation under the reactor vessel of a specially designed system to recover, contain and cool the molten core (“corium catcher”);**
- **measures to make situations liable to lead to significant early radioactive releases extremely improbable, with a high degree of confidence;**
- **a minimum operating life of 60 years foreseen by the designer;**
- **the separation of the safety systems into 4 geographically independent divisions, giving the installation greater protection against the effects of internal and external hazards;**
- **the use of more efficient fuel management, leading to a reduction in long-lived radioactive waste;**
- **significant reactor pressure vessel changes, as detailed in section 1.3.**

<u>Figure 1: Cross-section of the EPR</u>
(Source: EDF)



1.2 The Flamanville EPR reactor pressure vessel

The reactor pressure vessel is an **essential equipment item,** because it contains the nuclear fuel. It is part of the reactor coolant system of a nuclear power plant.

The nuclear safety case precludes reactor pressure vessel rupture, because no reasonable measures for mitigation of the consequences, for management of the installation, for the personnel, the population and the environment can be defined. This approach is based on particularly demanding requirements in terms of design, manufacture and in-service monitoring, with the aim of preventing rupture.

The reactor pressure vessel is a part of the second containment barrier for the radioactive elements (the first being the fuel assembly cladding and the third the containment) and its role in the safety of the installation is crucial. Its **integrity** must be guaranteed and demonstrated in all normal, incident and accident reactor operating situations and for the entire duration of its service life.

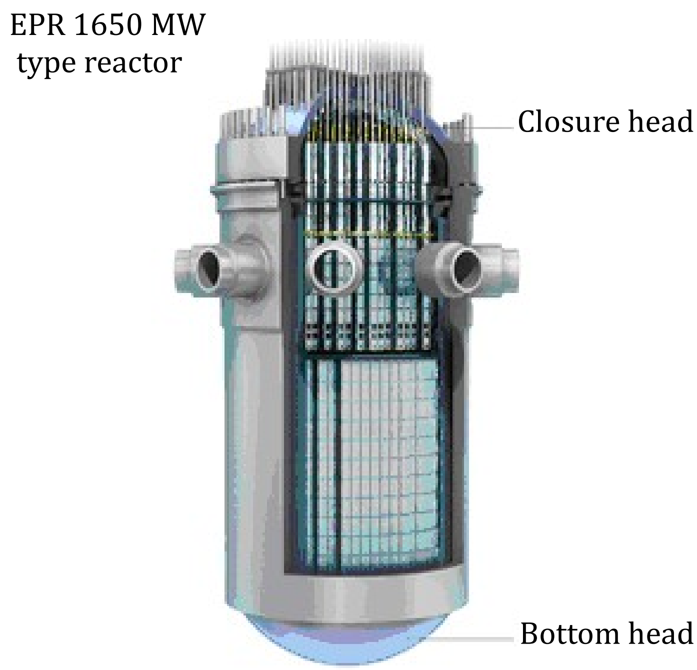
A reactor pressure vessel consists mainly of two types of parts:

- the shells, making up the cylindrical part of the vessel,
- the domes forming the lower (bottom head) and upper (closure head) parts. The domes are very thick dished parts.

During operation, the reactor pressure vessel is subjected to the pressure and temperature conditions of the reactor coolant system, as well as neutron irradiation created by the nuclear reactions taking place in the core (although with a lesser impact in the EPR than with a conventional vessel, owing to the specific protections). This irradiation primarily concerns the cylindrical parts (**shells**) of the vessel located opposite the core.

Unlike other equipment in the reactor coolant system, such as the steam generators or the vessel closure heads, replacement of a reactor pressure vessel body cannot be envisaged by the licensee after commissioning of the reactor: the operating lifetime of the vessel therefore directly determines the operating lifetime of the installation.

Figure 2: EPR reactor pressure vessel
(Source: ASN)



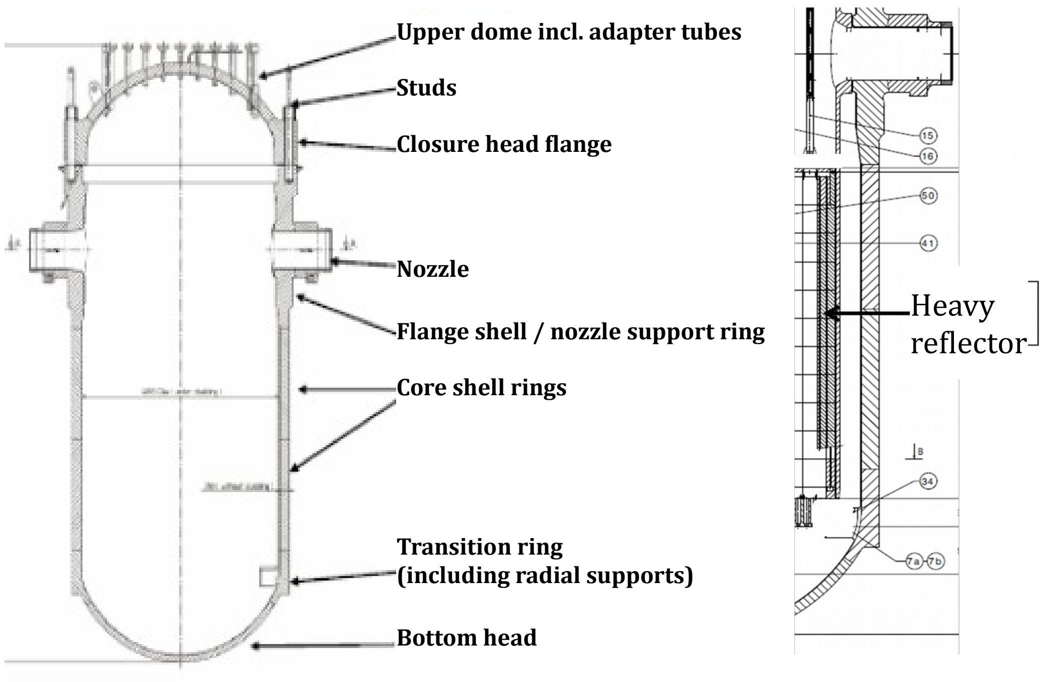
The characteristics of the Flamanville 3 EPR reactor pressure vessel are as follows:

- **height about 13 metres (excluding instrumentation at the top);**
- **outside diameter about 5.8 metres excluding nozzles and 7.5 metres with nozzles;**
- **weight about 510 metric tons (weight of vessel body and closure head with adapters).**

The EPR reactor pressure vessel comprises:

- **two core shell rings;**
- **one nozzle support ring, with integral flange;**
- **eight nozzles;**
- **a transition ring and a closure head flange;**
- **a vessel bottom head or bottom dome;**
- **a closure head or upper dome.**

Figure 3: EPR reactor pressure vessel components



The dimensions of the EPR reactor pressure vessel domes are specified in the following table:

	Closure head dome	Bottom head dome
Thickness	230 mm	145 mm
Vessel inside diameter	4885 mm	4885 mm
Inside bend radius	2695 mm	2695 mm
Number of penetrations[6]	107	0

[6]Penetrations to allow passage of the control rod drive shafts for modulating the neutron flux and consequently the power of the reactor

1.3 EPR reactor pressure vessel design improvements

The reactor pressure vessel was designed over the period 1995 – 2003.

The designer focused on the points considered to be the most significant for safety, on which major progress has been made:

- Improvement to the end-of-life mechanical characteristics through a reduction in the neutron flux on the reactor vessel shells, by installation of a heavy reflector between the core and the vessel and a greater thickness of water;
- Improved safety by eliminating the vessel bottom head penetrations: the reactor core instrumentation is inserted through penetrations in the vessel closure head;
- Improved conditions for the production of certain welds: nozzle flanges more favourable to welding and weld inspection;
- Fewer welds liable to constitute weak points:
    - elimination of a weld at the join between the nozzle support ring and the vessel flange (single forged assembly);
    - beyond the pressure vessel, the main reactor coolant system pipe connections between the auxiliary systems and the reactor coolant system are solid forgings and no longer connected by welding;
- Reinforced robustness and mechanical properties of the pressure vessel through the choice of materials: reduction in sulphur and phosphorus contents.

2. Reactor pressure vessel dome manufacturing techniques

Most of the large components of a reactor are forged, which enables high quality parts to be obtained, free of all flaws such as the shrinkage that is inevitable with casting processes for example.

With regard to reactor pressure vessels, the shells which make up the cylindrical part of the vessel and the domes which form the lower (bottom head) and upper (closure head) parts are forged using different processes.

2.1 Dome manufacturing technique in the Creusot Forge plant

The manufacturing technique adopted for the manufacture of the domes of the Flamanville EPR reactor pressure vessel is based on the “conventional ingot”. It is specific to the Creusot Forge plant. Other manufacturing processes exist for forging pressure vessel domes, as detailed in section 2.5.

During the steelmaking process, the operators of the steel mill and the forge aim to control the chemical composition of the steel, including its carbon content, owing to its influence on the mechanical properties of the part. One of the goals at the steelmaking stage is to limit the intensity of the carbon segregation phenomenon or the heterogeneity of the carbon composition in order to guarantee satisfactory mechanical properties for the part with regard to the stresses to which it is subjected during its lifetime.

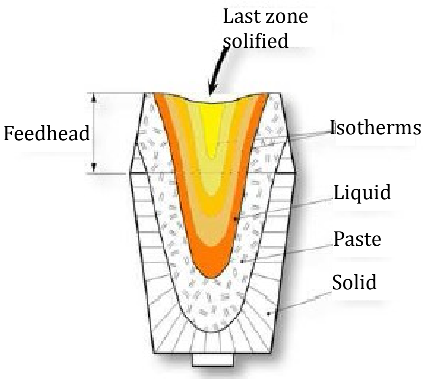
Forging of a part from a solid ingot such as that chosen for production of the domes of the Flamanville 3 reactor pressure vessel, comprises several phases, described below:

1- **Production of the ingot**: the molten steel is poured into a mould. Owing to the heat exchanges, the metal situated along the walls and bottom of the mould solidifies before that in the centre and at the top.

2- **During this solidification phase**, the carbon migrates to the still liquid areas; the carbon concentration is thus higher than average in the parts which solidify last - the upper and central part of the ingot - and is lower than average in the areas which solidify first - the edges and the bottom. The carbon segregation and heterogeneity phenomena in large metal parts are classic and known to all metallurgists.

   They are all the more significant as the size of the ingot increases. We talk of positive carbon segregation in areas where the carbon content is higher than average and negative segregation in areas where it is lower than average.

Figure 4: Production of the ingot
(Source: AREVA)



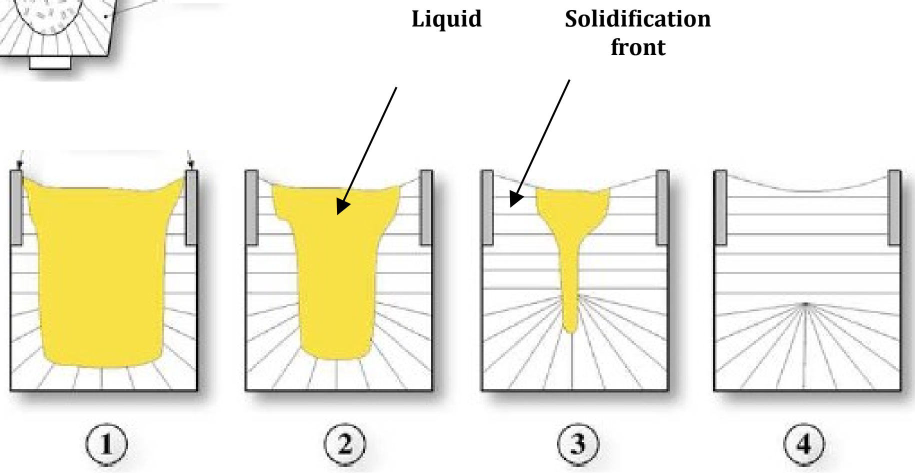
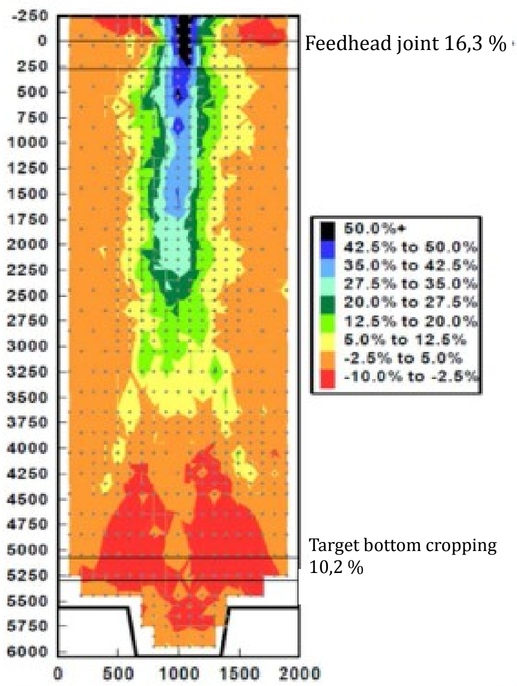
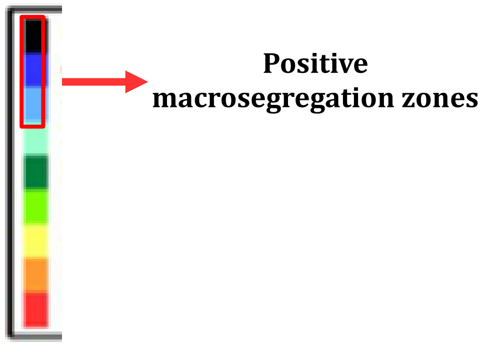


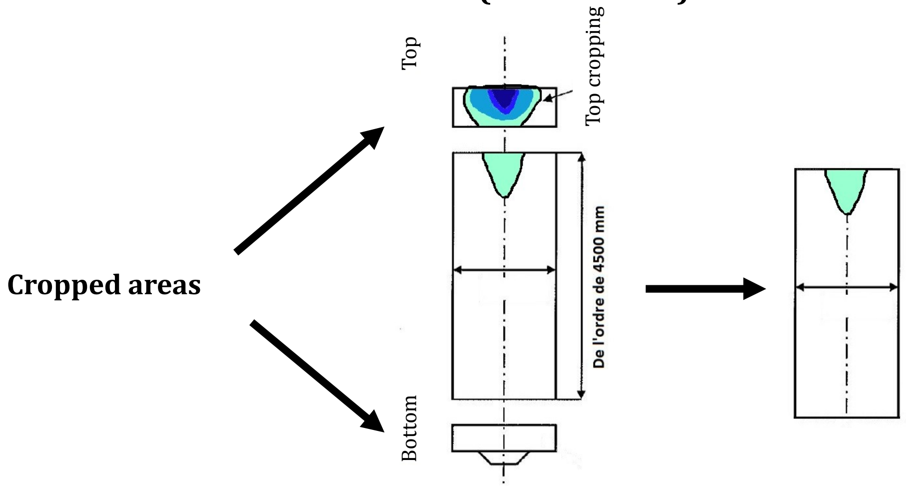
Figure 5: Carbon distribution in the vertical plane at the centre of the ingot
(Source: AREVA R&D programme)





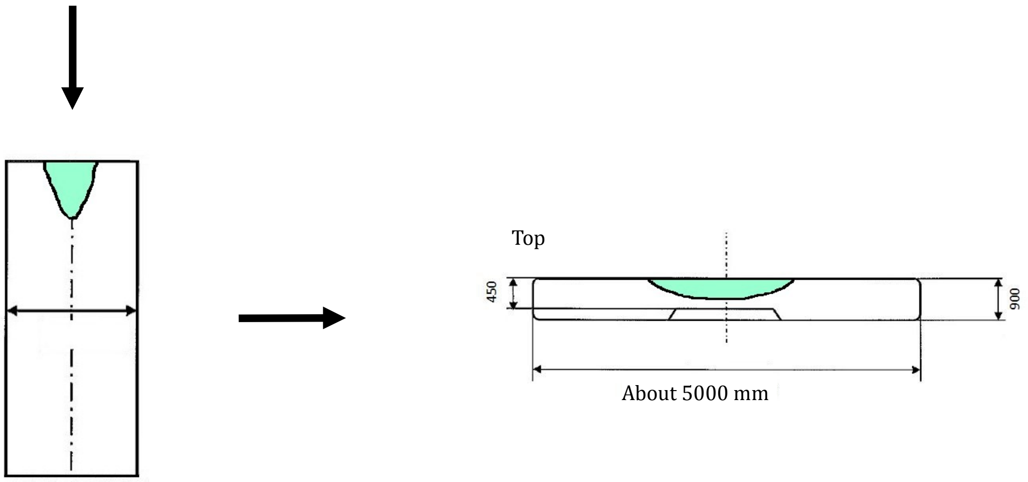
3- **Cropping phase**: the upper and lower parts of the ingot are then removed during the "cropping" operation. "Cropping of the upper part in principle enables the area of the part with the highest carbon concentration to be removed (shown in blue in figure 6 below), but it does leave an area with a higher carbon concentration in the upper area of the part (green zone in figure 6) the consequences of which are explained in section 2.3.

<u>Figure 6: Ingot cropping</u>
(Source: IRSN)



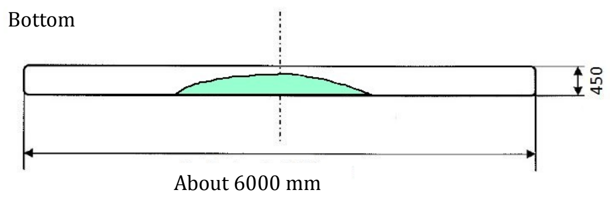
4- **Crushing phase:** the part is then crushed. As a result of this operation, the area with the highest carbon concentration extends over a greater diameter and with a smaller absolute height (about 10 times smaller).

<u>Figure 7: Ingot crushing</u>
(Source: IRSN)



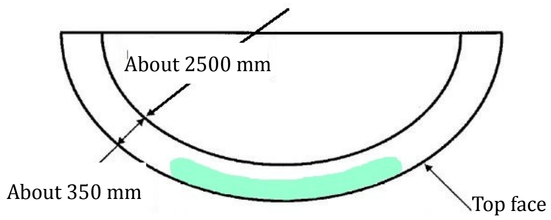
5- **Machining phase:** the part is then machined on both sides to achieve the required dimensions before the dishing phase described in 6. During this operation, the part retains the same diameter and its height is reduced. Some of the area with the highest carbon concentration is removed. The part is positioned so as to guarantee a minimal carbon concentration on the inner face (area in which the liner will be welded for certain parts including the domes).

Figure 8: Ingot machining
(Source: IRSN)



6- **Forming phase:** the part is drawn out to the required shape (hemispherical for a dome). Following this operation, the area with the highest carbon concentration is thus on the outside of the vessel.

Figure 9: Ingot forming
(Source: IRSN)



7- **Final machining phase and heat treatments:** Following forming, the part undergoes another machining operation on each side, prior to heat treatment (quenching). Subsequently, the part is again machined to obtain the final dimensions. The three successive machining operations carried out after forging contribute in practice to eliminating the most intense positive or negative segregation zones.

2.2 Role of carbon

Carbon is a steel alloy element: it gives the metal its mechanical strength. As the carbon content increases, the mechanical strength increases, but the metal also becomes both harder to weld (risk of creating flaws during welding) and less ductile. **Ductility** characterises the metal's ability to deform before breaking.
The carbon content also influences the **toughness** of the metal, which characterises its rupture tolerance in the event of metallurgical flaws, for example cracks. The **bending rupture energy** corresponds to a material's ability to absorb energy under the effect of an impact and is an indicator of the level of toughness.

The fast fracture phenomenon can occur in the event of a combination of:

- a flaw in the part (crack),
- insufficient material toughness at the temperature in question,
- stresses induced by mechanical loads at pressure and/or temperature.

The average carbon content is thus specified within a range guaranteeing good mechanical strength, good ductility and good toughness for the metal. The steels used for reactor pressure vessels are of a grade offering good mechanical properties (ductility, toughness, etc.), notably able to withstand high levels of pressure, with reasonable thicknesses and good weldability properties. When producing the ingot and during forging, the inevitable segregation phenomena (positive or negative) should be avoided.

With regard to the domes of the EPR reactor pressure vessel, the AREVA data indicates that they were manufactured with a target average carbon content on pouring of 0.18%. The carbon content on pouring is thus representative of the average carbon content of the ingot. As previously explained, the carbon segregation phenomenon occurs as the ingot cools. In certain areas, it is therefore possible for the carbon content to reach 0.22%[7], owing to this segregation phenomenon, without this being considered prejudicial to the quality and safety of the part.

The quality of the steels has also benefited from progress in the management of impurities (sulphur, phosphorus, hydrogen, etc.) and their metallurgical structure, which are other essential factors which determine the quality of the parts and their mechanical characteristics.[8]

2.3 Potential consequences of high carbon concentrations

An increase in the carbon concentration in a part reduces the ability of the steel to withstand the propagation of a crack (toughness) in the event of a pre-existing flaw. The toughness of a material corresponds to the force necessary for propagation of a

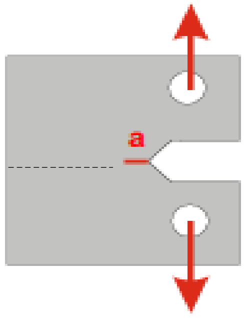
[7] Or 0.16% in the case of a negative segregation phenomenon

[8] Typically, production contemporaneous with that of the reactor pressure vessel domes shows:

- phosphorus contents of about 0.005%,
- sulphur contents of about 0.002%,
- hydrogen contents of about 0.5 to 0.6 ppm.

crack (shown in figure 10 by the solid red line). It can be measured on test specimens (sample of the material).

Figure 10: Crack propagation
(Source: IRSN)



The behaviour of the material varies according to the temperature ranges.

Figure 11 below illustrates the variation in toughness according to the temperature of the material.

In the temperature range corresponding to reactor normal operating conditions, the material's behaviour is entirely ductile.
As the temperature decreases, the toughness of the material diminishes and its behaviour in the event of a crack and high mechanical stresses gradually goes from a ductile fracture mode to a cleavage (or brittle) fracture mode. It should be pointed out that the brittle-ductile transition temperature[9] should be as low as possible in order to minimise the risk of fast fracture.

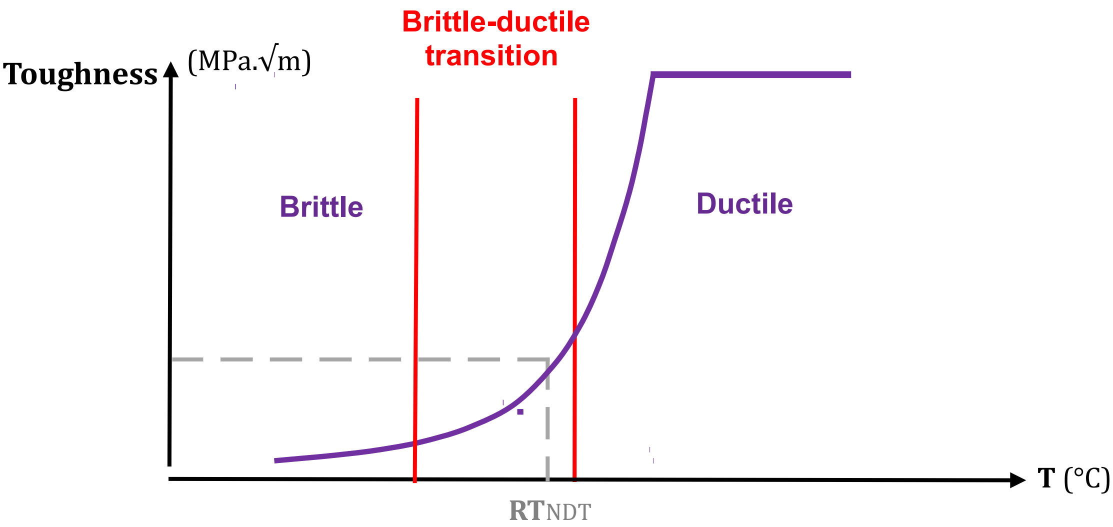
In the areas with the higher carbon concentration, embrittlement of the steel is typically observed, leading to a drop in bending rupture energy, which is an indicator of toughness and to an increase in the brittle-ductile transition temperature.

The studies demonstrating the absence of the fast fracture risk, confirm that in all situations (normal, incident or accident), the loads remain lower (with margins) than those which could lead to a fast fracture phenomenon should there be a pre-existing flaw

[9]Brittle-ductile transition temperature: temperature characterising the transition from the ductile behaviour domain to the brittle behaviour domain.

Figure 11: Toughness versus temperature curve

(Source: IRSN)

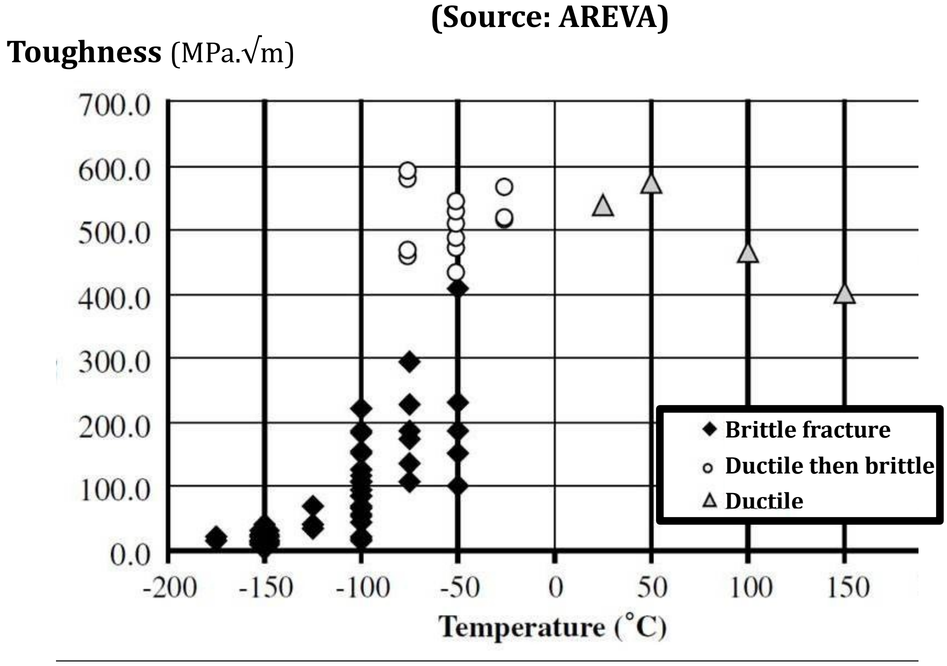


The shape of the toughness curve was established on the basis of experimental programmes carried out first of all in the United States and then in France. The RT_{NDT} index characterises the transition temperature between the brittle domain and the ductile domain. Typically, the RT_{NDT} values for forged steel parts such as the vessel domes are about -20°C to -45°C.

The principle of this curve is that it must cover the actual toughness values of the material. An example of actual toughness measured on a reactor pressure vessel material is shown in the following figure:

Figure 12: Toughness measured on a material of the vessel versus temperature

(Source: AREVA)



The position of the curve on the X-axis, characterised by this RT_{NDT} index, is thus crucial. The higher the carbon concentration, the further the toughness curve and the brittle/ductile transition temperature zone will shift to the right, that is towards higher temperatures. The positioning of this curve is determined by means of mechanical tests.

The toughness and brittle-ductile transition temperature values measured on the test specimens are used to define the limit toughness curve to be followed in the mechanical studies.

The general demonstration of the vessel's ability to withstand the risk of fast fracture is based on:

- a postulated flaw, the presence of which cannot be ruled out despite the inspections,
- the toughness versus temperature characteristics,
- the loads defined by the pressure and the temperature,
- verification of compliance with criteria plus safety coefficients to ensure that the stress from the flaw induced by the loading remains below the toughness.

2.4 Choice of suppliers

The vessel manufacturer, AREVA, orders reactor pressure vessel parts from its subcontractors, especially forged parts: shells and domes. Its general industrial policy consists whenever possible in calling on several potential suppliers for a given part, to ensure long-term security of supply. Insofar as is possible, its buying policy is also to identify or maintain a French procurement source for all parts, including forgings.

The general process is as follows:

- The AREVA engineering teams design the part: choice of geometry (thicknesses, etc.), of materials, etc.
- The AREVA Saint-Marcel plant (which manufactures equipment from forged parts) draws up a procurement specification to be transmitted to the foundry in charge of producing the part.
- The foundry produces a technical manufacturing programme (PTF) which details all the steps in manufacturing, the parameters to be monitored and the acceptance ranges for these parameters. The PTF is sent to ASN, which can make comments.
- This document is reviewed by AREVA Engineering, the teams from the AREVA Saint-Marcel plant and EDF, which give their approval before pouring the part.

2.5 General history of manufacturing processes

There are different manufacturing techniques, which were used to make the reactor pressure vessel domes, based on forming of a disk, obtained by cutting thick sheets produced in a rolling mill, or crushing of an ingot.

At Le Creusot, two types of ingots are traditionally available for manufacturing reactor pressure vessel domes, more generally parts referred to as crushed (in other words shaped from a forged disk obtained by crushing an ingot: pressure vessel domes and pressuriser domes, steam generator domes, steam generator tubesheet, etc.):

- the "conventional" ingot;
- the "directional solidification (DS) ingot" limiting carbon segregations associated with manufacturing from conventional ingots; it is of limited size which means that it cannot be used to make the largest parts for today's reactors.

As of the early 1990s, in order to improve safety by reducing the number of welds on the equipment of the NSSS, larger parts were envisaged. This was the case first of all with the channels heads of replacement steam generators in the 1990s and then the replacement closure heads in the 2000s. The size of these parts was not compatible with a process using the DS ingot, so these items were produced from a conventional ingot, the use of which has gradually developed.

For the French NPP fleet, several manufacturing processes were thus used in succession for forging reactor pressure vessel domes:

- **900 MWe plant series (1973 – 1987):** forming of a disk from thick plates produced in a rolling mill;
- **1300 MWe plant series (1977 – 1993) and N4 plant series: (1984 – 1999):** forming of a disk from thicker plates rolled in Japan (by The Japan Steel Works, LTD / JSW) and then from disks forged by Creusot Forge, taken from directional solidification ingots;
- **Replacement reactor pressure vessel closure heads for the 900 MWe plant series (1994 – 2008):** same as original manufacturing first of all, then four monobloc[10] closure heads were forged, two by JSW and then two by Le Creusot, from larger "conventional ingots" thus replacing the DS ingot (2006-2007). The monobloc closure heads mean that no welding is required;
- **Replacement closure heads for the 1300 MWe plant series (1995 – 2008):** same as original manufacturing.

With regard to the manufacture of the Flamanville EPR reactor pressure vessel domes, AREVA decided to forge them from a conventional ingot. This choice is explained in section 3.2.

[10] The closure heads traditionally consisted of a dome (the formed part) and a flange (to secure the closure head to the vessel), assembled by a weld. With regard to the monobloc closure heads, they are forged as a single part, which avoids the need for a weld. This is to meet the general objective of improving safety by minimising the number of welds whenever possible.

It should be noted that with regard to the production of domes for the Finnish OL3 EPR reactor pressure vessel, the manufacturer JSW (Japan Steel Works) also opted to forge them from a conventional ingot. However, the specific forging technique developed by JSW enables the final part to be positioned outside the positive macrosegregation zone of the ingot. Consequently, according to AREVA's data and that of STUK, the Finnish nuclear safety regulator, the domes manufactured by JSW for the Finnish EPR reactor contain no positive macrosegregation zones.

With regard to the domes of the two EPR reactors currently under construction in Taïshan, China, they were manufactured in the Creusot Forge plant using the same manufacturing process as that employed for the domes of the Flamanville EPR reactor pressure vessel.

2.6 Current status of the regulations applicable to the design and manufacture of the Flamanville 3 EPR reactor pressure vessel

The requirements applicable to the coolant system of nuclear reactors have changed since the French NPP programme was designed, to take account of operating experience feedback, changing knowledge and modifications to the regulatory framework for non-nuclear equipment.

The regulations applicable to the manufacture of the pressure vessels of the nuclear reactors currently in operation consisted of the order of 26 February 1974 relative to the construction of the main primary system of nuclear steam supply systems , implementing the decree of 2 April 1926 regulating steam pressure vessels.

In the late 1990s, ASN worked on defining the rules applicable to future reactors, notably the EPR reactor, being designed at that time. On this occasion, it referred the matter to the standing nuclear section (SPN) of the French Central Committee for Pressure Equipment (CCAP), which in October 1999 approved a document entitled "*Technical rules for the construction of main primary and secondary systems of PWR nuclear reactors*", subsequently distributed by ASN. The requirements in these technical rules, notably the minimum values for the mechanical properties and the qualification requirements, were the forerunners of the requirements of the current regulations[11].

The regulations applicable to the conformity assessment of the Flamanville EPR reactor pressure vessel consists of:

- decree 99-1046 of 13 December 1999 on pressure equipment;
- the order of 12 December 2005 on nuclear pressure equipment, known as the "ESPN order". In accordance with this order , the reactor pressure vessel is an equipment item classified level **N1**[12], that is the most important for safety. For this type of equipment, this order requires that the material must be

[11] The technical rules for the construction of the main primary and secondary systems of PWR nuclear reactors, require that with respect to the choice of materials *"Unless specifically justified, the materials chosen must have individual, qualification and acceptance characteristics compliant with 2 to 4 below [including the minimum bending rupture energy values]".*

sufficiently ductile and tough. In this respect, for the steels such as that used for the reactor pressure vessel, these requirements are met if the material has the following properties:

- with regard to ductility: an elongation value at least equal to 20% at a temperature of 20°C after fracture in a tensile test;
- with regard to bending rupture energy: an impact toughness energy of at least 60 Joules at 0°C.

These values have not been significantly altered since the order of 1974.
It should also be noted that this "ESPN" order of 12 December 2005 made provision for a transitional period allowing application of the order of 26 February 1974 for the nuclear pressure equipment making up the main primary system of PWR nuclear steam supply systems, for which manufacturing had started less than five years after its publication.

Since then, decree 99-1046 of 13 December 1999 has been codified in the Environment Code, with little change to the law. The assessment of the conformity of the Flamanville EPR reactor pressure vessel is currently ongoing, pursuant to the new texts resulting from this codification:

- section 12 of chapter VII of title V of book V of the Environment Code;
- the order of 30 December 2015 concerning nuclear pressure equipment, which replaced the order of 12 December 2005 concerning the part relative to the manufacture of new equipment.

Since 2005, the regulations require that the manufacturer provide additional guarantees of equipment quality by comparison with the previous regulations. The manufacturer must thus provide more justifications and demonstrations. The risk assessments, qualification methods and inspections are thus expanded.

[12]The order of 12 December 2005 defines level N1 equipment as follows: "The N1 classification is for nuclear pressure equipment which, if it were to fail, could lead to situations for which the safety analysis report of the basic nuclear installation on which it is or will be installed, supplemented by the corresponding files, makes no provision for returning the installation to a safe state, as well as for nuclear pressure equipment making up the main primary system and the main secondary systems of PWR NSSS as defined by the order of 10 November 1999".

3. Qualification of Flamanville 3 EPR reactor pressure vessel domes

3.1 Choice of suppliers

For the manufacture of vessel components for the Flamanville EPR reactor, AREVA used two suppliers:

- **Creusot Forge (France)** for the upper and lower domes[13], as well as for the nozzles;
- **JSW (*The Japan Steel Works, LTD.)* (Japan)** for the shells and transition ring.

It was only possible to procure the nozzle support ring from JSW, which is the only company in the world with the industrial capacity for forging this very large part, an EPR innovation designed to avoid having to weld the shells together.

This procurement system was confirmed in September 2005 by AREVA, notably taking account of the workload and manufacturing schedules both at JSW and at Creusot Forge. The customer and ASN were informed as usual.

The development and revision of the Technical Manufacturing Programme (PTF) took place in the first half of 2006. It was transmitted to ASN on 27 June 2006 and ASN submitted questions on 21 August 2006, more specifically concerning the singularities of the central zone and the homogeneity of the mechanical characteristics.

The vessel closure head dome was poured on **5 September 2006** and its manufacture was completed on **10 October 2006**. The vessel bottom head dome was poured on **23 January 2007** and its manufacturing was completed on **14 December 2007**.

Figure 13: Components procurement table
(Source: ASN)

Component procurement	Component	Manufacturer	Date of casting	Manufacturing completion
	Nozzle support ring with integral flange	JSW	12/08/2005	24/08/2006
	Nozzles G1, G2 and G4	Creusot Forge	01/04/2006	05/10/2006
	Nozzle G3	Creusot Forge	10/01/2007	20/07/2007
	Nozzles H1 to H4	Creusot Forge	27/03/2006	08/12/2006
	Core shell C1	JSW	25/10/2006	14/02/2007
	Core shell C2	JSW	25/10/2006	14/02/2007
	Transition zone	JSW	25/05/2006	04/10/2006
	Vessel bottom head dome	**Creusot Forge**	**23/01/2007**	**14/12/2007**
	Vessel closure head dome	**Creusot Forge**	**05/09/2006**	**10/10/2006**
	Closure head flange	JSW	05/09/2006	10/10/2006

[13] The Creusot Forge plant also supplied the reactor coolant system nozzles.

3.2 Choice of manufacturing process

In accordance with the rules, Creusot Forge drew up a Technical Manufacturing Programme (PTF), which more specifically made provision for the use of a conventional ingot.

This choice of conventional ingot by AREVA for the EPR reactor pressure vessel domes might appear to contradict the efforts made in the early 1980s to produce DS ingots. It was however part of a general trend towards larger parts, driven by the reduction in the number of welds and implying more widespread use of this ingot, which is significantly larger than the DS ingot.

Creusot Forge thus rules out the DS ingot for the EPR reactor pressure vessel closure head, because with the forging processes at Le Creusot, it was not large enough to ensure a satisfactory forging ratio[14] for this part that was thicker than the previous closure heads[15]. The choice of conventional ingot was also consistent with the manufacture of a monobloc closure head for reactor N°3 for the Cruas NPP. Before manufacture of the Flamanville 3 EPR vessel closure head was launched, AREVA and EDF had access to the favourable test results on the central zone of the monobloc vessel closure head intended for Cruas reactor N°3.

For the vessel lower dome, whose dimensions, close to those of the N4, would have probably enabled a DS ingot to be used, Creusot Forge decided to apply the same manufacturing process as for the closure head, for reasons of industrial standardisation.

In accordance with the procedures in force, the PTF was then submitted to the metallurgy and specifications department of the AREVA Saint-Marcel plant (the forged parts customer), to AREVA's materials and engineering technology department in Paris and then to EDF.

Several exchanges and updates of the PTF took place between the stakeholders, without calling into question the forging process using a conventional ingot.

The PTF was developed and revised in the first half of 2006, after which it was transmitted to the ASN Nuclear Pressure Equipment Department (27 June 2006), which issued a number of requests.

The upper dome was poured on 5 September 2006 and the lower dome on 23 January 2007.

After publication of the "ESPN order" of 12 December 2005, the other components of the vessel were all poured between 1 April 2006 and 23 January 2007. Manufacture of the vessel domes was completed on 14 December 2007.

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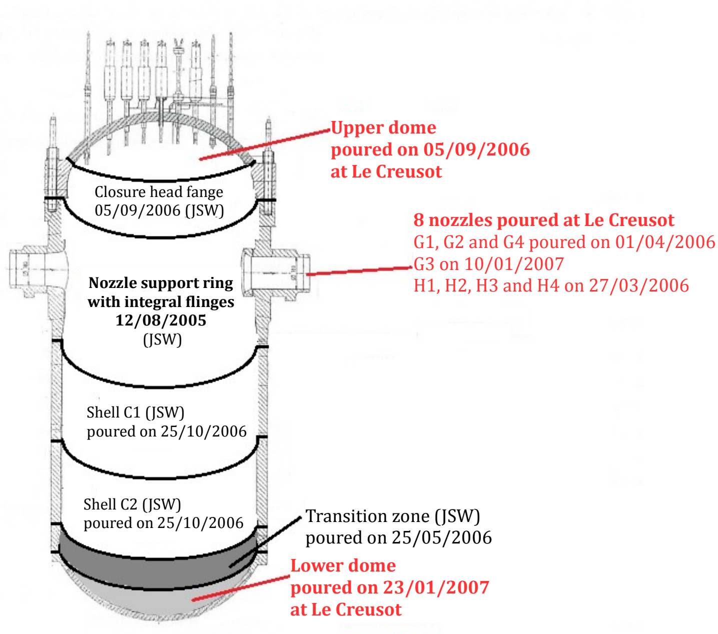
[14]The forging ratio measures the degree of deformation of the part under the effect of forging. It is the deformation under the action of forging which gives the metal the principal characteristic of forged products, by closing any flaws linked to pouring, such as cracks or cavities, by refining the metallurgical structure and increasing the mechanical properties of the steel. The larger a part by comparison with the initial volume of metal, the lower the deformation before the final shape of the part is reached and the lower the forging ratio.

[15]By comparison with the N4 plant series, the EPR vessel closure head is significantly thicker in order to counteract the larger number of penetrations, as the instrumentation passes through the closure head and no longer through the bottom head, with a less pronounced dished form.

These different parts were then assembled and covered with an internal liner in the Saint-Marcel plant. Only the 2 domes and 8 nozzles were forged in France.

Figure 14: Manufacture of reactor pressure vessel parts (Source: ASN)



3.3 Origin of the anomaly

The Flamanville 3 EPR reactor pressure vessel domes were manufactured from an **ingot of 156 metric tons:** the lower and upper domes followed the same manufacturing process from pouring of the ingot up to the forming operation. Only the machining was different, owing to the different thicknesses of the domes (reminder: 145 mm for the lower dome and 230 mm for the upper dome).

The manufacturing process chosen for the Flamanville reactor pressure vessel domes was unable to limit the scale of the heterogeneity in the part.

The anomaly in the Flamanville EPR reactor vessel domes is linked to the presence of an excessive positive macrosegregation zone leading to bending rupture energy values that are below 60 Joules (requirement of the ESPN order)[16]. This positive segregation zone comes from the ingot used for forging of the part. It was not totally eliminated during the cropping and machining phases, as presented in section 2.1.

The following diagrams symbolically illustrate the origin of the anomaly, highlighting the location of this residual positive macrosegregation zone following the ingot cropping operation. At the end of the forming and final machining phase, also presented in section 2.1, it is on the central and external surface of the domes.

[16] Reminder: as mentioned in section 2.2, the target average carbon content on pouring for the EPR vessel closure heads was 0.18%.

Figure 15: Cropping of ingot during forging of the EPR reactor vessel domes
(Source: IRSN)

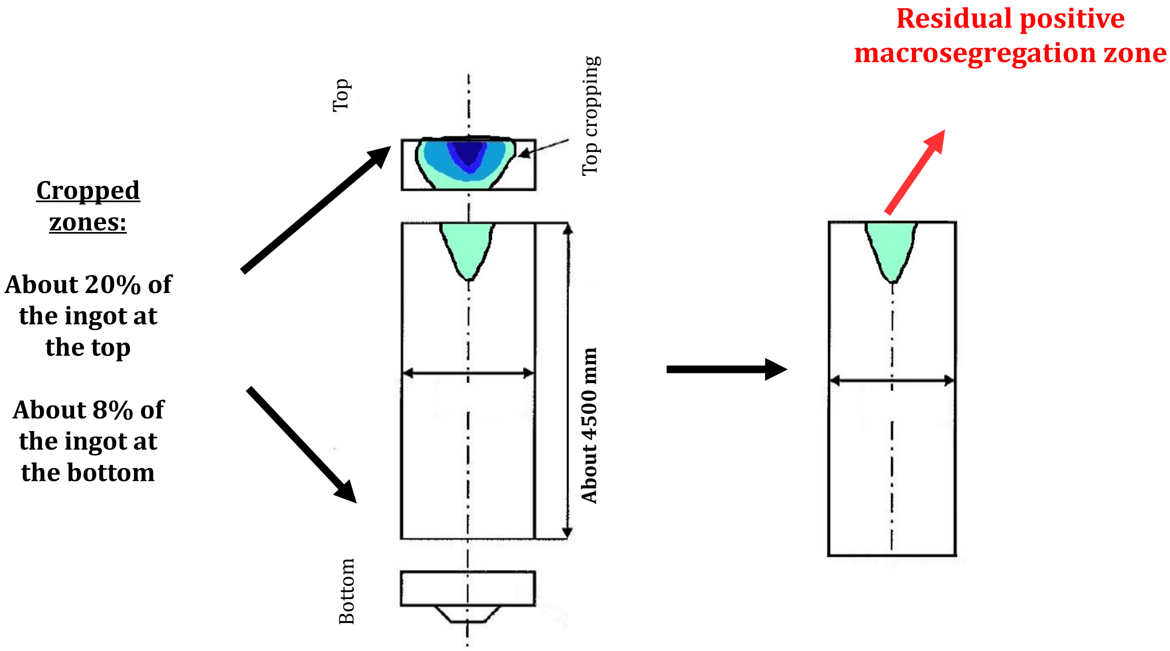
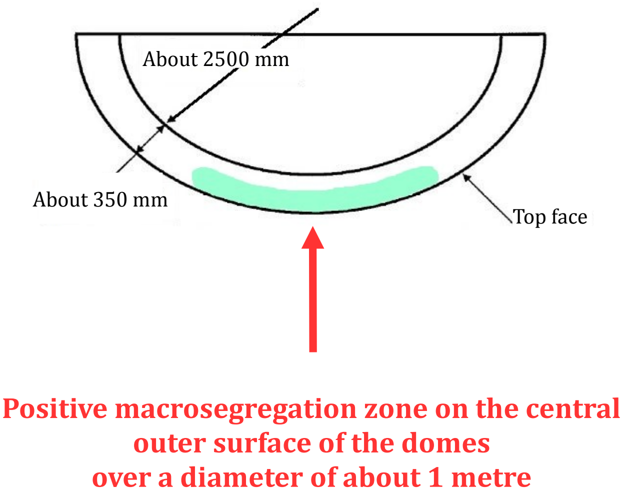


Figure 16: EPR ingot forming
(Source: IRSN)



The manufacturing process for the Flamanville EPR reactor pressure vessel domes was significantly different from the processes used for the N4 reactor pressure vessel domes. The risk involved in this change (a lack of homogeneity in the domes resulting from this change with an ingot of greater mass) was not clearly understood by either the manufacturer or the licensee. For them, the qualification of the monobloc closure head manufactured for the Cruas NPP reactor N°3 (replacement closure head) gave every indication of a favourable outcome for the Flamanville 3 vessel. The weight of the ingot used for its manufacture was about 195 metric tons. That used to manufacture the Flamanville 3 dome, with about 156 metric tons, in principle was no more susceptible to segregation. However, the lower cropping ratio in order to achieve the final weight required meant that the part was left in a zone which proved to be more segregated.

3.4 Regulatory context and requirements expressed by EDF

As previously specified in section 2.6, the regulations applicable at the time of pouring of the components of the Flamanville EPR reactor pressure vessel comprised:

- decree 99-1046 of 13 December 1999 concerning pressure equipment;
- the order of 12 December 2005 concerning nuclear pressure equipment, known as the "ESPN order", published on 22 January 2006.

Given the date on which manufacture of the Flamanville 3 reactor pressure vessel was initiated, the interim provisions of the referenced order of 12 December 2005 meant that the regulations previously in force applied, that is the order of 26 February 1974 relative to the construction of the main primary system of nuclear steam supply systems, supplemented by the technical rules for the construction of main primary and secondary systems for PWR nuclear reactors of October 1999. These tests set out requirements for the properties of comparable materials, more specifically with regard to the bending rupture energy values.

However, the licensee and the manufacturer decided that as of Flamanville 3, the provisions of the referenced order of 12 December 2005 would be applied. The creation authorisation application for the Flamanville EPR reactor, filed by EDF on 9 May 2006, indicates that the referenced order of 12 December 2005 would be applied to the nuclear pressure equipment.
This initiative was positively received by ASN. However, the scale of the work needed to define the methods for application of these provisions had at the time been underestimated, both by AREVA and EDF as well as by ASN.

It should also be noted that the contract placed by AREVA with FRANCE ESSOR (and subsequently Creusot Forge)[17] in 2005 to order the Flamanville 3 reactor pressure vessel domes specified that the requirements to be adhered to were those of the

[17] FRANCE ESSOR is an industrial holding company of the Groupe BOLLORE (Michel-Yves) created in 1986, which bought the Creusot Forge company from the ARCELOR group in 2003 before selling it to AREVA in 2006.

"ESPN" order of 12 December 2005 as well as those of the Design and Construction Rules for Mechanical Equipment (RCC-M)[18].
As mentioned further on, the interpretation concerning the application of minimum values outside the acceptance zones was still being debated by AREVA and ASN at that time.

The reference technical specification of the RCC-M applicable to the vessel domes more particularly stated that, for the forging operations,

- sufficient cropping is required to eliminate shrinkage and most of the segregations,
- the lower face of the dome must be situated on the ingot bottom side (outside the positive macrosegregation zone), in order to avoid the risk of flaws under the liner.

EDF expressed no additional requirement, notably with regard to the segregations in the central and outer part of the domes, considering that this zone was not usually among those considered to be susceptible and that the technical assessment did not at the time anticipate any segregation liable to compromise its mechanical characteristics.

3.5 History of technical qualification of the domes of the Flamanville EPR reactor pressure vessel and identification of the anomaly in 2014

The principle of technical qualification of the components, defined in the technical rules of October 1999, was taken up in the "ESPN" order of 12 December 2005. It designates the process whereby one demonstrates that one will achieve the required quality defined in the part specifications, that one is in control of all the parameters which influence them and that one can ensure that manufacturing is reproducible.

For level N1 nuclear pressure equipment, such as the pressure vessel, the "ESPN" order requires that prior to production, the manufacturer first of all identifies the components for which there is a risk of heterogeneity in their characteristics owing to the steelmaking process or to the complexity of the planned manufacturing operations. All of the manufacturing operations must undergo technical qualification in order to ensure that the components manufactured will have the required characteristics.

Following the 22 January 2006 publication of the "ESPN" order, the methods for justification of compliance with the technical qualification requirement took several years to stabilise.

The manufacture of most of the large components intended for the Flamanville EPR, including the vessel domes, began in 2005 before the technical qualification procedures pursuant to application of the "ESPN" order had been defined and stabilised. The stabilisation of these procedures took time, owing to the changes to the regulations following 30 years of application of the previous regulations.

[18] The RCC-M is the industrial code which prescribes the procedures, rules and practices constituting the professional state of the art for the design, manufacture, inspection and justification of mechanical parts intended for PWR nuclear reactors.

The industrial risk was assumed de facto by the manufacturer. ASN had in fact drawn AREVA's attention to this assumption of industrial risk in a letter dated 16 July 2007.

The first discussions concerning the technical qualifications started in mid-2005 and as of 2006 focused on the development of a generic method for justification of compliance with the requirement. AREVA wished to use the “M140” qualification previously defined in accordance with the RCC-M and which corresponds to an industrial qualification developed by the French Association for NSSS Equipment Design, Construction and In-service Monitoring Rules (AFCEN).

After several years of debate and rejected dossiers, ASN finally stated on 19 February 2008 that the M140 qualification could not act as an ESPN technical qualification as it failed to meet all of its objectives.

The M140 qualification is an industrial qualification **which does not aim to characterise the entire volume of the component,** but focuses on zones identified at the design stage as being susceptible, for example to the risk of fast fracture (e.g.: weld zones). Moreover, it can be based on tests performed on components produced using another technical manufacturing programme.

In this respect, the Flamanville EPR reactor pressure vessel domes obtained their M140 qualification but the conditions necessary for their ESPN technical qualification were not met.

It should be noted that, as of 2006, even if the procedures for demonstration of technical qualification had not yet been stabilised, ASN (BCCN) questioned AREVA about how to prove the homogeneity of the mechanical properties of the domes (ASN letter of 21 August 2006).

In a letter dated 27 November 2006, AREVA replied that this question would be covered by future technical qualification dossiers, following definition of the methods for application of the ESPN order. AREVA was then convinced that M140 qualification of the RCC-M would comply with the technical qualification requirements of the ESPN order and that the domes would meet the requirements of this order.

In September 2009, after numerous exchanges on the contents of the technical qualification dossiers, **ASN and the manufacturer clarified the entire technical qualification process as defined by the ESPN order, its application practicalities and the role of each party.** Technical and metallurgical issues were restored to their place as the focal point of the discussions.

Previously, in 2008, ASN had asked that any pouring of new parts be subject to the prior transmission of a first acceptable version of the technical qualification dossier. The parts of Flamanville 3 poured before that date should undergo subsequent technical qualification meeting the requirements of the ESPN order.

AREVA produced several versions of Technical Qualification Summaries for the domes between 2008 and 2010. With regard to the central external zone, they considered that, after machining, only residual segregations would remain, ensuring correct mechanical properties. This judgement was based on the knowledge available at that time on the segregation of conventional ingots, and in particular on the satisfactory bending rupture energy results obtained on a core sampled from the central part of the monobloc vessel head made for Cruas 3 and on the estimated positioning of the part in the ingot. However, this argument did not appear in the qualification dossiers transmitted to ASN.

During the course of the technical discussions with ASN on the substantiation of management of the risks of heterogeneity and after initially working on numerical simulations based on experimental data for manufacture of forged parts, AREVA in 2011 proposed producing **"scale-one replica"[19] parts to characterise the heterogeneity risks**.

Thanks to the data acquired on the "scale-one replica" parts produced since 2011, the available knowledge has gradually evolved.[20]

In the same year, ASN contacted the **Advisory Committee for nuclear pressure equipment (GP ESPN) concerning the technical qualification rules to be applied, pursuant to the ESPN Order, to parts liable to contain heterogeneous characteristics.**

At its session of 23rd November 2011, the GP ESPN[21]:

- confirmed that the values given in the regulations needed to be verified as individual values rather than simply averages;
- considered that the demonstration of attainment of the characteristics specified in the order was required at all points, including when it could be shown that the zone was not susceptible to fast fracture[22]**;**
- defined the approach to be followed to rule on the aptitude for service of a part for which the state of the art and current practice were unable to demonstrate compliance with the values of the ESPN order at all points, outside the susceptible zones.

This opinion constituted a significant change in terms of technical qualification, with respect to the RCC-M practice which had hitherto been applied.

The fundamentals and the methods for proving technical qualification of the lower and upper domes of the Flamanville EPR reactor then differ slightly.

In February 2012, AREVA transmitted an update of its technical qualification document for the Flamanville EPR reactor parts poured before January 2008 (prior parts) including the lower dome of the EPR reactor pressure vessel in order to analyse

[19] Certain zones of the parts cannot be assessed without destroying the part. Scale-one replica parts are then, when necessary, manufactured and assessed when developing a process or parts that are sufficiently different from the previous ones so that their properties cannot be guaranteed without a specific assessment.

[20] The generic decision was taken in January 2011 that, given the lack of calibrated simulation models with a sufficient range of experimental data from destructive examinations of forged parts, scale-one replica parts would be used.

[21] The GP ESPN opinion of 23 November 2011 states that *"The Advisory Committee considers that, during qualification, the individual mechanical characteristics of the components must be at least equal to those stipulated in the ESPN order. A component which fails to meet the values given in this order, in certain zones, can only be deemed acceptable if a specific justification demonstrates that this difference entails no consequences. The Advisory Committee considers that such a demonstration can only be carried out subsequent to an inconclusive technical qualification with regard to the requirements given in the specifications. It may only be performed on a case by case basis on components for which there is precise knowledge of the mechanical properties obtained."*

[22] In the light of the mechanical loadings and the possibility of appearance of flaws.

the differences between the new stabilised technical qualification requirement practice and the previous one applied by AREVA.

AREVA proposed that technical qualification of the lower dome be accepted as-is, in the light of the results of M140 qualification (including a carbon concentration in the specification at the top, centre), with no specific complement for the central zone.

In July 2012, given that on the one hand the carbon measurements taken during manufacture of the upper dome gave a high carbon concentration at the top and, on the other, that another dome (called UA upper[23]) had become available for testing, **AREVA proposed to ASN that a core be taken from the axis of this dome for performance of mechanical tests and chemical analyses, in order to complete the upper dome file.** The core from the UA upper dome is considered to be a complement to qualification, with AREVA being sure that the requirements would be met.

On 15 October 2012, ASN gave its consent for the UA upper dome coring operation and this was carried out on 12th November 2012.

On 24 January 2014, the EPR reactor pressure vessel was positioned in the cavity in the centre of the reactor building.

It was only **in September 2014 that the core sampled from the UA upper dome was analysed,** following a series of exchanges on how the test specimens were to be made.

The results were forwarded in October and November 2014 to EDF and then to ASN, demonstrating that the values mentioned by the regulations were not reached in the central, outer part of the domes and that the carbon concentration was appreciably higher than expected.

The values measured on two series of three test specimens, sampled from the UA upper dome and representative of those intended for the Flamanville EPR, show an average bending rupture energy value of 52 Joules at 0°C and a minimum value of 36 joules at 0°C, below the bending rupture energy value of 60 Joules mentioned in the ESPN order of 12th December 2005 (see section 3.4).

The investigations carried out by AREVA to determine the origin of these nonconforming values revealed the presence of a positive macrosegregation zone over a diameter of about 1 metre and the presence of these segregations at one-quarter thickness. AREVA attributes the low bending rupture energy values measured to the presence of the positive macrosegregation zone from the ingot used for forging, which was not totally eliminated by the cropping operations.

[23] The UA upper dome was intended for an EPR project in the United States. It was then set aside as a replacement part in the event of failure of the operations to modify the vessel closure head for installation of control rod drive mechanism adapters in 2011. In July 2012, following discussions with ASN further to the back-up scenario being abandoned, the decision was made that the UA upper dome would be used to supplement the prior justification of dome conformity.

3.6. Analysis of the anomaly detection time-line

With hindsight, there were already early warning signs indicating the presence of positive macrosegregations as early as 2007:

- **High carbon concentration value on the upper dome brought to light when metal chips were sampled in 2007**

When forging the domes, AREVA verified the correct orientation of the forged blanks (flat disks) for the two domes, before proceeding with forming to give them their hemispherical shape. The inner liner on the reactor vessel must be welded to the face coming from the bottom of the steel ingot, in other words that on which the carbon concentration is lowest.

To check this, AREVA sampled and analysed several material chips from the two faces of each forged blank in 2007. On the top side, the two upper dome samples gave high carbon concentration values (0.265% and 0.277%) which could have led to questions being asked as to the presence of excessive positive macrosegregations. It should however be remembered that at that time, for the Creusot Forge plant personnel, the only specified purpose of these measurements in the manufacturing process was to ensure that the top and bottom sides of the ingot were correctly identified.

These values appear in 2007 in the M140 qualification summary file of January 2010 which indicates that the results are conforming, as well as in the technical qualification files of April 2010 transmitted to ASN. In these files, AREVA states that the machining carried out after these sampling operations would eliminate the positive macrosegregation zone.

- **Incorrect results brought to light in 2013 during tests performed by the AREVA R&D department**

Additional tests carried out in 2013 on the steel of a steam generator channel head (of the same type as that of the Flamanville EPR reactor vessel domes) gave mediocre results. These tests performed by AREVA R&D, in Lyon, during work to calibrate the numerical models and which were independent from the above-mentioned qualification processes, should have alerted AREVA.

The teams in charge of qualification were not informed of these results by R&D. It should also be pointed out that neither ASN, nor EDF had been notified of these poor results. The personnel at the Le Creusot forge, which was then part of AREVA, were also aware of these poor R&D results (the report had been sent to the AREVA head office from Le Creusot), but there appears to have been no reaction with regard to the consequences for the quality of the steel in the reactor vessel domes at this stage.

4. Approach adopted by AREVA to deal with the anomaly detected in 2014 on the EPR reactor pressure vessel domes

In late 2014, following detection of lower than expected results for the bending rupture energy tests performed for technical qualification of the reactor pressure vessel bottom head and closure head domes on a dome representative of those of the EPR reactor pressure vessel domes, AREVA proposed an approach in 2015 to demonstrate the strength of the vessel domes in normal, incident and accident operating conditions.

The demonstration approach is based on:

- a test programme on test specimens sampled from domes produced using the same manufacturing process (scale-one replicas) in order to estimate the mechanical properties of the zones with a high carbon concentration, primarily the toughness and the brittle-ductile transition temperature.
- A metallurgical analysis of the manufacturing processes and operating conditions demonstrating the absence of any harmful flaw (perpendicular to the surface) in the domes, in particular taking account of the high forging ratio (factor 10 crushing of the material) and the performance of additional checks to confirm this (checks on the vessel bottom head, on the closure head and on scale-one replica parts).[24]
- A file substantiating the transposition of the results obtained on scale-one replica domes to the Flamanville EPR reactor pressure vessel domes, based on a comparison of the manufacturing parameters, on a comparison of the mechanical characteristics in the acceptance zones and a comparison of the surface carbon measurements.
- The calculation of the maximum stresses induced by the pressure and temperature loads in the vessel domes resulting from normal, incident and accident operating conditions. These calculations are performed using thermal-hydraulic and mechanical software. The accident operating situations considered notably take account of thermal shocks (hot or cold).
- The verification that the stresses in the domes in normal and accident operating conditions, taking account of the applicable safety coefficients, remain below criteria (limit toughness curve) which would lead to the propagation of a postulated crack decoupled from and perpendicular to the surface.

[24] It should be noted that AREVA carried out inspections on the EPR reactor pressure vessel domes during manufacturing and the results did not identify any unacceptable flaws:

- a visual inspection of all the surfaces during the various manufacturing phases presented in section 2.1,
- a dye-penetrant inspection of the inner and outer surfaces of the domes after final machining,
- a volumetric ultrasound inspection after final machining.

The demonstration approach proposed by AREVA was submitted to ASN for its opinion in 2015. After examination of the file jointly with its technical support organisation, IRSN, and after obtaining the opinion of the Advisory Committee for nuclear pressure equipment (GP ESPN) which met to discuss this subject on 30 September 2015, **ASN issued a position statement on 14 December 2015 considering that the approach proposed by AREVA was in principle acceptable and expressing no objections to initiating the new test programme scheduled, provided that its observations and requests were taken into account.**

AREVA started the mechanical tests campaign in 2016 in a number of laboratories accredited in accordance with standard NF EN ISO 17025 in order to reinforce the robustness of the results of the test programme and the confidence in its impartiality, as requested by ASN:

- the laboratory at the AREVA Technical Centre in Erlangen, Germany (laboratory involved in the assessment programmes for foreign nuclear reactors, more specifically Doel 3, Tihange 2 and Olkiluoto 3).
- the SCK.CEN laboratory at Mol in Belgium,
- the AMEC laboratory in England.

The carbon contents in each test specimen were measured in the Filab laboratory in France, also accredited in accordance with standard NF EN ISO 17025.

A total of 1722 test speciments were tested during the test programme:

- 797 at the AREVA Technical Centre laboratory in Erlangen,
- 670 at the SCK.CEN laboratory,
- 159 at the AMEC laboratory,
- 96 drop-weight tests at the mechanical testing laboratory in the AREVA Saint-Marcel plant.

ASN also entrusted the BUREAU VERITAS with monitoring of the implementation of the experimental programme as a whole.

In the end, three scale-one replica domes from the same manufacturing process as the Flamanville EPR reactor pressure vessel domes manufactured at the Creusot Forge plant, as opposed to the two initially planned, were used for the test programme: one upper dome manufactured in 2013 and originally intended for the Hinkley Point project in the United Kingdom, two upper and lower domes manufactured between 2009 and 2011 and originally intended for a project in the United States.

In December 2016, AREVA transmitted its file substantiating the adequate toughness of the Flamanille 3 reactor pressure vessel domes, including a file containing the results of tests on the various scale-one replica domes and the limit toughness curve, as well as the calculations of the maximum stresses induced by the pressure and temperature loads in the vessel domes, resulting from normal, incident and accident operating conditions.

These various elements, as well as the answers provided by AREVA to the requests made by ASN in its letter of 14 December 2015 are currently being examined by IRSN and ASN, in order to rule on their acceptability and the aptitude for service of the Flamanville EPR reactor pressure vessel closure head and bottom head.

5. Transparency and public information measures

The licensee EDF, the manfuacturer AREVA and ASN informed the public on 7 April 2015 of the anomaly detected in the Flamanville EPR reactor pressure vessel domes, during its technical qualification tests. The communications by each stakeholder aiming to inform the public about the origin of this anomaly and the steps carried out to deal with it are detailed below.

5.1 Information by EDF and AREVA of the public and the stakeholders concerned

By publishing press releases on their websites, AREVA and EDF informed the public about the anomaly detected on the EPR reactor pressure vessel during its technical qualification and about the progress of the additional tests being carried out to substantiate the strength of the reactor pressure vessel.

On 7 April 2015, they published a joint press release on the non-conformity of the results of the chemical and mechanical tests performed on a part representative of the vessel closure head and bottom head. In this press release, they indicate that their personnel are committed to carrying out additional tests, as early as possible, after ASN approval, and to providing ASN with information to demonstrate the safety and quality of the equipment concerned.

On 13 April 2016, they informed the public of the progress of the test programme on the vessel closure head and bottom head, by publishing a new joint press release. In it, they stated that the test programme had been extended to a third scale-one replica part in order to consolidate the representativeness of the parts tested and that the final report on the analyses conducted would be transmitted to ASN at the end of 2016.

In addition, on 8 July 2015, AREVA published a press release to inform the public about the objectives and time-line of the analyses performed during the reactor pressure vessel closure head and bottom head manufacturing phase, in response to statements in the press on this subject.

In a press release published on 19 April 2015, EDF also informed the public of the new ASN requirements regarding the mechanical specifications with which the EPR reactor equipment was required to comply, since the nuclear pressure equipment (ESPN) order of 2005.

On 3 September 2015, EDF also held a press briefing on the subject of the Flamanville EPR construction site and a press trip on 16 November 2016 to the Flamanville site. EDF also held a number of briefings on the subject of the EPR reactor pressure vessel during the Flamanville CLI meetings and more specifically during the meeting of 28 September 2015.

AREVA and EDF also took part in the technical dialogue day of 15 September 2016 (see section 5.3) to present their respective oversight and monitoring actions during manufacture of the Flamanville EPR reactor pressure vessel.

Within the framework of the anomaly investigation oversight group, set up by the HCTISN, AREVA and EDF presented information concerning the history of the design and manufacture of the Flamanville EPR reactor pressure vessel domes at the request of the members of the oversight group.

It should be noted that the file comprising the results of the tests carried out to demonstrate the strength of the vessel domes in normal and accident operating conditions, transmitted by AREVA to ASN in December 2016 was not made public. However, on 11 May 2017, AREVA published a summary report[25] on its website, giving the results and conclusions of its test and analysis programme carried out for the purposes of this substantiation approach. This report is based on 21 unpublished technical reports.

5.2 Information of the public and stakeholders concerned by ASN and its technical support organisations: IRSN and GPESPN

As part of its duties of nuclear safety and radiation protection oversight and information of the public in these fields, ASN informed the public of the manufacturing anomalies affecting the Flamanville EPR reactor pressure vessel domes in a press release published on its website on 7 April 2015. This communication gave a factual description of the information transmitted by AREVA at the end of 2014 with regard to the results of the bending rupture energy tests performed for technical qualification of the vessel, which were lower than expected. This press release also stated that to deal with this deviation, AREVA had proposed additional tests, with regard to which ASN would be issuing a position statement.

In order to inform the public about the anomaly itself and the progress of the steps taken to deal with it, the ASN website periodically published information notices on this matter and grouped them under a specific heading entitled “EPR reactor pressure vessel anomalies”. They are listed in the appendix to this report and primarily concern:

- the anomaly itself and the history of how it was brought to light, that is:
  - technical details on the EPR vessel manufacturing anomalies,
  - the history of how the anomaly affecting the vessel was brought to light and the exchanges between ASN and AREVA on the subject of the manufacturing of the reactor pressure vessel,

[25] Summary report available on the AREVA NP website: http://www.areva-np.com/businessnews/liblocal/docs/3_Actualites/Comprendre/Note_synthese_tenacite_calottes_cuve_EPR_FA3.pdf

- the ongoing analysis and examination of the anomaly processing file, more particularly:
  - the analyses by the Advisory Committee for nuclear pressure equipment (GPESPN) of the anomaly affecting the EPR reactor pressure vessel closure head and bottom head, which ASN uses as a basis for its resolutions,
  - the ASN position statements of 14 December 2015 and 26 September 2016 on the approach taken by AREVA to demonstrate the adequate toughness of the EPR reactor pressure vessel domes,

- the exchanges between ASN and EDF and AREVA:
  - release to the public of several letters sent by ASN to AREVA since 2006 concerning manufacturing of the vessel,
  - elements from the 8 December 2015 hearing by the ASN Commission of the licensees EDF and AREVA regarding application of the regulations on nuclear pressure equipment,

- ASN's answers to queries from the stakeholders and the public, more specifically with:
  - placing on-line of the ASN presentation to the hearing organised on 25 June 2015 by the Parliamentary Office for the Evaluation of Scientific and Technological Choices (OPECST)[26]
  - placing on-line of the ASN presentation to the hearing organised on 25 October 2016 by the OPECST on the safety of nuclear pressure equipment (ESPN) which heard ASN and its technical support organisation IRSN, the manufacturer AREVA, the licensee EDF and the High Committee for Transparency and Information on Nuclear Safety (HCTISN),
  - an ASN information notice of 4 August 2015 concerning the anomaly and informing the public of an answer transmitted by the ASN Chairman to the Chair of the work group for the monitoring of radioactive risks with regard to the anomaly and ASN communications on the subject.

ASN also gives access to information concerning this matter by providing the public with a section on its website dedicated to the Advisory Committee for nuclear pressure equipment (GPESPN)[27], the investigation reports on this matter and the opinions of this group. The following are in particular available:

- the two reports dated 16 September 2015 and 17 June 2016, issued by ASN and its technical support organisation, IRSN, to the GPESPN, concerning the "Analysis of the approach proposed by AREVA to demonstrate the adequate

[26] Created by Act 83-609 of 8 July 1983, following a unanimous vote by Parliament, the Parliamentary Office for the Evaluation of Scientific and Technological Choices (OPECST), comprising 18 members of Parliament and 18 senators, is tasked by the Act with "informing Parliament of the consequences of scientific and technological choices, more specifically so that it can make fully informed decisions". For this purpose, the Office "collects information, implements study programmes and carries out evaluations". It is assisted by a scientific council of 24 experts of international renown.

[27] Group consisting of experts from civil society, university research laboratories, inspection agencies, expert assessment bodies, the licensees concerned by the subjects covered and safety regulators from other countries.

toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head" and an interim review of this approach respectively,

- the GPESPN opinion of 30 September 2015 and its observations issued on 24 June 2016 concerning the approach proposed by AREVA to demonstrate the adequate toughness of the EPR reactor pressure vessel bottom head and closure head domes and the progress of this approach, respectively.

The ASN position statement letters of 14 December 2015 and 26 September 2016 further to the GPESPN opinions mentioned above, are available on this same page of the website.
All of these documents are also available in English in this same section.

Through its website, ASN's technical support organisation, IRSN, also gives the public access to its documents concerning the safety assessment of the Flamanville EPR reactor. Its opinions and reports on the anomaly are available on a specific page of its website. The IRSN also publishes information notices for the public. With regard to the anomaly, the IRSN placed the following on-line:

- its opinions and analysis reports on this matter, in response to the requests from ASN:

    - its opinion of 3 April 2015 on the technical qualification of the reactor pressure vessel closure head and bottom head domes transmitted to ASN following its request concerning the first data transmitted by AREVA to demonstrate the adequate toughness of the material of the vessel domes,
    - the previously mentioned 16 September 2015 report sent by ASN and IRSN to the GPESPN,

- information notices intended for the public:

    - an information notice of 9 June 2016 concerning the technical examination of the EPR reactor project in Flamanville following the publication of an article on 8 June 2015 by Mediapart mentioning "*a confidential IRSN report [...] on the EPR safety valves in Flamanville*" and "*another report sent in April by the IRSN to ASN [...] on problems with the manufacture of the reactor vessel closure head and bottom head*". In its information notice, IRSN informed the public of the investigations currently in progress on these subjects and the drafting of working documents for the purpose of these investigations. IRSN also stated that in-depth analyses were still needed before it transmitted the conclusions of its investigation to ASN and that these conclusions could be made public on the IRSN website, following the ASN position statement.
    - An information notice of 18 October 2016 concerning the anomalies and irregularities on the EDF reactors in service found during the investigations further to the anomaly concerning the EPR reactor pressure vessel domes.

- The IRSN's replies to the queries from the stakeholders and more specifically its presentation at its OPECST hearing of 25 October 2016 and the video of the hearing.

5.3 Information of the public by other stakeholders and access to assessment of the file

> ➢ HCTISN monitoring of the file concerning the Flamanville EPR reactor pressure vessel anomaly

Following the ASN communication of 7 April 2015 on the manufacturing anomalies affecting the manufacture of the Flamanville EPR reactor pressure vessel, the HCTISN addressed this file and made a precise review of the situation at the plenary meeting of 18 June 2015. It also periodically reported to all its members on the work by the oversight group set up specifically for this matter.
The presentations made during the plenary meeting of 18 June 2015 are available on-line on the HCTISN website (**www.hctisn.fr**) along with the minutes of all the meetings of the High Committee more specifically transcribing the exchanges concerning this matter.

The oversight group have met on seven occasions since the beginning of 2016 in order to record the history of the manufacture of the EPR pressure vessel and gain a clearer understanding of the implications of the anomaly detected, so that this report can summarise all the information collected.
During the course of its works, two visits were also organised for the members of the group by AREVA:

- The first visit took place on 13 May 2016 in the AREVA Technical Centre in Erlangen, Germany, where some of the additional tests are carried out on the scale-one replica parts in the approach to demonstrate the adequate toughness of the reactor pressure vessel domes. During this visit, the entire characterisation programme of the tests performed on the scale-one replica parts was presented to the members of the oversight group, as was the actual performance of certain tests. BUREAU VERITAS, the organisation accredited for evaluating the conformity of pressure equipment and mandated by ASN to monitor the additional tests performed by AREVA, was also presented with the test monitoring procedures (documentary verification, monitoring of operations, traceability, etc.);

- The second visit, dated 23 November 2016, took place at AREVA's "Creusot Forge" plant, where the two vessel closure head and bottom head domes were forged. The history of the plant, the discovery of the manufacturing irregularities[28] brought to light during the manufacturing quality review held following the late 2014 detection of the Flamanville EPR reactor pressure

[28] Although these irregularities were brought to light on the occasion of the quality review initiated following the discovery of the anomalies affecting the EPR vessel domes, they are unrelated to the positive macrosegregation technical problem dealt with in this document.

vessel anomaly and the process to deal with these irregularities were presented to the members of the oversight group. A visit to the workshops also took place.

Via its website (www.hctisn.fr), the HCTISN gives the public access to the working documents drawn up by the oversight group. The list of these documents is given in appendix 4 to this report.

➢ Public hearings of the main stakeholders organised by the OPECST

Hearings open to the press were organised by the Parliamentary Office for the Evaluation of Scientific and Technological Choices on 25 June 2015 and 25 October 2016. They concerned the implications of the manufacturing anomalies detected on the Flamanville EPR reactor pressure vessel and the safety of nuclear pressure equipment. The videos and the minutes of these hearings are accessible on the respective websites of the National Assembly and the Senate. The reports resulting from these hearings are listed in the appendix to this report.
During these hearings, the main stakeholders concerned were asked to shed light on the nature of the flaws, the conditions in which they were identified, the investigations in progress and the foreseeable corrective measures. The following were in particular given a hearing:

- the licensee EDF and the manufacturer AREVA,
- ASN and its technical support organisation IRSN,
- the HCTISN.

Representatives from the following also took part in the first hearing:

- the General Directorate for the Prevention of Risks at the Ministry responsible for the environment and energy,
- the International Atomic Energy Agency (IAEA),
- the French Association for design, construction and in-service monitoring rules for NSSS equipment (AFCEN) and the Association for the quality of pressure vessels (AQUAP),
- CEA and the Catholic University of Louvain.

➢ “Technical dialogue” days organised by IRSN, ANCCLI, the Flamanville CLI and ASN

“Technical dialogue” days concerning the anomalies affecting the EPR reactor pressure vessel were also organised by IRSN, the National Association of local information committees and commissions (ANCCLI)[29], the Flamanville CLI and ASN.
The HCTISN participated as part of a process of dialogue, notably in terms of access to the scientific and technical knowledge of the IRSN. The Flamanville CLI also convened its members on 28 September 2015 on this subject.
Since December 2015, three “technical dialogue” meetings held on 2 December 2015, 6 April 2016 and 15 September 2016 have enabled civil society stakeholders to learn about the safety issues and make their own contribution. The aim of these days is to enable the members of the CLI and the stakeholders in general to access the expert assessment of the anomaly in the composition of the steel in the Flamanville EPR reactor pressure vessel and to be able to discuss it throughout the investigation process.

Among the questions tackled at the request of the participants from civil society, the approach to demonstrate the quality of the vessel despite the anomalies observed and the representativeness of the tests were very much in the spotlight. The agendas of these meetings and the presentations made to them are listed in the appendix to this report and are published on the websites of the organisers (websites of IRSN, ANCCLI and ASN).
A further meeting is scheduled for 5 July 2017 and should be an opportunity to discuss the main elements of the ASN and IRSN investigation report presented to the GPESPN in June 2017 concerning the file demonstrating the adequate toughness of the Flamanville 3 reactor pressure vessel domes transmitted by AREVA in December 2016.

5.4 Information of the public by the environmental protection associations

A number of environmental protection associations presented their viewpoints on the subject of the Flamanville EPR vessel anomaly via their respective websites, notably the international “Greenpeace” organisation (https://www.greenpeace.fr/), the “Réseau sortir du nucléaire” organisation (http://www.sortirdunucleaire.org/) and the association for information and monitoring of radioactivity (ACRO) on a specific website (http://transparence-nucleaire.eu.org/).

6. HCTISN opinions and recommendations

The HCTISN points out that since it was revealed on 7 April 2015 by ASN, EDF and AREVA, the information concerning the anomaly detected on the domes of the Flamanville EPR reactor pressure vessel, during the tests conducted for its technical

[29] The National Association of local information committees and commissions is a non-profit organisation bringing together 37 local information committees. In France, each nuclear facility has a local information committee (CLI) which informs the population about nuclear activities and which permanently monitors the impact of the nuclear facilities.

qualification, have been the subject of widely differing communications to the public by the various stakeholders concerned.

The HCTISN underlines the fact that ASN regularly published information notices on this subject, notably to inform the public about the history of its exchanges with AREVA on the subject of vessel manufacturing and to inform the public of its position with regard to the approach proposed by AREVA to demonstrate the aptitude for service of the reactor pressure vessel. ASN thus released to the public a number of letters it had sent to AREVA since 2006 concerning the manufacturing of the reactor pressure vessel. AREVA's replies to these letters have not however been made public. ASN posted an “information package” on its website, specifically on the subject of the “EPR reactor pressure vessel manufacturing anomalies”[30] giving the public easy access to all ASN information notices on this subject, in accessible and informative language and enabling them to obtain the latest news.

Similarly, since 2015, the IRSN has given the public access to its expertise on this subject by regularly publishing its opinions, its information notices and its presentations on the matter to the OPECST and the HCTISN, on a specific page of its website[31]. The posting on-line, in the “Actualités” (News) section of the IRSN's website, of the presentations made to the technical dialogue meetings set up by IRSN, the ANCCLI, the Flamanville CLI and ASN on this subject, gives the general public further expert information about this matter.

The HCTISN does however note that communication by the licensee EDF and the manufacturer AREVA intended for the public on this subject is rather more succinct. On 7 April 2015, these stakeholders informed the public of the anomaly detected in the reactor pressure vessel domes and then, one year later, on 13 April 2016, they made public the progress of the additional testing programme being carried out to demonstrate the aptitude for service of the vessel.
EDF and AREVA did not give the public an explanation of the origin of the anomaly or the history of the design and manufacture of the EPR reactor pressure vessel. EDF and AREVA only presented these aspects to the HCTISN oversight group. They will in fact become accessible to the public with the publication of this present report. The HCTISN also wishes to point out that these stakeholders, at the urging of all the members of the oversight group, provided precise information on this subject during the exchanges at the meetings of the group as well as during visits to the AREVA Technical Centre in Erlangen, Germany and to the AREVA “Creusot Forge” plant (see section 5.3).

In addition, EDF and AREVA did not inform the public, at the end of 2016, of the submission to ASN of the final analysis report produced for the demonstration of the serviceability of the EPR reactor pressure vessel. The public was informed neither of

[30] Information package devoted to the “EPR reactor pressure vessel manufacturing anomalies” available on the ASN website, at the following address: https://www.asn.fr/Informer/Pedagogues/Anomalies-de-la-cuve-de-l-EPR-et-irregularites-usine-Creusot-Forge-d-AREVA

[31] Page of the IRSN website for “Opinions and reports on the carbon segregation anomalies affecting the Flamanville 3 EPR reactor pressure vessel domes and certain SG channel heads in the NPPs in service” http://www.irsn.fr/FR/expertise/theme/Pages/Avis-rapports-segregation-carbone.aspx#.WRIbQFXyjIU

the form nor of the content of this file produced by AREVA at the time it was submitted to ASN.
Since then, AREVA published the summary report on this file[32] on its website on 11 May 2017 with certain points blanked out on the grounds of industrial confidentiality.

The HCTISN also notes that EDF and AREVA issued no public communication regarding the alternative scenarios envisaged if the results of the demonstration of the aptitude for service of the EPR reactor pressure vessel were to prove inconclusive.

The HCTISN considers that the public was informed of the anomaly relating to the composition of the steel in certain zones of the Flamanville EPR reactor pressure vessel closure head and bottom head, primarily as a result of active and regular communication by ASN and its technical expert, IRSN, with documents being posted on their respective websites. They also answered queries from the media.

Public access to the minutes of the 25 June 2015 and 25 October 2016 hearings of all the stakeholders by the OPECST on the websites of the National Assembly and the Senate, shed additional light on this matter. These hearings were an opportunity to make public the viewpoints of EDF and AREVA on the causes of the reactor pressure vessel manufacturing flaws and the steps being taken to demonstrate its aptitude for service.

The HCTISN also welcomes and encourages the initiatives taken by IRSN, ANCCLI, the Flamanville CLI and ASN to foster access to expert opinion on this subject, notably by organising technical dialogue meetings and posting the corresponding presentations on-line.

The HCTISN considers that AREVA and EDF should publish the answers to the letters sent to them by ASN since 2006 regarding vessel manufacturing, in order to improve the public's understanding of this matter. The HCTISN also considers that periodic and more frequent information of the public by EDF and AREVA, to present the contents of the approach being followed to demonstrate the strength of the vessel domes, as detailed in section 4 of this report, and to inform it of the progress of this approach, would have enabled the public to gain a clearer appreciation of the objectives and scope of the additional analyses and studies to be carried out.
The HCTISN also considers that public communication by EDF and AREVA on the alternative technical scenarios envisaged should the investigation lead to rejection of the reactor pressure vessel closure head and bottom head, would also have completed its information regarding the matter as a whole and more specifically on the potential consequences of the vessel anomaly.

To all the stakeholders concerned, the HCTISN recommends increased transparency on this matter, to enable each individual to gain access to all the

[32] Summary report available on the AREVA NP website: http://www.areva-np.com/businessnews/liblocal/docs/3_Actualites/Comprendre/Note_synthese_tenacite_calottes_cuve_EPR_FA3.pdf

information needed to follow the decision-making process and participate in the resulting public consultation. The HCTISN in particular recommends that EDF and AREVA make public the final report on the analyses performed as part of the approach to demonstrate the aptitude for service of the EPR reactor pressure vessel - on the basis of which ASN will issue its position statement – and inform the public of the alternative solutions envisaged if the aptitude for service of the reactor pressure vessel were not to be demonstrated.

The HCTISN therefore recommends that all stakeholders ensure that the information made available to the public is prioritised, accompanied by explanations and drafted in plain language making it easier to understand, as the subject is a complex and highly technical one.

Finally, the HCTISN notes with interest the communication by ASN to its foreign counterparts regarding the Flamanville EPR reactor pressure vessel manufacturing anomalies. The HCTISN recommends that all the stakeholders (manufacturer, licensee, ANCCLI, environmental protection associations, technical experts, etc.) share this information with their foreign counterparts. The English translation of this report will facilitate this information dissemination process.

More generally, the HCTISN notes that the work of the oversight group has triggered a change in attitude leading to the creation of a new dynamic within the oversight group and a move towards transparency by all those involved.

The HCTISN thus expects the oversight group to continue its mission until the publication of the ASN technical position statement on this matter.

APPENDIX 1:

LIST OF FIGURES IN THE REPORT

APPENDIX 2:

LIST OF MEMBERS OF THE HCTISN OVERSIGHT GROUP FOR THE EPR REACTOR PRESSURE VESSEL ANOMALY

Name	HCTISN member / invited outside personality	HCTISN / Company or Organisation College
Ancelin Claudie	Invited outside personality	EDF
Bettinelli Benoît	HCTISN general secretary	
Blaton Elisabeth	HCTISN technical secretary	
Boilley David	HCTISN alternate member	Association College (ACRO)
Bonnemains Jacky	HCTISN full member	Association College (Robin des bois)
Catteau Rémy	Invited outside personality	ASN
Collet Julien	Invited outside personality	ASN
Comets Marie-Pierre	HCTISN Chair	College of qualified personalities
De L'Epinois Bertrand	Invited outside personality	AREVA
Faucheux Christophe	HCTISN alternate member	College of trade union organisations (CFDT)
Gosselin-Fleury Geneviève	HCTISN full member	College of members of Parliament
Guétat Philippe	HCTISN alternate member	College of trade union organisations (CFE-CGC)
Guillemette Alain	HCTISN full member	State College (DSND)
Herviou Karine	Invited outside personality	IRSN
Lacote Jean-Paul	HCTISN full member	Association College (FNE)
Laurent Michel	HCTISN full member	CLI college
Marchal Bruno	Invited outside personality	AREVA
Miraucourt Jean-Marc	Invited outside personality	EDF
Pochitaloff Pierre	HCTISN full member **Head of oversight group**	College of trade union organisations (SPAEN)
Rollinger François	HCTISN alternate member	State College (IRSN)
Rousselet Yannick	HCTISN full member	Association College (Greenpeace)
Sené Monique	HCTISN full member	CLI college
Spautz Roger	HCTISN alternate member	Association College (Greenpeace)
Viers Stéphanie	HCTISN technical secretariat	
Wallendorff Claude	HCTISN full member	College of CLI

APPENDIX 3:

REFERRAL LETTER FROM THE MINISTER DATED 5 OCTOBER 2015

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

MINISTÈRE DE L'ÉCOLOGIE, DU DÉVELOPPEMENT DURABLE
ET DE L'ÉNERGIE

La ministre

Paris, le 0 5 OCT. 2015

Madame la Présidente,

L'Autorité de sûreté nucléaire (ASN) a rendu publique le 7 avril 2015 une anomalie de la composition de l'acier dans certaines zones du couvercle et du fond de cuve du réacteur de l'EPR de Flamanville.

AREVA a proposé à l'ASN de réaliser une campagne d'essais approfondie sur un couvercle représentatif pour connaître précisément la localisation de la zone concernée ainsi que ses propriétés mécaniques. L'ASN doit maintenant se prononcer sur le programme d'essai proposé, s'assurer de sa bonne réalisation et enfin statuer sur la résistance de la cuve du réacteur EPR de Flamanville, et fait appel pour cela à son appui technique, l'Institut de radioprotection et de sûreté nucléaire (IRSN) et au groupe permanent d'experts dédié aux équipements sous pression nucléaires.

En vertu des missions que la loi confie au Haut comité à la transparence et à l'information sur la sécurité nucléaire que vous présidez, je souhaite vous saisir afin que le Haut comité veille à la transparence du processus et s'assure de la bonne transmission des informations vers la société civile.

Je souhaite en particulier qu'il examine les conditions dans lesquelles le public est informé des réponses aux questions suivantes :

- Comment cette anomalie s'est-elle produite et pourquoi a-t-elle été révélée 9 ans après la fabrication des pièces incriminées ?

Madame Marie-Pierre COMETS
Présidente du Haut-Comité pour la transparence et l'information sur la sécurité nucléaire
DGPR Tour Séquoia
92055 PARIS LA DEFENSE CEDEX

Hôtel de Roquelaure – 246, boulevard Saint-Germain – 75007 Paris – Tél : 33 (0)1 40 81 21 22
www.developpement-durable.gouv.fr

- Quels sont les phénomènes physiques sous-jacents et leurs conséquences en terme de sûreté dans le contexte de l'EPR, expliqués dans un langage pédagogique ?

- Quelles sont les mesures prises par AREVA et EDF pour assurer l'information du public et la transparence de ce programme d'essais sur la cuve témoin, en particulier sur les tests qui seront réalisés et les résultats obtenus, ainsi que sur l'analyse de la conformité de la cuve de l'EPR de Flamanville 3 au regard de la règlementation relative aux équipements sous pression nucléaires ?

Je souhaite qu'il ne puisse subsister, à l'issue du processus de tests et d'analyse, aucune zone d'ombre sur leurs conditions de réalisation et la teneur de leurs résultats.

Vous prendrez contact avec l'Autorité de sûreté nucléaire, l'Institut de radioprotection et de sûreté nucléaire, AREVA et EDF pour organiser votre mission. L'agenda de votre mission sera élaboré en fonction de celui de l'instruction technique pilotée par l'ASN et se conclura par la rédaction d'un rapport public que vous me remettrez à l'issue de ce processus.

Je vous prie d'agréer, Madame la Présidente, l'expression de mes salutations les meilleures.

Ségolène ROYAL

APPENDIX 4:

WORKING DOCUMENTS PRODUCED BY THE OVERSIGHT GROUP

- ASN note of 21 March 2016 on the manufacturing history of the vessel and the technical qualification of its domes, on the regulatory context and the checks it carried out and asked to have carried out on the reactor pressure vessel: "Preparatory note for the meeting of 23 March 2016 of the HCTISN oversight group for the Flamanville 3 reactor pressure vessel anomaly"

- EDF report of 29 June 2016: "EDF history of Flamanville 3 reactor pressure vessel domes"

- AREVA report of 26 June 2016: "History of FA3 reactor pressure vessel domes"

- 13 May 2016 visit by members of the oversight group to the AREVA Technical Centre in Erlangen, Germany: Presentations by AREVA of the test programme run on the scale-one replica domes and by Bureau Veritas on the test monitoring procedures

- 23 November 2016 visit by the members of the oversight group to the AREVA Creusot Forge plant: Presentation by AREVA of the history of the Creusot Forge plant, of the discovery of the manufacturing irregularities[33] brought to light during the manufacturing quality review carried out further to the detection at the end of 2014 of the anomaly in the Flamanville EPR reactor pressure vessel and the process for dealing with these irregularities

- Minutes of the meetings of the oversight group on 27 January 2016, 23 March 2016, 29 June 2016, 5 October 2016, 21 February 2017, 25 April 2017 and 24 May 2017

[33] Although brought to light on the occasion of the quality review initiated further to the discovery of the anomalies on the EPR reactor pressure vessel domes, these irregularities are unrelated to the positive macrosegregation problem dealt with in this document.

APPENDIX 5:

PUBLIC COMMUNICATIONS CONCERNING THTE FLAMANVILLE EPR REACTOR PRESSURE VESSEL ANOMALY

1. Communications by AREVA:

- Press release:

Press releases available on the following page of its website: *http://www.areva.com/FR/actualites-10753/epr-de-flamanville-etat-d-avancement-du-programme-d-essais-de-la-cuve.html*

- Joint AREVA and EDF press release of 13 April 2016: Flamanville EPR: state of progress of vessel test programme

- Joint AREVA press release of 8 July 2015: Flamanville EPR vessel: the chronology clearly shows transparency on the part of AREVA

- News file:

File published on 11 May 2017 on its website, concerning the "Quality of manufacture of nuclear reactor components: focus on the Flamanville 3 EPR reactor pressure vessel" notably comprising the summary report called "Demonstration of adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes"
File available on the following page of its website: http://www.areva-np.com/FR/businessnews-377/qualite-des-fabrications-des-composants-des-reacteurs-nucleaires-focus-sur-la-cuve-du-reacteur-epr-de-flamanville-3.html

2. Communications by EDF:

- Press release:

Press releases available on the following page of its website: *https://www.edf.fr/groupe-edf/espaces-dedies/medias/tous-les-communiques-de-presse/epr-de-flamanville-etat-d-avancement-du-programme-d-essais-de-la-cuve*

- Joint AREVA and EDF press release of 7 April 2015: Flamanville EPR: continuation of vessel qualification tests

- EDF press release of 2 June 2015: Conformity of Flamanville 3 equipment with the new requirements applicable to nuclear reactors

- Joint AREVA and EDF press release of 13 April 2016: Flamanville EPR: state of progress of vessel test programme

- Press briefing and press trip:

EDF organised a press briefing on 3 September 2015 on the subject of the EPR construction site at Flamanville.

A press trip was also organised on 16 November 2016 to the Flamanville 3 site, for about thirty journalists.

3. Communications by ASN:

- Press release:

Press releases available on the following page of the ASN website:
https://www.asn.fr/Informer/Actualites/
https://www.asn.fr/Informer/Dossiers-pedagogiques/Anomalies-de-la-cuve-de-l-EPR-et-irregularites-usine-Creusot-Forge-d-AREVA/Anomalies-de-la-cuve-de-l-EPR

- Press release of 7 April 2015 "Manufacturing anomalies in the Flamanville EPR reactor pressure vessel"

- Press release of 26 October 2016 "OPECST hearing on the anomalies and irregularities detected on nuclear pressure equipment. ASN reviews the dossier": On 25 October 2016, ASN took part in the hearing organised by the Parliamentary Office for the Evaluation of Scientific and Technological Choices, concerning the safety of nuclear pressure equipment (ESPN). OPECST heard ASN and its technical support organisation, IRSN, the manufacturer AREVA NP, the licensee EDF, and the High committee for Transparency and Information on Nuclear Security (HCTISN).

- Information notices:

Information notices available on the following page of the ASN website:
https://www.asn.fr/Informer/Dossiers-pedagogiques/Anomalies-de-la-cuve-de-l-EPR-et-irregularites-usine-Creusot-Forge-d-AREVA/Anomalies-de-la-cuve-de-l-EPR

- ASN information notice appended to the press release published on 8 April 2015 on "Technical clarifications on the manufacturing anomalies affecting the Flamanville EPR reactor pressure vessel"

- Information notice of 23 June 2015: News letter n°17: ASN actions to monitor the Flamanville EPR reactor construction site: significant points

- Information notice of 8 July 2015: History of the discovery of the anomaly affecting the Flamanville EPR reactor pressure vessel (excessive carbon content in the vessel closure head and bottom head)

- Information notice of 4 August 2015: Information notice on the anomaly in the Flamanville EPR reactor pressure vessel domes, informing the public of an answer transmitted by the ASN Chairman to the Chairman of the association for the control of radioactive risks concerning the anomaly in the EPR vessel domes and the ASN communication on the subject

- Information notice of 30 September 2015: ASN convened the Advisory Committee for nuclear pressure equipment regarding the anomaly affecting the Flamanville EPR reactor pressure vessel closure head and bottom head

- Information notice of 16 December 2015: Flamanville 3 EPR reactor pressure vessel: ASN has no objection to the initiation of a new test programme, with a link to the letter of 14 December 2015 sent by ASN to AREVA

- Information notice of 19 January 2016: Nuclear pressure equipment: the ASN Commission gave a hearing to EDF and AREVA

- Information notice of 20 April 2016: ASN makes available to the public several letters sent to AREVA since 2006 on the manufacture of the Flamanville EPR reactor pressure vessel

- Information notice of 3 May 2016: AREVA informed ASN of irregularities concerning components manufactured in its Creusot Forge plant

- Information notice of 13 June 2016: ASN publishes a notice on the history of its exchanges with AREVA on the subject of the manufacture of the Flamanville EPR reactor pressure vessel

- Information notice of 16 June 2016: Irregularities detected in the AREVA Creusot Forge plant: interim review by ASN

- <u>Examination reports, GPESPN opinion and ASN position statement letters</u>*:*

Documents available on the following page of the ASN website:
https://www.asn.fr/L-ASN/Appuis-techniques-de-l-ASN/Les-groupes-permanents-d-experts/Groupe-permanent-d-experts-equipements-sous-pression-nucleaires-GPESPN

- Report drawn up by IRSN and the ASN Nuclear Pressure Equipment Department (DEP) for the Advisory Committee on nuclear pressure equipment "Analysis of the approach proposed by AREVA to demonstrate the adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes " - Session of 30 September 2015 (Reference: CODEP-DEP-2015-037971 - Report IRSN/2015-00010 Public version / shaded parts subject to industrial confidentiality)

- GPESPN opinion of 30 September 2015 concerning the approach proposed by AREVA to demonstrate the adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes

- ASN position statement letter to AREVA NP of 14 December 2015 concerning the approach to demonstrate the adequate toughness of the reactor pressure vessel bottom head and closure head domes

- Summary report of 17 June 2016 to the Advisory Committee for nuclear pressure equipment "Approach proposed by AREVA to demonstrate the adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes – Interim review" (Reference: CODEP-DEP-2016-019209 - Report IRSN/2016-00005)

- GPESPN comments of 24 June 2016 concerning the progress of the approach proposed by AREVA to demonstrate the adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes

- ASN position statement letter to AREVA NP of 26 September 2016 concerning the interim review of the approach to demonstrate the adequate toughness of the bottom head and closure head domes, asking AREVA NP to prepare a public version of the file to be submitted to ASN

4. Communications by IRSN:

- IRSN opinions and analysis reports:

Documents available on the following page of the IRSN website:
http://www.irsn.fr/FR/expertise/theme/Pages/Avis-rapports-segregation-carbone.aspx

- Report issued by IRSN and the ASN Nuclear Pressure Equipment department (DEP) to the Advisory committee for nuclear pressure equipment "Analysis of the approach proposed by AREVA to demonstrate the adequate toughness of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head domes" - Session of 30 September 2015 (Reference; CODEP-DEP-2015-037971 - Report IRSN/2015-00010 Public version / shaded parts subject to industrial confidentiality)

- IRSN opinion 2015-00118 of 3 April 2015: Technical qualification of Flamanville EPR reactor pressure vessel closure head and bottom head domes – Opinion published on 24 June 2015 in reply to a request from ASN, regarding the choice of the "vessel dome" chosen for performance of the regulation tests and the corresponding cutting programme, further to discovery of a manufacturing problem affecting the closure head and bottom head of the Flamanville EPR reactor pressure vessel.

- IRSN information documents:

Documents available on the following pages of the IRSN website:
http://www.irsn.fr/FR/expertise/theme/Pages/Avis-rapports-segregation-carbone.aspx

and
http://www.irsn.fr/fr/actualites_presse/actualites/

- IRSN information notice of 18 October 2016: EDF NPP fleet in service - Anomalies and irregularities detected during investigations further to the anomaly concerning the Flamanville EPR reactor pressure vessel domes

- IRSN information notice of 9 June 2015 concerning the technical investigation into the Flamanville EPR reactor project

- IRSN presentation to the OPECST on 25 October 2016: Manufacturing anomalies affecting the FA3 EPR vessel domes and the steam generators in the EDF NPP fleet

- Video of the OPECST hearing of 25 October 2016

5. OPECST reports

Documents available on the following pages of the websites of the National Assembly and the Senate:
http://www.assemblee-nationale.fr/documents/index-general-oecst.asp
and
http://www.senat.fr/opecst/rapport.html

- Report on behalf of the OPECST of 9 July 2015 on "The monitoring of nuclear pressure equipment: the case of the EPR reactor pressure vessel" - Minutes of the public hearing of 25 June 2015 and the presentation of the conclusions of 8 July 2015
National Assembly reference: 2968 (14th legislature)
Senate reference: 613 (2014-2015)

- Report on behalf of the OPECST of 9 March 2017 on "The safety of nuclear pressure equipment" – Minutes of the hearing open to the press on 25 October 2016 and the presentation of the conclusions of 8 March 2017
National Assembly reference: 4579 (14th legislature)
Senate reference: 462 (2016-2017)

6. “Technical dialogue” days concerning the Flamanville 3 EPR reactor pressure vessel manufacturing anomaly

Presentations made during the course of these days available on the following page of the IRSN website:
http://www.irsn.fr/FR/connaissances/Nucleaire_et_societe/expertise-pluraliste/IRSN-ANCCLI/Pages/19-Seminaire-reacteur-EPR-cuve-anomalie_2015-2016.aspx

- Meeting of 2 December 2015 - Issues of the demonstration approach for the EPR vessel

  - Presentation of the Flamanville 3 EPR reactor pressure vessel and its domes, history of manufacturing of the domes and the qualification approaches (ASN)
  - Domes demonstration approach (IRSN)
  - Interface between demonstration approach and the regulations (ASN)

- Meeting of 6 April 2016 – ASN position statement letter on the demonstration approach presented by Areva, as well as on the representativeness of the scale-one replica parts:

  - Reminder of conclusions of the meeting of 2 December 2015 (IRSN)
  - ASN position statement letter of 14 December 2015 (ASN)
  - Tests on scale-one replica parts: representativeness (IRSN)
  - Other ASN requests (ASN)
  - Schedule and progress of operations (AREVA)

- Meeting of 15 September 2016 - Manufacturing anomalies on forged parts, checks performed at manufacturing of the Flamanville 3 reactor pressure vessel, changes to the demonstration approach:

  - Manufacturing anomalies on parts of nuclear pressure equipment (ASN review / viewpoint of Greenpeace)
  - Checks performed at manufacturing of the reactor pressure vessel (AREVA, EDF, ASN)

7. Communication to the public by environmental protection associations

Several environmental protection associations presented their views on the anomaly affecting the Flamanville EPR reactor pressure vessel via their respective websites, notably:

- the “Greenpeace” international organisation: https://www.greenpeace.fr/
- the “Réseau sortir du nucléaire” association: http://www.sortirdunucleaire.org/
- the information and monitoring of radioactivity association (ACRO) on a dedicated website: http://transparence-nucleaire.eu.org/

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