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Analysis of the procedure proposed by AREVA to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel (RPV) lower head and closure head

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References

[1] Directive 97/23/EC of the European Parliament and of the Council of 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment

[2] Decree of 2 April 1926 regulating steam pressure vessels

[3] Decree 99-1046 relative to nuclear pressure equipment

[4] Decree 2007-534 of 10 April 2007 authorising the creation of the BNI referred to as Flamanville 3, comprising an EPR type nuclear reactor, on the Flamanville site (Manche département);

[5] Order of 26 February 1974 relative to the construction of the main primary system of nuclear steam supply systems

[6] Order of 12 December 2005 relative to nuclear pressure equipment, called the "ESPN order".

[7] Order of 7 February 2012 setting the general rules concerning basic nuclear installations

[8] Technical rules relative to the construction of the future main primary system (MPS) and main secondary system (MSS) of 19 October 1999

[9] RCC-M Code, 2007 edition, AFCEN

[10] Communication at the "10th International Forging Conference, Sheffield (UK) 23-25 September 1985": "Application of Directional Solidification Ingot (LSD) in forging of PWR Reactor vessel heads – Benhamou, C. Poitrault".

[11] AREVA Technical Notice D02-PEE-F-15-0007 of 24 April 2015: "FA3 reactor pressure vessel (RPV) domes - Design and fabrication"

[12] AREVA Technical Notice D02-PEEM-F-15-0368 of 11 May 2015: "Justification procedure for the FA3 reactor pressure vessel (RPV) closure head and lower head"

[13] Note PFCSGN/NCR0003 revision B of 10 March 2015: "Programme of tests on scale-one replica: first phase"

[14] Note MDHTDM DT 15.020 revision A of 30 April 2015: "Programme of tests on scale-one replica dome: determination of the zone with major positive carbon segregation in the thickness"

[15] Note PFCSGN/NCR0002 revision C of 30 July 2015: "Programme of tests on scale-one replica dome: mechanical tests"

[16] Note PFCSGN/NCR0004 revision A of 30 July 2015 : "Cutaway of the upper segregation zone of UK dome for Carbon mapping"

[17] Note PFCSGN/NCR0005 revision A of 30 July 2015: "First stage of the test programme on UA lower scale-one replica"

Acronyms, abbreviations and designations

ASME: American Society of Mechanical Engineers

ASTM: American Society for Testing and Material

ASN: Autorité de Sureté Nucléaire (French Nuclear Safety Authority)

CCAP: Central commission for pressure equipment

CHB: Chinon B nuclear power plant

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

CT: Compact Tension

DEP: Nuclear pressure equipment department of ASN

EPR: European Pressurized Reactor

NPE: Nuclear Pressure Equipment

FA3: Flamanville 3 EPR

FSH: Fessenheim nuclear power plant

GP ESPN: Advisory Committee of Experts for Nuclear Pressure Equipment

BNI: Basic Nuclear Installation

IRSN: Institut de Radioprotection et de Sûreté Nucléaire
(French Institute for Radiation Protection and Nuclear Safety)

JSW: Japan Steel Works

LSD: Directional solidification ingot

MWe: Megawatt electrical

N4: French reactors of 1450 MWe operated by EDF (Civaux 1 and 2, Chooz B1 and B2)

NDT: Nil Ductility Transition

OL3: Olkiluoto 3 EPR

PS: Maximum permissible pressure

QT: Technical qualification

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

RRA: Residual heat removal system

R_m: Tensile strength

RT_{NDT} : Reference Temperature for Nil Ductility Transition

RT_{T0} : Reference Temperature T_0

SPN: Advisory nuclear section of the CCAP

FBH: Flat-Bottom Hole

SRHT: Stress relief heat treatment

QHT: Quality heat treatment

US: Ultrasounds

1. Introduction

AREVA has asked ASN to evaluate the conformity of the reactor pressure vessel (RPV) for the Flamanville 3 EPR in application of the order reference [6].

The domes of the Flamanville 3 RPV closure head and lower head were manufactured in 2006 and 2007. AREVA identified that these components displayed a risk of heterogeneity of their characteristics and therefore carried out a technical qualification.

At the end of 2014, AREVA informed ASN of lower-than-expected results of impact tests conducted as part of this technical qualification on test specimens taken from a dome representative of those intended for Flamanville 3. The values measured on two series of three test specimens give a mean value of 52 joules which does not attain the quality standard expected by AREVA. This mean value is also lower than the bending rupture energy value of 60 joules mentioned in point 4 of appendix 1 of the order reference [6], with which compliance would have been sufficient to prove the toughness of the material.

AREVA carried out investigations to determine the origin of these noncompliant values. The carbon concentration measurements taken at the surface of the representative dome by portable spectrometry revealed the presence of a zone of major positive segregation (high concentration of carbon) over a diameter of about one metre. Furthermore, the examinations show that the segregation extends to a depth exceeding a quarter of the thickness of the dome. AREVA explains the non-compliance with the bending rupture energy criterion by the presence of this major positive segregation which came from the ingot used for the forging and was not completely eliminated by the cropping operations.

To deal with this deviation, AREVA plans proving that the material is sufficiently tough by conducting new tests on a material that is representative of the lower and upper domes of the Flamanville EPR reactor.

The body of the Flamanville 3 RPV, of which the lower dome is a part, has already undergone an in-plant hydraulic test. It was installed at the beginning of 2014 in the reactor pit situated in the reactor building and was welded to the primary branches. The vessel head produced from the upper dome underwent repairs after ultrasonic inspections revealed indications in the welds of the control rod drive mechanism (CRDM) penetrations. These repairs had been examined by the Advisory Committee of Experts for Nuclear Pressure Equipment during the session of 14 September 2011. Ultrasonic inspections of the new welds have been carried out since then and the work is nearing completion. The vessel head is still in the manufacturer's shops and must undergo a hydraulic test before being shipped to the site.

This report gives a recap of the regulatory framework and the history of application of the technical qualification requirement, then presents and analyses the procedure adopted by AREVA to prove the adequate toughness of the material of the domes of the Flamanville 3 EPR RPV. It adopts a position more specifically on the new test campaign proposed by AREVA to evaluate the mechanical properties of the segregation zone. The rapporteur underlines however that the proof of adequate toughness has been defined in the AREVA file on the basis of a list of operating situations that could not be analysed for inclusion in this report given the late date of transmission of the elements and the time available.

The results of the new tests that are going to be performed, the exhaustive and encompassing nature of the chosen operating situations and the impact of the mechanical properties of the segregation zone on the analysis of the mechanical behaviour of the vessel in incident, accident and test situations shall be analysed in a later phase.

This report has been drawn up jointly by IRSN and the Nuclear Pressure Equipment Department (DEP) of ASN.

The term "rapporteur" used in this report designates IRSN and the DEP personnel who assessed the AREVA file with a view to making a presentation before the Advisory Committee of Experts for Nuclear Pressure Equipment.

2. Regulatory framework and requirements applicable to the Flamanville 3 EPR reactor pressure vessel (RPV)

The regulations applicable to the fabrication of the Flamanville EPR RPV comprise the following texts:

- decree 99-1046 of 13 December 1999 relative to pressure equipment reference [3] which transposes into French law the directive reference [1];
- the order of 12 December 2005 (ESPN) relative to nuclear pressure equipment reference [6]; Under this order, the RPV is a level N1[1] equipment item, that is to say the most important for safety.

It is to be noted that the temporary provisions of the order reference [6] enabled AREVA, in view of the starting date of manufacture of the Flamanville 3 RPV, to the apply the regulations previously in force (decree reference [2] and order reference [5]). These regulations mentioned comparable bending rupture energy values (see Appendix 2).

Furthermore, the Flamanville 3 EPR is subject to the order of 7 February 2012 setting the general rules relative to basic nuclear installations [7].

Lastly, the Flamanville 3 EPR reactor must comply with the requirements set by the installation creation authorisation decree reference [4].

This chapter details the regulatory requirements applicable to the design and manufacture of the Flamanville 3 EPR RPV necessary for a clear understanding of the analysis of the file presented by AREVA.

2.1. Defence in depth and break preclusion

Defence in depth

The design of nuclear installations is based on the principle of defence in depth, which leads to the implementation of successive defence levels (intrinsic characteristics, material provisions and procedures), intended to prevent incidents and accidents then, in case of failure of the prevention measures, to mitigate their consequences:

- The aim of the *first level of defence* is to prevent incidents: provisions are defined for equipment items to ensure a high standard of quality in their design and manufacture and to provide a high level of guarantee on that quality;
- The aim of the *second level of defence* is to detect the occurrence of such incidents and apply measures that will firstly prevent them from leading to an accident, and secondly restore a situation of normal operation or, failing this, place and maintain the reactor in a safe condition. For items of equipment, this necessitates that their design hypotheses hold true during operation, and in particular:
    - operating provisions for ensuring that the equipment is used in the operating envelope

[1] The order reference [6] defines the level N1 equipment as follows: "The N1 classification comprises nuclear pressure equipment whose failure can lead to situations in which the safety report for the basic nuclear installation in which they are or will be installed, supplemented by the associated files, does not provide measures for restoring the installation to a safe state, and the nuclear pressure equipment constituting the main primary system and the main secondary systems of the nuclear steam supply system as defined by the abovementioned order of 10 November 1999".

defined by the design hypothesis,
    - maintenance provisions for ensuring that the equipment remains in a condition compliant with that considered at the time of design;
- The aim of the *third level of defence* is to control any accidents that could not be avoided or, failing this, to limit their aggravation by regaining control of the installation in order to return it to and maintain it in a safe condition: for the items of equipment, provisions are made to mitigate the consequences of their failure;
- The aim of the *fourth level of defence* is to manage accident situations resulting from failure of the provisions of the first three levels of defence in depth, in order to mitigate their consequences, especially for persons and the environment. This fourth level allows the management of accident situations involving fuel melt-down;
- The *fifth level of defence* concerns the intervention of the public authorities to mitigate the consequences of an accident for the general public and the environment.

These levels of defences are sufficiently independent for the failure of one level not to call into question the defence in depth ensured by the other levels.

Application of the defence in depth principle is required by article 3.1 of the order reference [7].

Break preclusion

Precluding the breaking of a component means that its failure is not postulated in the safety case. Thus, nothing is planned under the third level of defence to mitigate the consequences of its failure. Consequently, the break-preclusion hypothesis makes it necessary to reinforce the first two levels of defence in depth in order to ensure a satisfactory level of safety.

Breaking of the RPVs is excluded at the design stage, such that the principle of reinforcing the two levels of defence mentioned above applies to this component.

In this respect, as the SPN (advisory nuclear section) of the CCAP (central commission for pressure equipment) pointed out during its meeting of 21 June 2005 devoted to the break preclusion of the main primary and secondary system pipes of the EPR project, the first level of defence in depth *"comprises the guarantee of the quality of design, of manufacture and of in-service monitoring, on the understanding that the guarantee of the quality of design and manufacture is based jointly on the quality of the rules applied, the verification of their application and the final check of the expected result. The elements that constitute this first level are all of the same importance."*

Thus, the requirements for the first level of defence are:
- application of the most severe design and manufacturing criteria that result in adequate and coherent margins enabling the exclusion of any risk of damage in operation; at the design stage, mechanical studies are required for any area that can display a risk of fast fracture;
- the utilisation of load envelopes that encompass the actual stresses in the mechanical studies;
- the defining and verification of the parameters that can generate manufacturing flaws, and the establishing of a qualification programme proving the quality achieved over all the areas; the manufacturing checks must be consistent with the quality guarantee targets.

For the second level of defence, the provisions made for in-service inspection must be able to guarantee the maintaining of component integrity, that is to say the absence of deterioration over time calling into question the prevention of the damage modes.

In the case of the RPV, these principles apply for the different stages of the manufacturing process.

Firstly, a forged component must display sufficient mechanical characteristics irrespective of its subsequent usage. This requirement is expressed in the regulations for pressure equipment, and nuclear pressure equipment in particular, by the compliance with the criteria concerning the mechanical characteristics.

The component moreover undergoes a series of machining and welding operations. These operations must be of the best possible quality in terms of execution and inspection. They must also be kept to the absolute minimum to limit the creation of residual stresses.

Lastly, the elements of proof and validation must be provided with regard to the manufacturing and inspection process and the mechanical behaviour of the equipment in the various operating situations (normal, tests, incident and accident). The studies of fast fracture mechanics must be able to demonstrate the "robustness" of the design against relatively large flaws, defined conventionally independently of the mechanisms that could favour their existence.

Section II-1 of article 2 of the authorisation decree for the creation the Flamanville 3 basic nuclear installation base reference [4] details the specific provisions associated with break preclusion.

2.2. State of the art and current practice at the time of design and manufacture

Appendix 1 of the decree reference [3] obliges the manufacturer to use the best techniques available by stipulating: *"the essential requirements must be interpreted and applied so as to take into account the state of the art and current practice at the time of design and manufacture, and technical and economic considerations compatible with a high level of protection of health and safety"*.

In the case of the RPV, which is one of the nuclear pressure equipment items the most important for safety (level N1), and for which break preclusion is postulated, the degree of protection of health and safety is necessarily very high, which greatly limits the extent to which economic considerations can be taken into account.

The requirement to use the state of the art and current practice at the time of design and manufacture contributes in particular to the first level of defence in depth.

2.3. Essential requirements concerning the properties of materials and technical qualification

The requirements applicable to the main primary and secondary systems of nuclear reactors have evolved since the construction of the French nuclear programme started, integrating experience feedback, advances in knowledge and changes in the regulatory framework relative to non-nuclear equipment.

At the end of the 1990's, ASN worked on defining the rules applicable to the future reactors, particularly the EPR reactor which was on the drawing board at the time. In this context, it made a referral to the SPN (advisory nuclear section) of the CCAP (central commission for pressure equipment), which in October 1999 approved document entitled *Technical rules relative to the construction of main primary and secondary systems of pressurised water nuclear reactors* issued by ASN by the correspondence reference [8].

The requirements figuring in these technical rules - and notably the minimum mechanical property values

and the qualification requirements - foreshadowed the requirements of the order reference [6] of December 2005.
The requirements applicable to the materials and technical qualification for the Flamanville 3 EPR are detailed below.

The requirements of the technical rules, and those of the prior regulations in effect at the time of construction of the French nuclear power fleet are detailed for information in Annexe 2.

2.3.1. Requirements concerning the properties of materials

The decree concerning pressure equipment reference [3], which is applicable to all the equipment, whether nuclear or not, requires (point 4.1.a of its appendix 1) that *"the materials intended for the pressurised parts shall […] in particular be sufficiently ductile and tough"*.

This decree also stipulates (point 7.5 of its appendix 1) that *"a steel is considered to be sufficiently ductile to satisfy point 4-1 a) if its residual elongation in a tensile test performed to a standard procedure at least equals 14% and if its bending rupture energy on an ISO V test specimen at least equals 27 J, at a temperature at the most equal to 20°C, but not exceeding the lowest planned operating temperature"*.

For the nuclear pressure equipment of level N1, that is most important for safety, more constraining minimum values have been set by the order reference [6].They are respectively, for steels of the type of that used for the RPV, equal to 20% for the elongation values at 20°C, and 60 J for the bending rupture energy at 0°C. These values, if respected, are considered to demonstrate that the material is sufficiently tough and ductile. If these values are not respected, the manufacturer must prove the implementation of appropriate measures to obtain an equivalent overall level of safety: *"the following measures are applicable as a general rule. However, if they are not applied, including in cases where the materials are not specifically targeted and where the harmonised standards are not applied, the manufacturer must prove implementation of appropriate measures to obtain an equivalent overall level of safety"* (point 7 of appendix 1 of the decree reference [3]).

2.3.2. Technical qualification requirement

For nuclear pressure equipment of level N1, the essential safety requirement defined in 3.2 of appendix 1 of order [6] as the "technical qualification" requires that *"prior to manufacture, the manufacturer identifies the component that present a risk of heterogeneity in their characteristics linked to the production of the materials or the complexity of the planned manufacturing operations. All the manufacturing operations form the subject of a technical qualification. Its purpose is to ensure that the components manufactured under the qualification conditions and procedure will have the required characteristics"*.

The technical qualification of the RPV domes concerns the production of the material which presents a risk of heterogeneity in its characteristics.

To assess compliance with this requirement, the current practice leads the manufacturer to submit to ASN, before producing the material for a component identified by the manufacturer as requiring technical qualification, a request for an assessment of compliance with this requirement. This request is accompanied by a technical document that details in particular:

- the required quality of the material, resulting from the particular assessment of the material which must determine the values that will be used in the design calculations, and the essential characteristics of the material and of its utilisation;

- the analysis of the risks of heterogeneity of these characteristics;
- the destructive and non-destructive tests that serve to characterise the effect of the heterogeneities;
- the methods of measuring the manufacturing parameters that influence the risks of heterogeneity and whose impact is only verified on a qualification component ("essential" parameters).

To prove control of the properties that cannot be measured on all the components, the manufacturer may be obliged to produce a scale one replica on which to perform the abovementioned tests.

3. Background to the technical qualification procedure and specific case of the Flamanville 3 RPV domes

3.1. Presentation of the main characteristics of the RPV intended for the Flamanville 3 reactor

The diagram of the Flamanville 3 RPV is shown in Figure 1, its components are listed in Table 1 and the materials of the main components are identified in table 2.

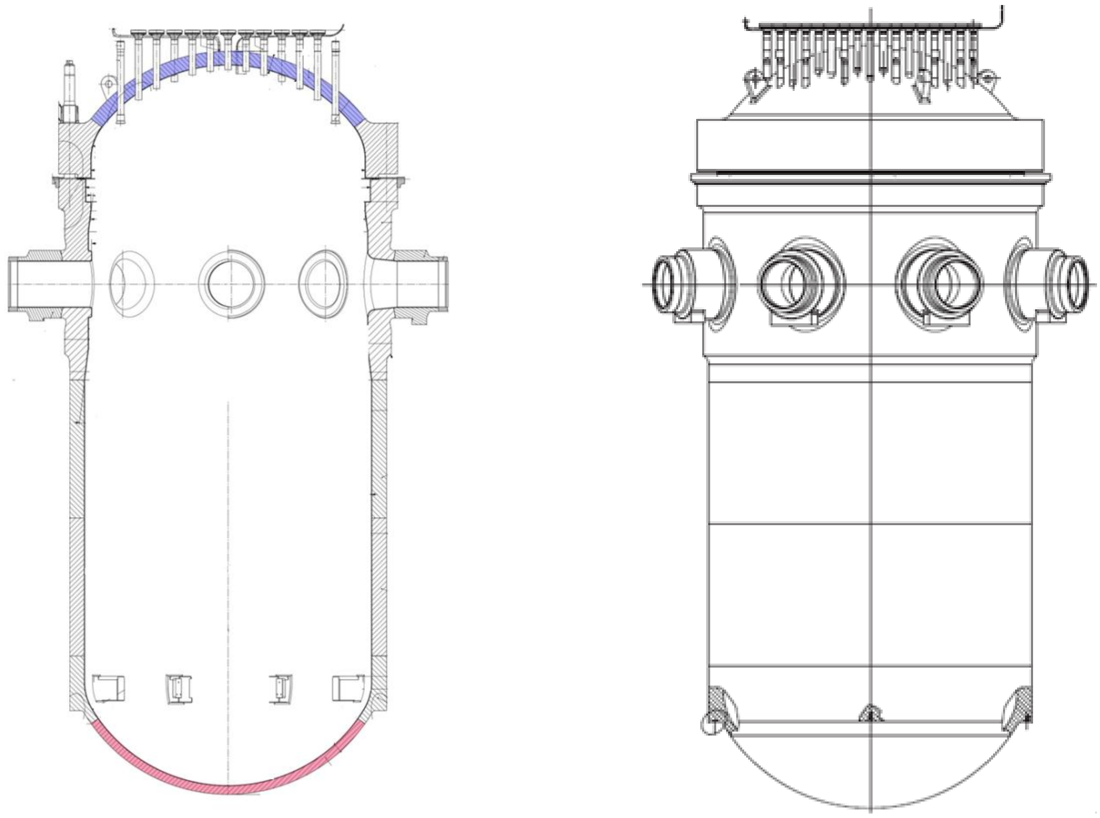


Figure 1: Diagrams of the Flamanville 3 RPV - the domes are shown in colour

Reactor vessel body	Reactor vessel head
The RPV body comprises the following elements, from bottom to top: – lower section: - a lower bottom (dome), - a transition ring, - 8 radial guides. – cylindrical shell: - 2 core shells - one nozzle shell, - 4 inlet nozzles, - 4 outlet nozzles, - 8 safe ends, - one seal ledge, - one leak monitoring tube.	The RPV closure head comprises the following elements: - one RPV closure head flange; - a upper dome; - 89 CRDM (control rod drive mechanism) adaptor tubes; - 89 CRDM adaptor flanges; - 16 instrumentation adaptor tubes, equipped with lower section guiding cones; - 16 instrumentation adaptor flanges; - one vent nozzle; - one dome temperature measurement nozzle and its endpiece; - 4 lifting lugs.

Table 1: Reactor pressure vessel components

The materials used in the supplies of parts are those given in table B2200 of the RCC-M. The table below indicates the applicable specification and material grade.

Components	RCCM Specification	Grade
Nozzle flange/shell	M2112	16 MND 5
Nozzles	M2114	16 MND 5
Safe ends	M3301	Z2 CND 18 12 with controlled nitrogen
Core shells	M2111 or M2111 bis	16 MND 5
Transition ring	M2113	16 MND 5
Lower dome	M2131	16 MND 5
Radial guides	M4102	Alloy 690
Vessel head flange	M2113	16 MND 5
Upper dome	M2131	16 MND 5
CRDM and instrumentation adaptor tubes	M4108	Alloy 690
CRDM and instrumentation adaptor flanges	M3301	Z2 CN 19 10 with controlled nitrogen
Vent tube penetration	M4109	Alloy 690
Vent tube	M3304 or M3301	Z2 CND 17 12
Studs	M2311	40 NCDV 7 03
Nuts	M2312	40 NCDV 7 03
Washers	M2312	40 NCDV 7 03
Penetration for dome thermocouple tube and thermocouple guide	M4109	Alloy 690
Dome thermocouple tube and thermocouple connection tube	M3304 or M3306	Z2 CND 17 12 Z2 CND 18 12 with controlled nitrogen
Leak monitoring tube	M3301 or M3306	Z2 CND 17 12

Table 2: Materials of the main RPV components

For the design and manufacture of the RPV, AREVA has chosen to use the RCC-M code reference [9] (2007 edition supplemented by a number of amendment sheets).

The EPR RPV comprises two domes (see Figure 1), one constituting the lower head and the other the closure head. For the Flamanville EPR reactor, these domes were manufactured by Creusot Forge, from a upset then hot formed conventional ingot .The vessel head dome is assembled to the vessel head flange by welding. This dome comprises 107 penetrations for the control rod mechanisms, in-core instrumentation and vent tube. The RPV closure head dome has an outside diameter of 4720 mm and is 232 mm thick.

The RPV lower head dome is welded to the other components to form the RPV body. For the EPR reactor, the RPV lower head has an outside diameter of 4675 mm and is 147 mm thick.

The main changes in the EPR RPV compared with the RPVs installed on the fleet in operation are as follows:

- there is no longer a penetration in the lower dome because the core instrumentation is introduced via additional penetrations in the RPV closure head;

- the RPV body flange and the nozzle shell originate from a single forged part;
- the nozzle welds are butt welds.

3.2. Presentation of the production process for the Flamanville 3 RPV domes and background history of similar components

AREVA indicates in its document reference [11] that it based its choice of manufacturing process for the domes of the EPR RPV closure head and lower head on an examination of the processes used to produce the domes of the closure heads and lower heads of the 900 MWe, 1300 MWe and 1450 MWe RPVs. All the domes manufactured for the French fleet were shaped by hot-forming a disk whose dimensions varied from one type of reactor to another. The difference in the manufacturing process lies essentially in the method of obtaining the disk, which was successively:

- by cutting hot-rolled plates for the 900 MWe RPVs and for five RPV lower domes for 1300 MWe reactors;
- by upsetting a directional solidification ingot (LSD) then machining to dimensions, for all the RPV lower and upper domes of the 1300 and 1450 MWe reactors, apart from the five abovementioned lower heads;
- by upsetting of conventional ingots for four monoblock replacement RPV closure heads for 900 MWe reactors, two of which were produced by Creusot Forge.

		RPV closure head domes				
		From thick hot rolled plates		From upset blanks		
		MARREL	JSW	JSW conventional ingot	"Creusot" LSD ingot	"Creusot" conventional ingot
900 MWe series	All except for the 4 one-piece closure heads	45 t				
900 MWe series – One-piece vessel head	Chinon B4 and Chinon B1			220 t		
	Cruas 3 and Chinon B3					**195 t**
1300 MW series	All				58 t	
N4 series	All				63 t	

		RPV lower head domes				
		From thick hot rolled plates		From upset blanks		
		MARREL	JSW	JSW conventional ingot	"Creusot" LSD ingot	"Creusot" conventional ingot
900 MWe series	FSH1 to CHB	34 to 40 t				
1300 MWe series	Q1 to Q5		46 t			
1300 MWe series	Q6 to Q20				46 to 49 t	
N4 series	Chooz B1 to Civaux 2.				55 t	

Table 3: Development of the weight of the ingots and plates used for the lower heads and closure heads of the various French RPVs

The main changes in the design of the domes of the Flamanville 3 EPR RPV, as indicated earlier, lie primarily in the absence of penetrations in the RPV lower head and the significant increase in their number in the closure head. With regard to dimensions, the EPR RPV lower head dome, though slightly wider, is not fundamentally different from that of the N4 reactor and its thickness is virtually identical. For the purpose of comparison, the respective dimensions and the number of penetrations in the domes of the EPR and N4 RPVs are given in Table 4.

	RPV closure head dome		RPV lower head dome	
	EPR	N4	EPR	N4
Thickness	230 mm	180 mm	145 mm	144 mm
Inside diameter of vessel	4885 mm	4486 mm	4885 mm	4486 mm
Internal bend radius	2695 mm	2303 mm	2695 mm	2310 mm
Number of penetrations	107	77	0	60

Table 4: Comparison of dimensions of EPR and N4 RPV domes

Given the dimensions of the EPR RPV closure head dome, the required disk has a diameter of 5800 mm and thickness of 300 mm, which cannot be produced either from plates or from the directional solidified ingot of the N4 series. AREVA considers more specifically that, even if an LSD ingot of sufficient tonnage existed, the shaping from such an ingot would not allow the achievement of the forging ratio[2] of greater than 3 recommended for the production of forged parts. This recommendation aims at favouring the shaping processes that result in a sufficient forging ratio to eliminate the majority of the solidification flaws (shrinkage, porosities and blowholes).

The manufacturing process used by Creusot Forge to produce the EPR RPV domes was therefore based on a conventional ingot of 157 tonnes, and had the following objectives:

- the surfaces of the final part to be cladded and areas where permanent joining operations will be performed must be free of positive macro-segregations;
- the zone of negative macro-segregation must be eliminated in order to guarantee sufficiently strong mechanical properties.

This is because large-sized cast parts, after casting and solidification of the steel, are not perfectly homogeneous in their chemical composition and mechanical properties (see Figure 2). They contain macroscopic heterogeneities corresponding to the macro-segregation of the carbon essentially, and of other alloying elements to a much lesser extent. Thus as a general rule with ingots, one finds a high level of negative macro-segregation in the bottom of the ingot (lower concentration than the mean value obtained during pouring). Moving from the bottom to the top of the ingot one finds a change in composition, going as far as a positive macro-segregation in the top of the ingot (higher concentration than the mean value obtained during pouring). Consequently, the area produced from the bottom of the ingot risks having lower tensile mechanical properties resulting from the negative macro-segregation of the carbon. The area produced from the top of the ingot can have its toughness affected by the positive macro-segregation (particularly in carbon).

Added to the macro-segregations are local segregations called ghost lines, which are always present in very large ingots of low alloy manganese nickel steel. The risk associated with these ghost lines concerns the weldability.

[2] According to RCC-M (M 380), the forging ratio represents, in each region of the part, the ratio of the lengths of a metal element measured in the direction parallel to the working direction, before and after the forging operation. The working direction is, in each region of the part, the direction in which the forging operation produces the maximum elongation. Paragraph M 353 states that *"The value of the overall reduction ratio in accordance with M 380 must not, as a general rule, be less than 3."*

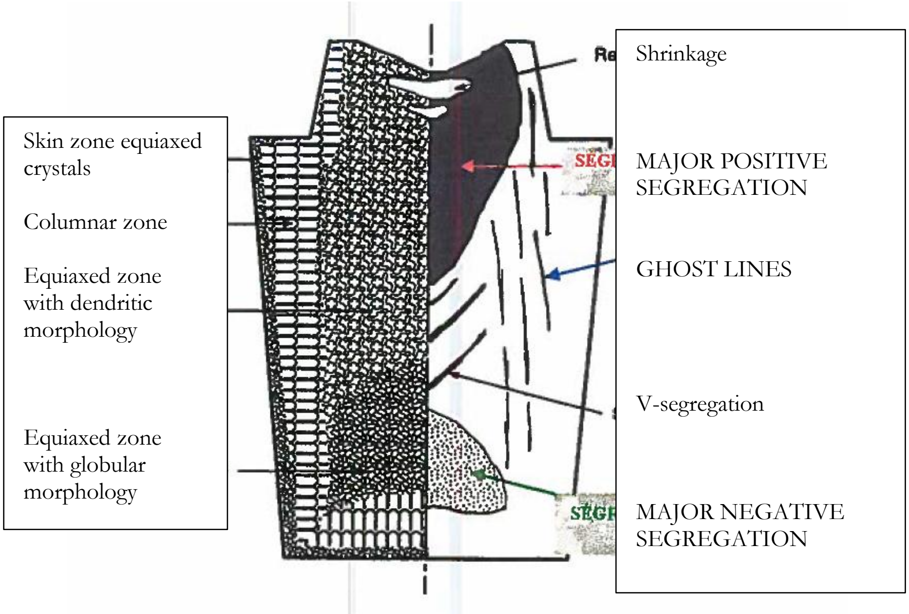
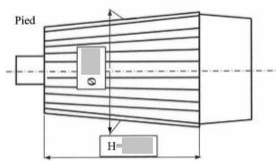
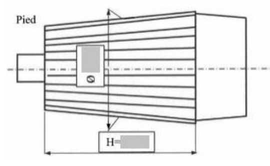
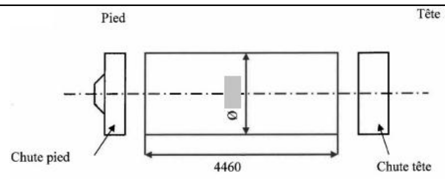
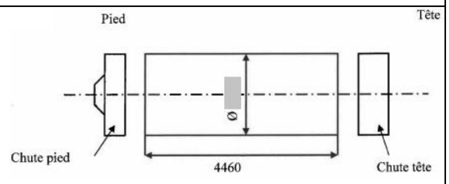
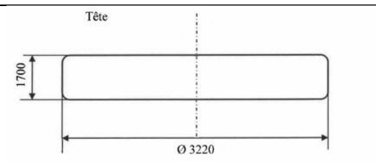
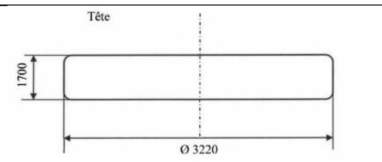
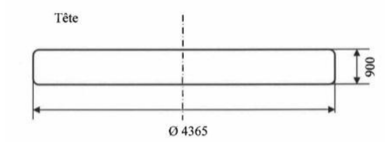
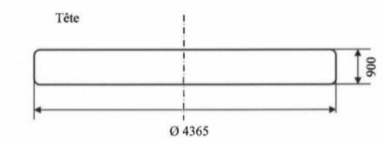
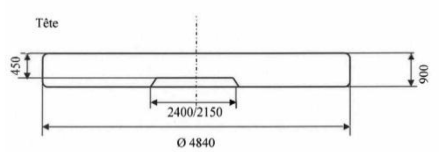
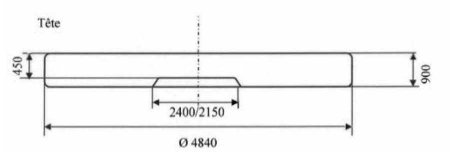
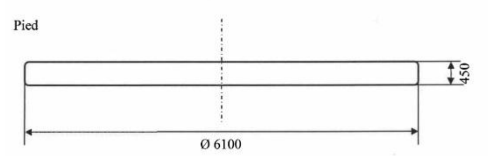
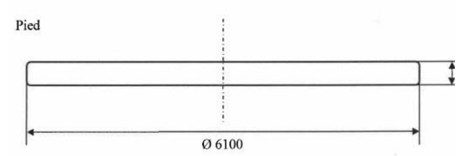
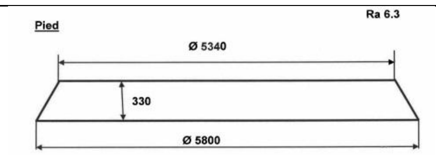
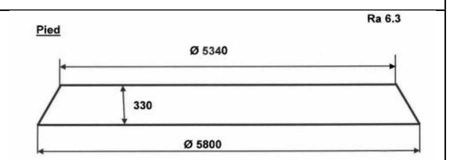
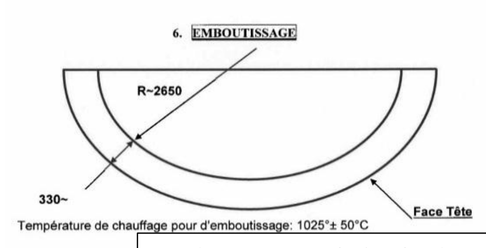
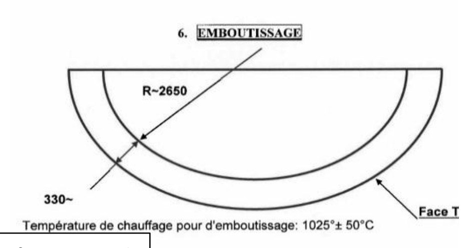


Figure 2: Morphology of the segregations of a conventional ingot

The successive forging operations in the process used to produce the two domes of the Flamanville 3 EPR RPV are shown schematically in Table 5. For the production of each of the domes for the Flamanville 3 EPR, after top and bottom discard of the 157-tonne type 2550 conventional ingot, by approximately 20% and 8% for the lower dome and 20% and 9% for the upper dome, the blanks undergo a preliminary heat treatment before hot-forming intended to reduce the hydrogen content of the steel and facilitate rough machining of the blank before the hot-forming operation. After hot-forming, a second machining operation is carried out to cut the domes to profile for their "quality heat treatment". Both domes are machined from a 330-mm thick disk obtained by hot-forming a forged blank of 450 mm thickness and 6100 mm diameter produced from a 157-tonne ingot. Further machining operations reduce the nominal thickness to 147 mm for the bottom dome and 232 mm for the vessel head dome. After final machining, ultrasonic inspection of the volume is carried out.

Forging process	FA3 vessel bottom head dome	FA3 vessel head dome
Ingot		
Blooming and discarding		
Upsetting between plates		
Upsetting in parallel passes		
		
		
Machining prior to hot-forming		
Hot-forming		

Heating temperature for hot-forming: 1025 ± 50°C Head

Table 5: Comparison of the forging processes for the FA3 bottom and top domes

For production streamlining reasons, the same forging process was kept for the bottom dome, which is much thinner. Thus, the bottom and top domes follow the same forging process from casting of the ingot through to hot-forming. The sequences performed after hot-forming through to final machining to the delivery profile with a view to performing non-destructive tests are shown in Table 6.

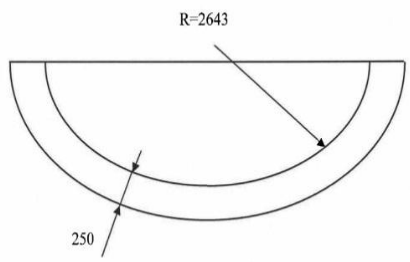
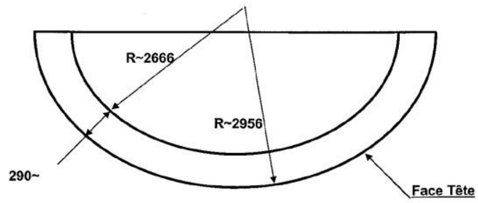
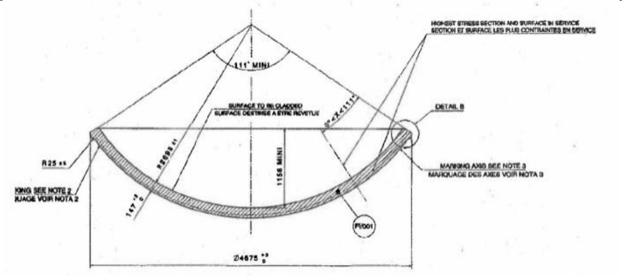
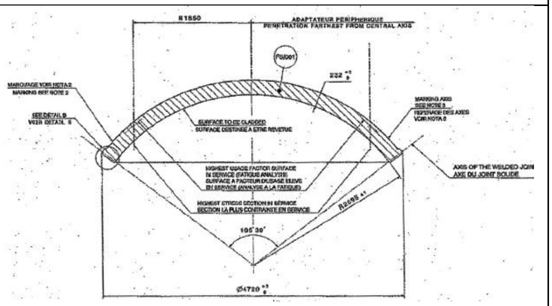
<table>
<tr><td>Machining process</td><td>FA3 RPV lower head dome</td><td>FA3 RPV closure head dome</td></tr>
<tr><td>Machining to profile for quality heat treatment (QHT)</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">QHT</td></tr>
<tr><td>Machining to delivery profile</td><td></td><td></td></tr>
</table>

Table 6: Machining sequences after hot-forming

The process adopted by AREVA (Table 5) does not enable the residual positive macro-segregation zone to be eliminated in the final part. In this respect, AREVA had specified that the stainless steel cladding would have to be performed on the bottom side of the ingot, the zone that displays no positive macro-segregation.

This process is similar to the one implemented for the monoblock vessel heads produced by Creusot Forge. AREVA nevertheless indicated that the monoblock RPV closure heads had been manufactured with a targeted carbon content on pouring of about 0.16%, less than that targeted for the EPR domes (0.18%).

AREVA points out that Japan Steel Works (JSW) also chose a conventional ingot for the production of the domes of the Finnish OL3 EPR RPV. The process developed by JSW however is specific and allows the final part to be positioned outside the zone of major positive segregations situated in the upper section along the axis of the ingot. This process allows the positioning of the part in the bottom and on the sides of the ingot (see Figure 3). In this case, the outer face of the domes corresponds to the bottom of the ingot, contrary to the Creusot Forge process. Consequently, the domes manufactured by JSW are free of positive macro-segregation zones.

AREVA also had JSW manufactured two monoblock replacement RPV closure heads for the 900 MWe series using this process.

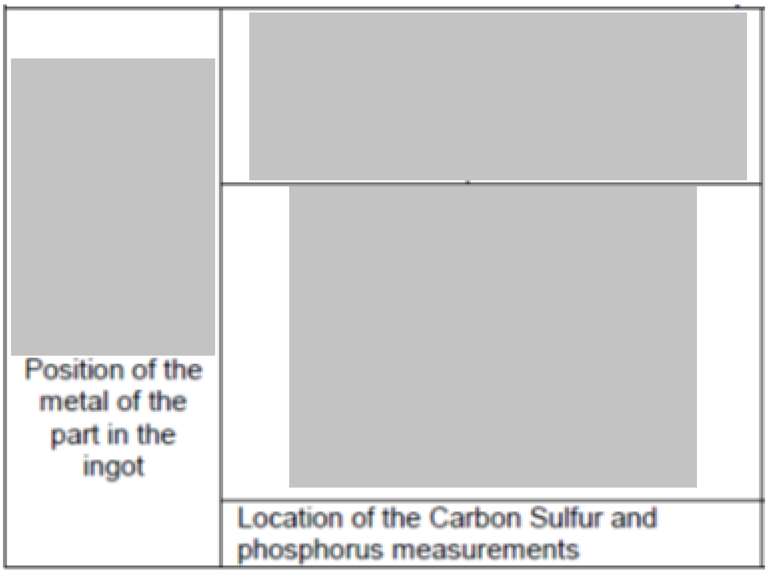


Figure 3: Position of the part in a conventional ingot produced by JSW

For information, the SPN (advisory nuclear section) of the CCAP had examined the design choices made for the RPV nozzle shell (conventional ingot of 490 tonnes) and those adopted for the manufacture of the RPV closure head during the sessions of 2 July 2003 and 5 January 2006. The design of the domes and their production process had not been specifically examined by the SPN at that time. However, in its follow-up letter, ASN had asked that the industrial feasibility analysis of the one-piece RPV closure head solution, which has the advantage of doing away with a welded joint, be taken to greater depth.

3.3. Files submitted by AREVA up until the tests of 2014

3.3.1. <u>First technical qualification file of the Flamanville 3 RPV domes</u>

This paragraph describes the context in which the RPV domes were produced, a context which goes beyond the case of the domes and more generally concerns all the parts subject to technical qualification under the order reference [6].

The methods of proving compliance with the technical qualification requirement are now stabilised; this was not the case during the manufacture of the first large components of the future Flamanville 3 EPR in the years 2005 to 2007. Apart from the fact that the order reference[6] was published on 22 January 2006, putting in place the methods of proving the technical qualification took several years.

The discussions on the technical qualification requirements focused as of 2006 on the development of a generic method for proving compliance with the requirement. AREVA wanted to use qualification M140 of the RCC-M to satisfy the requirement. ASN indicated that qualification M140 could not be used for technical qualification because it did not meet all of the qualification objectives. This is because the M140 qualification is an industrial qualification which does not aim at characterising the entire volume of the component, only the areas analysed in the design. Furthermore, it can be based on tests performed on components produced with another technical manufacturing programme. It can be noted in this respect that the domes of the Flamanville 3 EPR RPV obtained their M140 qualification but not their technical qualification.

Consequently, the discussions on the technical content of each of the technical qualification files were very limited at that time. It is to be noted that ASN raised the question of a risk of heterogeneity in the central area of the domes back in 2006. The question did not receive a substantive response, as at the time AREVA made reference to a future file.

In 2007, despite significant changes, the content of the technical qualification files remained insufficient to provide the justification for the chosen manufacturing process and the test programme proving control of the risks of heterogeneity. ASN then decided to put an end to this situation which enabled AREVA to continue manufacturing parts without providing satisfactory technical qualification files beforehand. Thus, as of 1 January 2008, ASN made it a requirement for a technical qualification file deemed admissible to be submitted for the any further manufacture of components. ASN set a hold point prior to pouring operations. The aim of this hold point was to enable ASN to verify that the technical qualification file was sufficiently complete to justify the choices of the technical manufacturing programme and to allow the inspection of the most sensitive manufacturing phases. These hold points did not concern equipment items whose components had already been produced, and whose manufacture therefore continued. ASN warned AREVA several times about the industrial risk represented by the continuation of manufacture of equipment without having completed the assessment of the technical qualification files for the components used in the manufacture of this nuclear pressure equipment.

The introduction of hold points undeniably resulted in improved quality of the technical qualification files. ASN has thus assessed the technical qualification files of numerous components in the nuclear power fleet. In 2009, assessment of the technical qualification of components intended for replacement steam generators finally led to a qualification file format and a method of analysing heterogeneous risks that ASN judged satisfactory. At the same time, the technical discussions on the tests proving control of the risks of heterogeneity were continuing. For example, in 2011 AREVA proposed producing scale-one replicas for the components produced from upset ingots or with complex geometry in order to characterise the effects of heterogeneity after having initially worked on digital simulations based on knowledge of the production of the forgings.

For the components produced before 2008, including the domes of the Flamanville 3 EPR, AREVA applied the retrospective technical qualification procedure. The production of the qualification files for the RPV domes was thus initially pushed back to late 2009. AREVA finally sent ASN a revision of the two technical qualification files in April 2010, one for the upper dome, the other for the lower dome. These files had nevertheless been drawn up before the discussions between the manufacturers and ASN had resulted in a stabilised practice for providing technical proof of control of the risks of heterogeneity.

3.3.2. Analysis of the differences in the methods of satisfying the technical qualification requirement

For the Flamanville 3 components subject to the technical qualification requirement, whose production began before the procedures for ensuring compliance with this requirement were stabilised, ASN asked AREVA to provide an analysis of the differences between the stabilised practice of the technical qualification requirement and the previous practice applied by AREVA. AREVA carried out a first analysis in 2010, in addition to the technical qualification files it had submitted. At the beginning of 2011, ASN considered that this analysis should be supplemented, and more specifically asked that the possibility of using tests performed or to be performed on other representative components, where applicable, be studied.

At the beginning of 2012, AREVA thus sent a new analysis for all the files of the components for the Flamanville 3 EPR. In this file, AREVA observes in the light of the stabilised practice that, for the RPV domes:

- the effect of the weight of the ingot, the type of ingot and the cropping percentage on the presence and scale of the positive and negative carbon segregations had not been characterised.

The weight and type of ingot effectively lead, after cropping, to residual areas of positive and negative segregations in the axis of the part (see Figure 2). The effect of these parameters is verified by chemical analyses and mechanical tests;

- The transfer time between removal from the heat treatment furnace and the quenching tank had not been identified as an influencing parameter, and yet it does influence the characteristics at the skin of the component.

Following this finding, AREVA proposed to ASN to perform tests on a part produced under the same conditions as the Flamanville 3 domes to verify the effect of these parameters. After technical discussions to ascertain the representativeness of the part on which these tests would be carried out and to get the manufacturer to define the required quality in the areas to characterise, AREVA submitted a file to ASN in 2012 in which it:

- substantiates that the upper dome procured under the UA contract from Creusot Forge with the same production parameters as for the Flamanville 3 RPV dome is representative of the effect of the positive or negative carbon segregations;
- proposes to conduct mechanical tests and chemical analyses in an 80-mm diameter core sampled from the central part of the UA upper dome (see Figure 4). These tests aim at characterising the effect of the ingot weight and type (chemical analysis in skin on top and bottom sides in the axis of the part and mechanical test in the axis of the part at ¼ thickness on the top and bottom sites), the effect of the cropping rate (chemical analysis in skin on top and bottom sides in the axis of the part and mechanical test in the skin on the top and bottom sides) and the effect of the transfer time (tensile test in skin in the thinnest section of the part, that is to say a surplus of the test coupon taken from the permanent joint between the dome and its flange);
- considers that the possible presence of residual carbon segregation would have no impact on the mechanical test values and does not change the required initial quality. AREVA specified in particular that *"the presence of major residual segregation has little impact on the mechanical properties of the part and that consequently no downgrading of the minimum tensile acceptance criteria or the bending rupture energy criteria is necessary in these areas"* and that *"this aspect, located in the axis of the part on the external surface will have no impact: on the mechanical properties […]."*

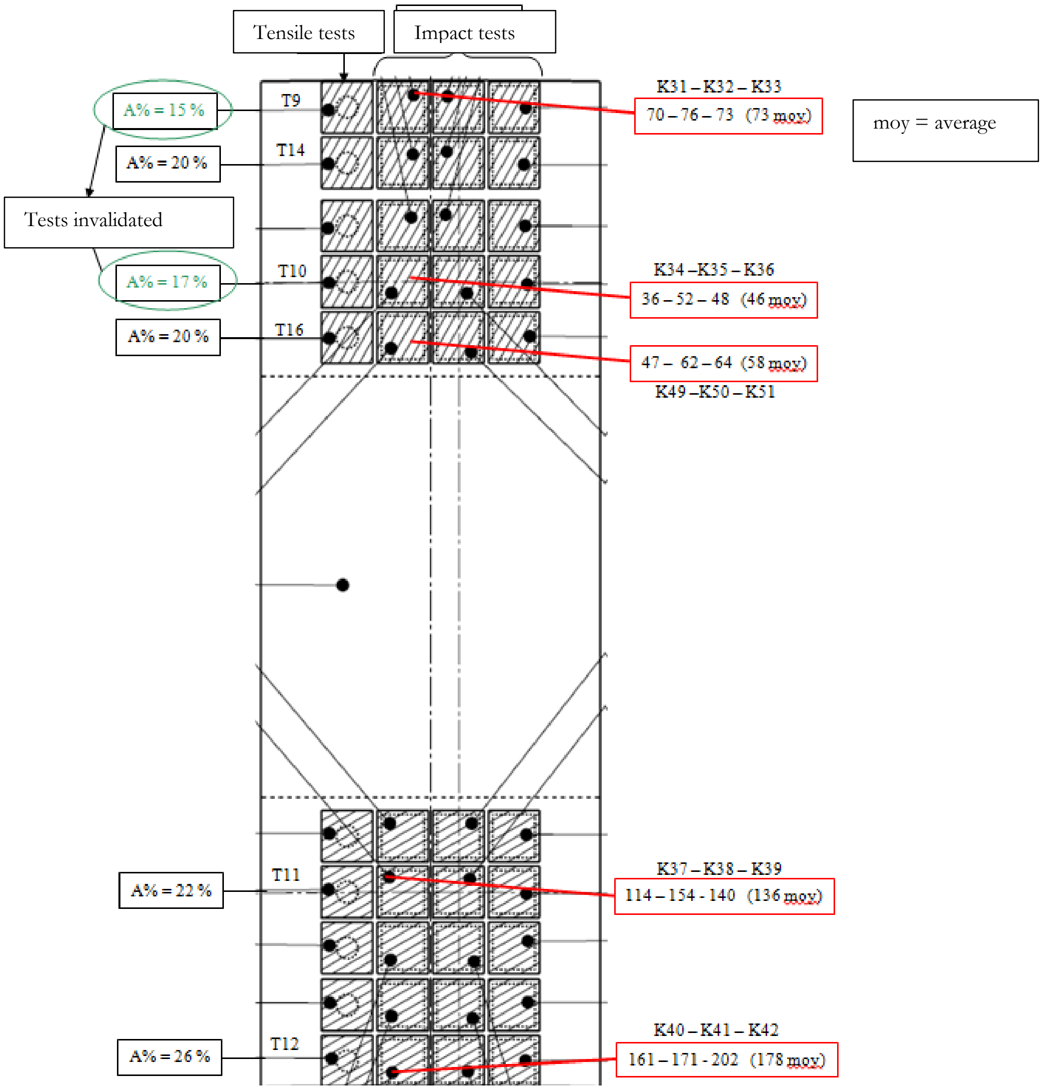


Figure 4: Location of the tensile and bending test specimens in the central core sample of the UA upper dome

In the light of these elements, ASN issued no objections to the taking of core samples from the UA upper dome and the associated mechanical tests programme.

3.3.3. Tests on the UA upper dome

The results of the tests performed on the UA upper dome reveal that:

- two tensile tests were invalidated (test specimens T9 and T10) because the test specimens fractured outside the standardised range. The two test specimens T14 and T16 produced as substitutes gave compliant values;
- two series of three impact test specimens taken at ¼ thickness from the top side led to values that did not comply with those indicated in point 4 of appendix 1 of the order reference [6] and the required quality defined by the manufacturer (60 J): 36 J, 52 J and 48 J for the first series and 47 J, 62 J and 64 J for the second. The average of these values is 52 J.

Further to these tests, the manufacturer carried out investigations to determine the origin of these noncompliant values. The carbon measurements taken at the surface of the dome by portable spectrometry revealed the presence of an area of positive macro-segregation over a diameter of about one metre, slightly off-centred with respect to the centre of the dome (see Figure 5). Moreover, the metallographic examinations of the test specimens show the presence of these segregations at ¼ thickness. The bending rupture energy values, less than 60 J, are thus attributed to the presence of positive macro-segregations originating from the ingot and not completely eliminated by the top-cropping operation.

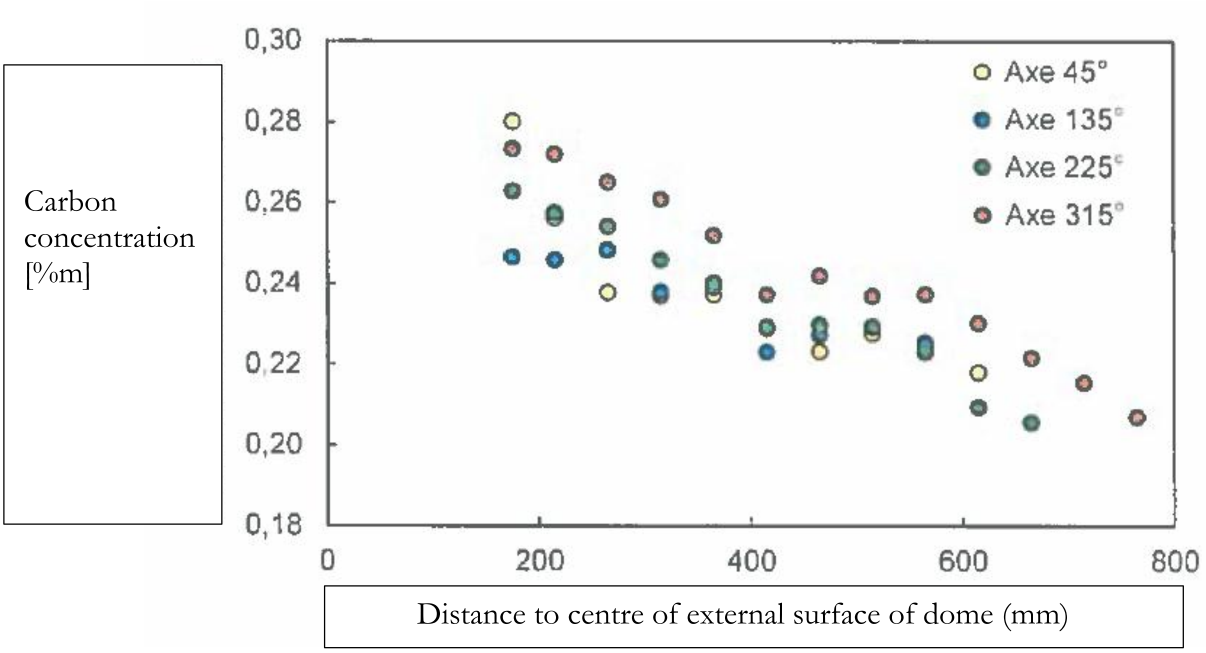


Figure 5: Carbon concentration as a function of the distance to the centre of the external surface of the UA upper dome

3.4. Position of the rapporteur

The RPV lower head and closure head domes were produced using the same process by the same supplier. Their technical qualification file was drawn up by the manufacturer before the practice to meet this requirement was stabilised, which had led ASN to make reservations on these files. The reconciliation of these files as from 2010 led the manufacturer to propose additional tests. These tests revealed that the impact and extent of the residual areas of positive macro-segregation in the centre of these domes had not been sufficiently anticipated.

<u>Qualification M140 of the RCC-M code</u>

During the assessment, the manufacturer presented the parts qualification procedure imposed by chapter M140 of the RCC-M code and the reason why such a procedure applied from the start of manufacture of the components intended for Flamanville 3 did not result in the identification of the risk induced by an area of residual positive macro-segregation in the centre of the domes. It emerges from AREVA's explanation that:

- the aim of chapter M140 of the RCC-M is to ask the manufacturer to verify that the components behave satisfactorily during the preparation operations and once in service;

- consequently, the mechanical properties are verified in priority in the areas that are important with regard to the use of the component;
- for the domes, the areas thus identified are the cladded surface which corresponds to the bottom side of the ingot, and the welded zone that corresponds to the zones where the upper dome is welded to the flange and where the lower dome is welded to the transition ring. These areas were characterised by mechanical tests and chemical analyses.

This approach therefore did not lead AREVA to ask questions about the characteristics of the central area, but led it to the following conclusion: "*The problem of macro-segregation in the external skin can lead to local reductions in the level of toughness, granted, but under RCC-M M140 it does not lead to specific verifications as part of a characterisation test programme. There is in effect no identified functional need, since the manufacturing process allows the exclusion of damaging flaws – flaws perpendicular to the skins or the flaws excluded on account of the forging process – in this area of positive macro-segregation, which is moreover not particularly stressed in service (no impact of cold shocks in this areas). Consequently there is no identified risk with respect to fast fracture[…]*" [3].

Application of chapter M140 therefore does not enable compliance with the technical qualification requirement as defined in point 3.2 of appendix 1 of the order reference [6] to be proven, because according to AREVA, chapter M140 does not oblige the examination of all the areas of the components, with the consequence that the volume is not characterised in its totality. The rapporteur nevertheless underlines that, under application of chapter M140, the manufacturer was particularly attentive to the changes in manufacturing process for the RPV parts of the fleet in operation in order to verify the required mechanical properties.

Choice of manufacturing process by the manufacturer

The rapporteur considers that the presence of these segregations results from the dome manufacturing process adopted by Creusot Forge, based on high-tonnage ingots. This process differs from those used for the domes of the RPVs of the fleet in operation, and from that used for the one-piece RPV closure heads as regards the targeted carbon content.

The segregation phenomenon is well known in forged parts produced from large ingots and it has been widely studied in the past, particularly for the shells of the RPV core areas, in view more specifically of its impact on the content of elements having an influence on irradiation ageing. The scale of the segregations is linked to the weight of metal cast to obtain the ingots, and their geometry (height/diameter ratio).

The change in dimensions associated with the high-power reactors (1300 MWe and N4) made it necessary - because available rolling capacities were insufficient - to produce the domes by hot-forming forged blanks. In order to limit the risks associated with the segregation phenomena when producing forged parts, the manufacturers developed a "directional solidification ingot" (LSD[4]), patented in 1978. Figure 6 taken from the publication reference [10] illustrates the difference in the morphology of the segregation areas between an LSD ingot and a conventional ingot: the area of positive macro-segregation of an LSD ingot is more superficial than in a conventional ingot and less extensive due to the difference in initial weight of the ingots (greater cropping in the case of a conventional ingot) and above all the control of cooling.

[3] The aspects associated with flaws and stresses are addressed in chapter 4
[4] LSD: French acronym meaning "lingot de solidification directionnelle" (directional solidification ingot)

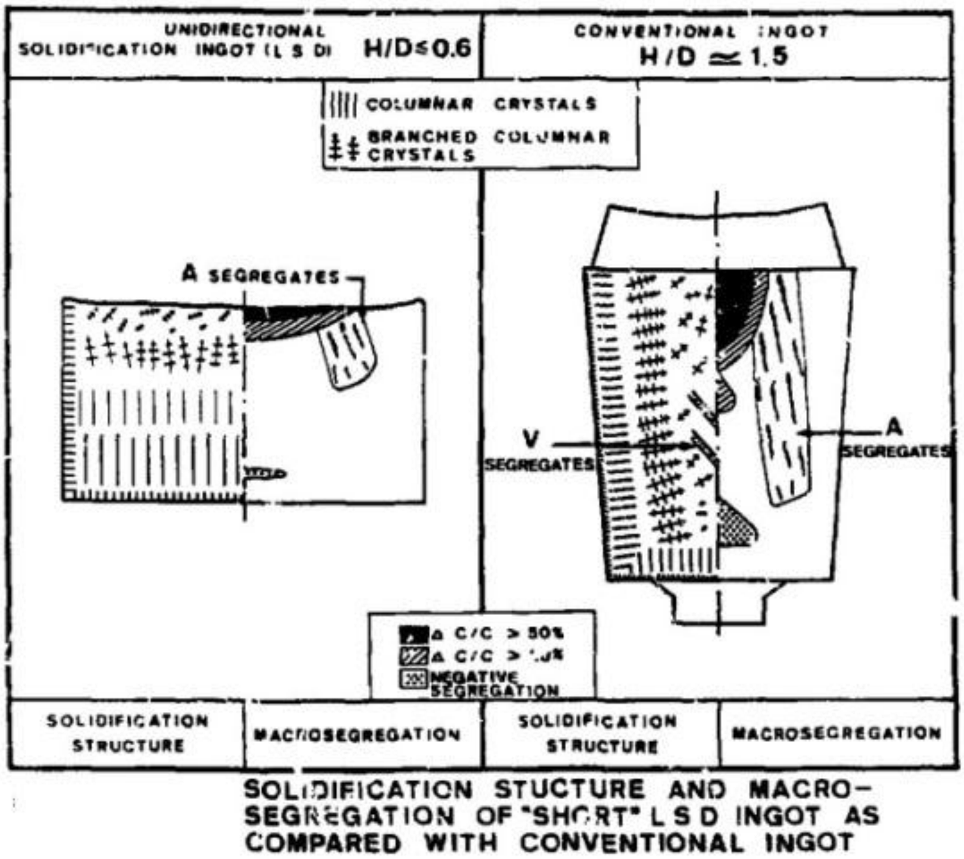


Figure 6: Morphology of the segregations of an LSD ingot and a conventional ingot

The characterisations carried out at the time on an experimental blank of 210 mm thickness produced from a 45-tonne LSD ingot had confirmed that the macro-segregations characterised by the ratio ΔC/C[5] remained below 23%. All the results obtained on the experimental blank (chemical analyses, mechanical characteristics) complied with the requirements and had shown that the acceptance tests remained representative of the part as a whole.

With regard to the Flamanville 3 EPR RPV domes, the type 2550 ingot used is the type used in the past for the shells of the 1300 MWe series RPVs, for which the manufacturing process includes hot-drilling of the ingot, which eliminates the positive macro-segregations situated at the top of the ingot and its axial section. This hot drilling operation, inherent to revolution parts, cannot be carried out on the domes, which is what led to the choice of an LSD ingot for the RPV domes of the N4 series reactors.

The rapporteur notes the following three orientations concerning the manufacturing process and its definition:

- AREVA decided not to use a directional solidification ingot. This choice results from the estimation of the forging ratio, which AREVA considered insufficient to eliminate the solidification flaws. At the design stage, AREVA favoured *"the elimination"* of these flaws (high forging ratio of above 12, compared with those of the N4 series vessel heads, which were about 3 to 5) at the expense of better control over the segregation phenomena which could have been

[5] The carbon content of a steel, measured in the liquid steel during casting (C) reflects the average carbon composition for the whole of a part. The difference with respect to the local carbon content measured at one point of the part (ΔC) enables the extent of subsistent segregations to be quantified (ΔC/C).

obtained by forging from a directional solidification ingot. This process, which would have necessitated developments to apply it to the EPR, would have been favourable for the homogeneity of the mechanical properties in the entire manufactured part. AREVA thus defined a forging process from a conventional ingot of 157 tonnes leading to the presence of an area of positive macro-segregation in the part;

- in view of this first choice, AREVA took care to ensure that the area of major positive segregation was positioned in an area where its consequences would not be unacceptable. Given that the presence of positive macro-segregations affects the material weldability and toughness, the forging process was devised so that this area would be located in the external skin of the domes. The external skin of the dome is effectively an area of the part in which no welds are planned. Furthermore, AREVA estimates the external skin to be "poorly sensitive to thermal shocks", therefore in principle the risk of fast fracture to be very slight. As a consequence, this obliged AREVA to differentiate in its manufacturing process the side of the forged blank situated on the top side of the ingot from that on the bottom side. AREVA thus provided for "foolproofing" measures between these two sides in its process;
- AREVA defined its forging process so as to eliminate the area of negative macro-segregation in order to guarantee minimum tensile properties of the material for the entire part.

The arguments presented by AREVA to justify not using a directional solidification ingot, developed for the production of the 1300 MWe and 1450 MWe RPV domes, are based in particular on the limitations of the above-developed LSD ingots and their incompatibility with the dimensions of the EPR vessel head dome, which are larger than in the preceding productions. The rapporteur considers that the possibility of adapting the existing LSD ingots to the EPR dome production needs should have been considered.

It must moreover be underlined that the arguments presented by AREVA do not apply to the vessel bottom head dome, for which the weight, diameter and thickness are lower. Thus, the choices made for the production of the vessel head dome were reproduced, with no particular justification, for the production of the vessel bottom head dome.

The manufacturing process developed by Japan Steel Works and used for the RPV domes of the Finnish EPR would also have satisfied the guidelines that were set at the design stage and, in addition, eliminated the zones of positive macro-segregation in the domes. Figure 3 shows the position of the part in the ingot which shows that the finished part is situated outside the segregation zones.

The use of a type 2550 ingot for the domes of the Flamanville 3 RPV led to the presence of positive macro-segregation in the finished part that reaches 50%, a value very much higher than those of the same types of parts of the reactor fleet in operation (maximum of 20% to 25%). It is to be noted that these zones of segregation on the RPV lower head dome and on the closure head of the FA3 reactor were confirmed in 2015 during examinations by optical emission spectrometry (non-destructive chemical analysis method): the chemical analyses which had been carried out during manufacture (a few foolproofing measures on the blank), had revealed high carbon concentrations at the centre of the Flamanville EPR RPV closure head dome, but had not at the time led anyone to ask any questions regarding their origin and potential consequences.

With regard to the two one-piece RPV closure heads manufactured by AREVA at Creusot Forge from a conventional ingot, ASN questioned EDF and AREVA to find out whether similar risks resulting from the presence of an area of positive macro-segregation exist. The file is currently being examined. AREVA and EDF have nevertheless provided elements indicating that the percentage of carbon in the melt is lower for these one-piece RPV closure heads (about 0.16% compared with 0.18% for the FA3 domes, which is linked to the tensile strength (R_m) values which are about 570 MPa for the one-piece parts and higher than 600 MPa for the FA3 domes) and that the tests performed in the hole intended for the passage of adaptor number 3 (near the centre) have revealed higher bending rupture energy values than those obtained on Flamanville 3. It is to be noted that these values were obtained on test specimens taken in the short transverse direction.

ASN also asked EDF and AREVA to draw up the inventory of all the components that could display areas of positive macro-segregation and which would not have been characterised during their production.

To conclude, the rapporteur considers that:

- application of chapter M140 cannot meet the objective of technical qualification defined in point 3.2 of appendix 1 of the order reference [6];
- the technical qualification file presented by AREVA for the Flamanville 3 RPV lower head and closure head domes shows that the risk of heterogeneity due to residual positive segregations has been poorly assessed and its consequences poorly quantified. AREVA has thus not complied with the technical qualification requirement for the domes of the Flamanville 3 RPV lower head and closure head;
- AREVA did not opt to choose the state of the art and current practice at the time of design and manufacture for the production of the Flamanville 3 EPR RPV domes.

These findings affect the first level of defence in depth - which aims at obtaining a high standard of quality of design and manufacture - due to the noncompliance with the above-mentioned requirements.

The rapporteur considers that the chosen manufacturing process does not give the same guarantee of quality as would have been obtained with the best technique available and a satisfactory technical qualification.

4. Demonstration approach proposed by AREVA

In the light of the elements presented in chapter 3, AREVA is required to demonstrate the adequacy of the toughness of the material by a means other than compliance with the bending rupture energy value mentioned in point 4 of Appendix 1 of the order in reference [6]. This approach is presented in this chapter.

The rapporteur recalls that §4 of Article 16 of the order in reference [5], in force during construction of the French NPP fleet, would also have led the manufacturer to carry out such an approach.

4.1. Principles of the demonstration approach

The assessments carried out on the UA sacrificial dome demonstrated that the material has a bending rupture energy at 0°C that does not meet the 60 J value mentioned in 4 of Appendix 1 of the order in reference [6], owing to the presence of a high level of segregation in the test zone. As the bending rupture energy level is an indicator of the level of toughness, the segregation zone could thus offer inadequate toughness to prevent the risk of fast fracture at the temperatures at which the steel is stressed and in particular in its brittle-ductile transition zone.

AREVA considers that the presence of positive macrosegregations does not compromise the prevention of excessive deformation damage and plastic instability in the RPV domes, verified in the design file, owing to the higher tensile strength in the positive segregation zones. The AREVA file therefore focuses on the prevention of the risk of fast fracture.

With regard to the brittle-ductile transition zone, AREVA transmitted its demonstration of the adequate toughness of the Flamanville 3 EPR RPV domes, which is the subject of the notes in references [11] and [12].

The demonstration approach adopted by AREVA comprises 3 main steps illustrated in Figure 7:

1. the determination (by calculation) of adequate toughness to prevent the risk of fast fracture, see §4.2;
2. the evaluation (by testing) of the minimum toughness in the positive macrosegregation zone of the material, see §4.3;
3. the comparison between the minimum toughness of the material and the adequate toughness determined, see §4.4.

As part of its approach, AREVA uses the formula in Appendix ZG 6110 of the RCC-M (see Figure 8) to express the adequate and minimum toughness values and determine the corresponding offset in the reference brittle-ductile transition temperature (RT_{NDT}[6]):

- the adequate RT_{NDT} is noted $RT_{NDT, allowable}$ on Figure 7;
- the minimum RT_{NDT} of the material is noted $RT_{NDT, ZS, FA3}$ on Figure 7.

[6] The RCC-M defines the RT_{NDT} as being the temperature which, when increased by 33°C, corresponds to a value of at least 68 J during the impact test (Charpy).

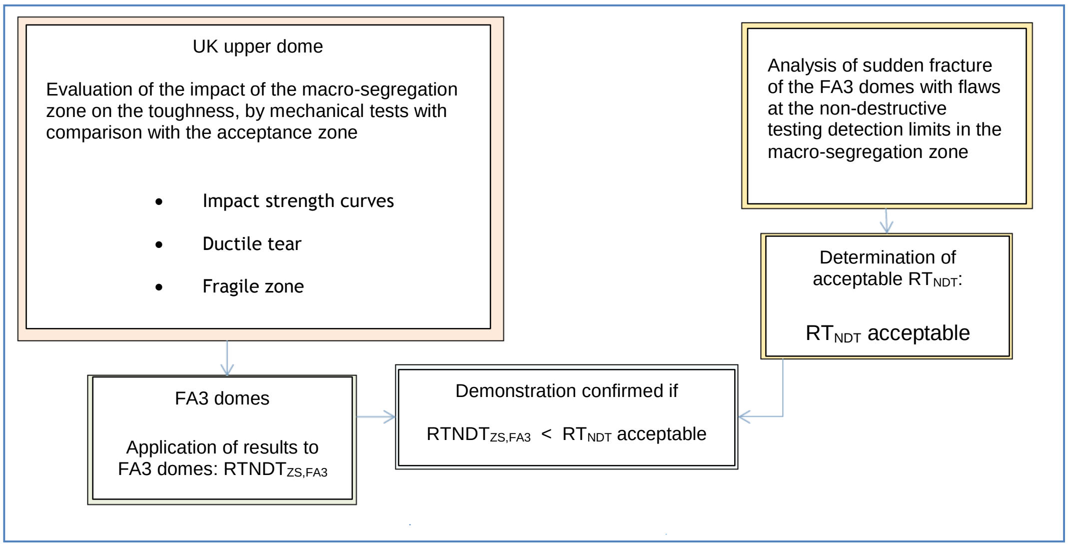
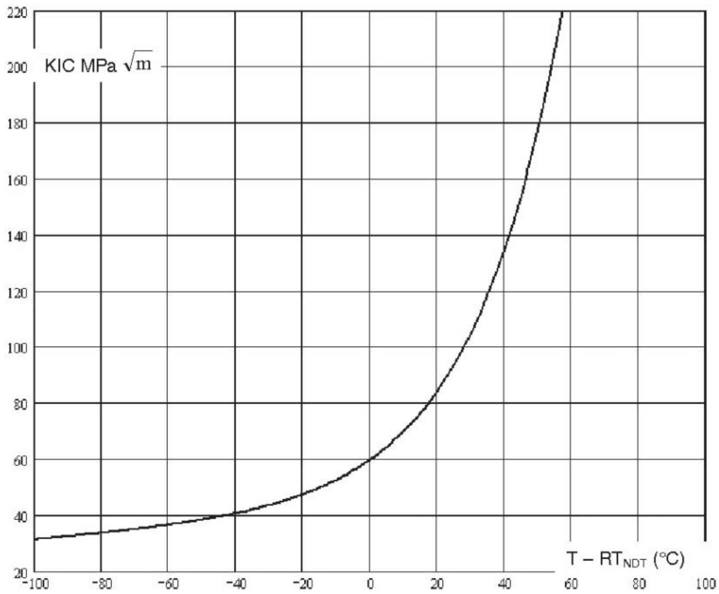


Figure 7: General demonstration approach



Fiqure Z G 6110

Reference toughness curve for low alloy steels covered by specifications M.2110 and M.2120

The analytical expression of the curve is as follows, in the $T - RT_{NDT} \leq 60°C.$

$$K_{IC} = 40 + 0{,}09\,(T - RT_{NDT}) + 20\, e^{0{,}038\,(T - RT_{NDT})}$$

où K_{IC} is expressed in $MPa\sqrt{m}$, and T and RT_{NDT} are expressed in °C

Figure 8: RCC-M indexed curve ZG6110

The effect of the offset in the transition temperature (for a loading at a given temperature) on the toughness is schematically represented in Figure 9.

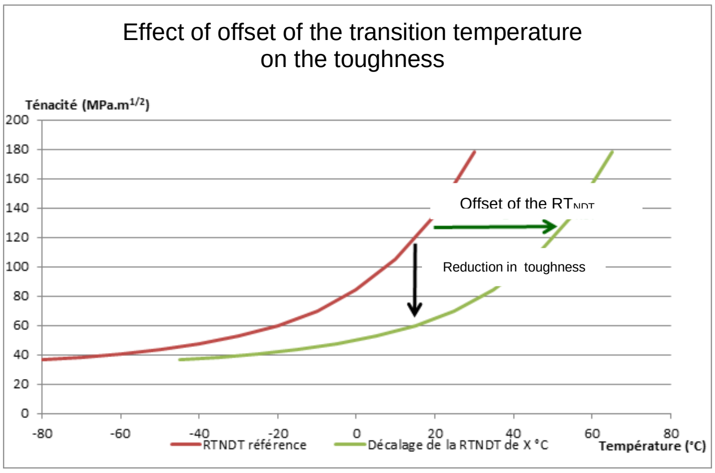


Figure 9: Effect on toughness of the offset in the transition temperature

Finally, AREVA produced an estimation in principle of the offset in the RT_{NDT} transition temperature in the segregation zone (between 35° and 70°C, excluding ageing), presented in Appendix 4. The impact of the segregation zone on the mechanical properties and in particular on the transition temperature, would at first appear to be significant. The design RT_{NDT} of the RPV being -20 °C, the RT_{NDT} of the segregation zone should be between 15°C and 50°C.

The AREVA approach for the ductile zone is also presented in §4.2.4.

4.2. Determination of adequate toughness

4.2.1. Definition of adequate toughness

4.2.1.1. AREVA proposal

AREVA gives the following definition of adequate toughness: *"It shall be considered that the toughness of the material is adequate if the values used for the fast fracture analyses with a conservative flaw 10 mm deep […] can guarantee the required design margins for operation, defined in Appendix ZG."*

Thus, for AREVA, the adequate toughness is a minimum material toughness value capable of meeting the criteria of RCC-M Appendix ZG to prevent the risk of initiation and unstable propagation of a flaw. This minimum value is calculated by considering:

- the flaws potentially present in the RPV closure head and RPV lower head (see §4.2.2);
- the stresses to which the flaws are subjected in the various situations;
- the margin coefficients on the criteria contained in RCC-M Appendix ZG for the risk of brittle fracture or instability of the ductile tearing, which is dependent on the situation category[7] (see Tableau 7).

[7] For the hydrostatic pressure test situations, the criteria chosen are the same as those chosen for the 3rd category situations (C criteria).

SITUATION CATEGORY	MARGIN CONCERNING BRITTLE FRACTURE OR INSTABILITY OF DUCTILE TEAR (1)	MARGIN CONCERNING INITIATION OF DUCTILE TEAR (2)	ENVELOPE MARGIN FOR INITIATION AND INSTABILITY OF DUCTILE TEAR (3)
Level A criteria	2	1.3	1.6
Level C criteria and testing	1.6	1.1	1.3
Level D criteria	1.2		1.0

Table Z G 3230 Safety margins to be followed in the sudden fracture strength analysis with regard to the instability risk and the initiation risk, according to the criteria level.

Table 7: Margin coefficients of RCC-M Appendix ZG 3230

RCC-M Appendix ZG states that: *"the zone is only declared to be robust in terms of resistance to fast fracture if it can be demonstrated that no flaw of a size larger than the justified flaw is possible, given the manufacturing processes used and the checks carried out on the corresponding zone"*. The adequate toughness can thus be defined according to AREVA as being a level of toughness such that it prevents fast fracture given the flaws potentially present in the structure, under the influence of the loadings applied to it.

4.2.1.2. Position of the rapporteur

The rapporteur shares the notion of adequate toughness defined by AREVA.

4.2.2. Flaws potentially present in the RPV domes

To justify the size of the flaw considered as being the largest flaw liable to exist in the RPV closure head and RPV lower head domes, AREVA followed the requirement of point 3.4 of Appendix 1 of the order in reference [6][8] concerning the detection of manufacturing flaws specified as being unacceptable. AREVA thus defined and justified the unacceptable flaw which must be detected by the non-destructive tests performed at manufacture.

4.2.2.1. Definition and justification of the unacceptable flaw liable to be present in the domes following their manufacture

For application of the order in reference [6], the exchanges between ASN and AREVA led to the definition of an approach for specifying the unacceptable flaws and verifying that the non-destructive tests are sufficient. When applied to the domes of the Flamanville 3 EPR RPV, the approach comprises the following steps:

[8] Point 3.4 of Appendix 1 of the order in reference [6]: "*The purpose of the non-destructive tests is to detect manufacturing flaws specified as being* unacceptable".

- *<u>step 1</u>: identification of potential flaws that can be generated by the manufacturing processes used;*
- *<u>step 2</u>: identification of the countermeasures used to prevent the appearance of the potential flaws identified in step 1; these countermeasures may rely on industrial know-how and feedback from previous manufacturing operations. At this stage, non-destructive inspections are not presented as countermeasures;*
- *<u>step 3</u>: definition of flaws specified as unacceptable, that is those which could appear in the light of the countermeasures adopted in step 2, with their acceptability criteria and the associated justifications. The flaws must be identified both quantitatively and qualitatively;*
- *<u>step 4</u>: verification that the manufacturing checks actually carried out are capable of detecting the unacceptable flaws identified in step 3, with the associated technical justifications;*
- *<u>step 5</u>: if the verification in step 4, with the associated justifications, does not provide all guarantees (inadequate performance or zones not checked), performance of additional checks or, if this is not possible, identification and processing in the notice of the unacceptable flaws liable to persist.*

To define and justify the unacceptable flaw liable to be present in the domes following manufacturing, AREVA carried out the specified operations in accordance with the procedures stipulated for the production of forged tubesheets intended for replacement steam generators and accepted by ASN during the conformity assessment of the equipment concerned.

The comparison between the production modes for the tubesheets and domes is summarized in Table 8 and shows that the potential flaws, up to the "blank" stage of the domes, are the same as for the tubesheets. The specific dome hot forming operations do not introduce any specific risk of the creation of new flaws but, in the outer surface part of the domes, can stretch flaws that already exist. This analysis leads AREVA to define the unacceptable flaws as being those identified in the case of replacement steam generator tubesheets. They are presented in Table 9.

Opérations		Plaque Tubulaire RP1	Calotte		Défaut		
Stade	Procédé		Inférieure	Supérieure	Potentiel	Résiduels attendus en fin de fabrication	Justification

Table 8: Potential flaws in the domes

Défauts	Origine	Caractéristiques (fin de fabrication)	Définition quantitative et qualitative des défauts inacceptables

Table 9: Specification of unacceptable flaws in the domes

4.2.2.2. Non-destructive tests performed on the domes

The checks carried out during the manufacture of the Flamanville 3 RPV closure head and RPV lower head domes are presented in the AREVA note in reference [11]. These checks are as follows.

- Checks performed with respect to the RCC-M code

  1. Visual check on all surfaces during the various manufacturing and machining phases.
  2. Dye-penetrant inspection of the inner and outer surfaces of the domes after final machining.
  3. Ultrasonic volume inspection after final machining or at a stage that is as advanced as possible for parts that cannot be inspected once completed.

  For the detection of flaws parallel or quasi-parallel to the skins, such as flaws caused by hydrogen (DDH), the ultrasonic volume inspections are performed using 4 MHz straight longitudinal waves (OL 0°) from the inner surface.

  To calibrate the sensitivity of the transducer, a reference block comprising flat-bottom holes (FBH) with diameters of 3 and 5 mm is used. The recordable threshold[9] corresponds to the equivalent of a FBH with a diameter of 3 mm accompanied by a rapid back echo attenuation. The rejection thresholds[10] are as follows:
  - individual isolated indication with a reflectivity greater than that of a 5 mm diameter FBH;
  - extended or grouped indications with a reflectivity greater than that of a 3 mm diameter FBH accompanied by rapid attenuation of the back echo;

To detect flaws perpendicular to the skins, the ultrasonic volume inspections are performed using shear waves at 45° (OT 45°) from the inner surface, along the 4 inspection directions: 2 circumferential directions and 2 axial directions (Figure 10).

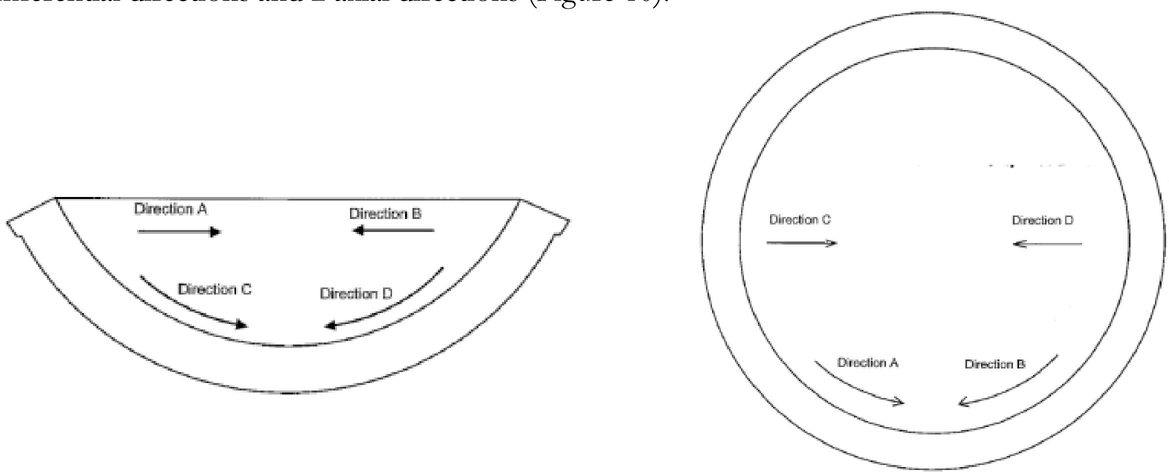


Figure 10: US inspection using 45° shear waves on the domes and direction of sensing

[9] The recordable threshold corresponds to the amplitude of the ultrasound echo measured on the flaw which leads to it being noted in the inspection report. This amplitude is defined by comparison with the amplitude of the echo obtained on a reference reflector such as a hole.

[10] The rejection threshold corresponds to the amplitude of the ultrasound echo measured on the flaw which leads to it being not accepted.

The OT 45° transducer is calibrated on a reference block comprising “generatrix” holes 2 mm in diameter, distributed through the thickness and used to establish an amplitude versus distance correction curve (DAC). The recordable threshold is as follows: any indication with an amplitude -6 dB greater than the reference curve is noted. The rejection criterion is as follows: any indication greater than the reference curve.

- Checks performed in addition to those of the RCC-M code

  Additional ultrasonic inspections were performed on the two domes. These were the same inspections as those required by the RCC-M using OL 0° waves, but with an additional gain [redacted] in order to detect very small indications.

4.2.2.3. *Detection performance*

Detection performance values are indicated by AREVA in its note in reference [11], for ultrasonic techniques intended for the detection of flaws parallel to the skins and flaws perpendicular to the skins (considered to be the most damaging but also, according to AREVA, the most improbable given the forging procedure).

Concerning flaws parallel to the skins which are detected with the OL 0° transducer calibrated on a 3 mm flat bottom hole, AREVA announced the detectability of 3 x 8 mm flaws for the lower dome and 3 x 10 mm for the upper dome.

Concerning flaws perpendicular to the skins, AREVA announced conventional performance values based on detectability using the OT 45° transducers of “flaws with a reflecting surface oriented in relation to the sensing angle”. AREVA also indicates that the evaluation of the inspection performance can be based on the work done for the UK EPR (same sensing angle and equivalent sensitivity). The main conclusions of this work are recalled in Table 10, extracted from [11].

[redacted]

Table 10: Evaluation of flaw detection capacity for the UK EPR

AREVA also indicates that the simulation results achieved with the CIVA software showed that a planar flaw with a minimum height of 5 mm will give an ultrasonic response higher than the recordable threshold for a distance between the outer skin and the flaw not exceeding 20 mm, owing to the corner effect.

Finally, for planar flaws perpendicular to the skins of the Flamanville 3 RPV domes, AREVA summarises the performance, indicating that its detectability remains heavily dependent on the "roughness of the flaw":

- if the flaw is rough, detection of a flaw of dimensions 10 x 20 mm is guaranteed:
  - for surface-breaking or underlying flaws,
  - for internal flaws, if not too mis-oriented;
- if the flaw is smooth, the inspections cannot guarantee detection for dimensions corresponding to a flaw with a rough surface. It does however remain correctly detected when surface breaking or with a ligament[11] to the surface, including with slight misorientation.

4.2.2.4. *Results of the inspections performed*

For the RCC-M code inspections, no non-conforming indication was found by the various techniques used (dye penetrant, ultrasonic using OL 0° and OT 45°).

For the ultrasonic inspections performed in addition to those of the RCC-M code, no indication was found on the upper dome and a few isolated indications lower than the improved recordable threshold, equivalent to the 2 mm diameter flat bottom hole were found on the lower dome.

To conclude, on the basis of the results of the inspections performed during manufacture of the Flamanville 3 RPV closure head and RPV lower head domes, AREVA confirms that there is no particular indication when the interpretations are carried out in accordance with the provisions of the RCC-M code.

4.2.2.5. *Position of the rapporteur*

The rapporteur does not question the definition and the justification of the unacceptable flaws considered by AREVA.

Moreover, the rapporteur has no particular remarks concerning the performance values announced by AREVA for ultrasonic volume detection of flaws parallel to the skins. In this respect, the checks in addition to those required by the RCC-M code, which improve the inspection sensitivity, further enhance confidence in the ability to detect this type of flaw.

The performance values indicated by AREVA for flaws perpendicular to the outer skin are on the whole consistent with current know-how. They are backed up by the simulations carried out for assessment of this file (see Annexe 3). Rough or smooth 10 × 20 mm flaws thus remain detectable when surface-breaking or with a small ligament separating them from the surface, including when there is a very slight misorientation as mentioned for the UK EPR study concerning planar type 2 or 3 flaws (see Table 10). The checks cannot however guarantee the detection of "rough" and "very smooth" flaws, in particular

[11] The ligament is the portion of the sound metal between the top of a flaw and the surface of the part being inspected. The absence of ligament or a short ligament means that the flaw is classified as surface-breaking.

when they are far from the outer skin and mis-oriented. "Very smooth" flaws do not however correspond to realistic flaws for the material in question.

AREVA carried out ultrasonic inspections and demonstrated the absence of flaws in the two Flamanville 3 domes on the basis of a performance evaluation study of the ultrasonic inspection methods used for the UK EPR and the inspection results obtained. The rapporteur agrees with AREVA's conclusions on the detectability of planar flaws and considers that the results enable one to conclude with a reasonable level of confidence that there are no unacceptable flaws in the domes.

However, with regard to the surface inspection, the rapporteur considers that a more pertinent inspection method would have been magnetic particle, as required by the ASME SA 508 code. This inspection was not performed by AREVA at the manufacturing stage, and they only carried out visual and dye-penetrant examinations. Magnetic particle inspection would have increased the confidence produced by the other surface inspections, in particular for small surface-breaking, mis-oriented flaws, possibly filled with oxide and with a smooth surface.

At the end of the assessment, AREVA undertook to:

- *"transmit a dye-penetrant inspection report for the Flamanville 3 RPV lower head, obtained after the grinding operation to eliminate the points of contact used for portable optical emission spectrometry kit;*
- *perform long-duration dye-penetrant inspection on the Flamanville 3 RPV lower head;*
- *perform magnetic particle inspection on a peripheral area of the Flamanville 3 RPV closure head, which is free of adapters;*
- *transmit magnetic particle inspection reports for the upper and lower UA domes;*
- *repeat a magnetic particle inspection and a long-duration dye-penetrant examination on the upper UA dome, which has undergone hydrostatic pressure testing since the previous magnetic particle inspection".*

This proposal does not include the performance of magnetic particle inspection of the Flamanville 3 RPV closure head or lower head. According to AREVA, magnetic particle inspection of the RPV lower head is *impossible* because it is in the "ceiling position" and in a configuration making this inspection hazardous for the operator. AREVA also considers that magnetic particle inspection of the RPV closure head entails risks for the equipment, in particular the risk of introducing a particle-charged "magnetic bath" into the adapter interstices, which could not be subsequently removed, and thus proposes limiting magnetic particle inspection to the peripheral area of the Flamanville 3 RPV closure head.

The rapporteur agrees with the risk assessment presented by AREVA for inspection of the RPV closure head. He also considers that the inspections proposed by AREVA for the peripheral area of the Flamanville 3 RPV are of no value in confirming the absence of flaws in the segregated area.

However, with regard to the magnetic particle inspections of the Flamanville 3 RPV lower head, the rapporteur considers that it would be possible to adapt the viscosity of the electromagnetic bath for the inspections in the "ceiling position", given that this type of inspection is performed elsewhere on other components in the vertical position.

The rapporteur also considers that the dye-penetrant inspections proposed by AREVA for the Flamanville 3 RPV cannot ensure the absence of small surface-breaking, mis-oriented flaws, possibly filled with oxide and with a smooth surface. Finally, the rapporteur considers that the inspections proposed on other domes cannot confirm the absence of flaws on the Flamanville 3 RPV domes.

Consequently, the rapporteur makes the following recommendation

Recommandation 1

The rapporteur recommends that AREVA perform non-destructive surface testing in addition to those tests already performed during manufacturing, to confirm the absence of flaws.

4.2.3. Analysis in the brittle and brittle-ductile transition zone

4.2.3.1. Flaws analysed

AREVA uses one of the methods of Appendix ZG of the RCC-M code, that is analysis of fast fracture known as "detailed" (Appendix ZG 4000). Consequently, the flaws studied are at the detection limits of the inspection processes and not a flaw with a height corresponding to the quarter of the thickness or 20 mm, whichever is the smaller, as required by the "conventional" analysis.

The flaw selected by AREVA is surface-breaking on the outer skin, placed in the most heavily stressed area and its size is defined according to the performance of the non-destructive test means, taking account of a margin on the size of this flaw (see §4.2.2).

For the upper dome, two types of flaws are considered:

- one surface-breaking at the corner of the adapter bore, semi-circular and with a depth of 10 mm;
- one surface-breaking in the continuous region, between two adapters, 10 mm in depth and 60 mm long.

For the lower dome, the flaw considered is a surface-breaking flaw on the outer skin, with a depth of 10 mm and a length of 60 mm.

To ensure robustness, a flaw with a depth equal to the mid-thickness of the domes, assuming the toughness outside the segregation zone being equal to the toughness of the acceptance zone, is also considered by AREVA. This flaw is only subjected to the loading induced during the hydrostatic pressure test in the factory (1.43 times the maximum allowable pressure PS).

4.2.3.2. Situations and loads

AREVA identified the normal, incident or accident operating situations for the main primary system of the NSSS which could lead to a high stress level associated with a low temperature in the vicinity of a flaw in the segregated area. AREVA considers that the pertinent situations to be considered for the risk of opening of a flaw on the outer skin of a dome are those initiated by a hot shock or by a high-pressure situation, given that the RPV is initially cold. A cold shock would tend to "close" the flaws on the outer skin and is not therefore studied.

In its analysis, AREVA concludes that the limiting loadings leading to opening of the flaw are the initial hydrostatic pressure tests and periodic requalification tests and the operating situation corresponding to transition from cold shutdown to hot shutdown (AAF-AAC).

4.2.3.3. Ageing

AREVA considers that the upper and lower domes are not subjected to irradiation ageing: the RPV lower head dome is separated from the lower core plate by more than one metre of water and the fast neutron flux is about 10^4 n/cm^2/s (as compared with a flux of 10^{10} n/cm^2/s on the core shells). The upper dome is separated by more than 5 metres of water, leading to a further flux reduction of several decades. For such levels of flux and consequently of fluence, no irradiation-induced damage can be expected.

The potential ageing mechanisms for the domes are therefore strain-induced ageing and thermal ageing, which lead to a lowering of the toughness. This reduction can be expressed by an offset in the RT_{NDT} in relation to the initial RT_{NDT}.

Strain-induced ageing is taken as being equal to 15°C. Thermal ageing, which depends on the phosphorus content of the material, was estimated at between 3 and 7°C for 60 years of operation. Given the conservative nature of the fixed value attributed to strain ageing, AREVA in the end adopts an RT_{NDT} increase of 15°C to take account of the combined effect of these two types of ageing.

4.2.3.4. Calculated stress intensity factors

For the situations (hot shock), AREVA states that for the flaw considered (10 mm), the maximum stress intensity factor obtained in a normal start-up situation, which is the only hot shock case included in the list of situations, remains below the historical asymptote (lower limit for low temperatures equal to 36.5 MPa.m1/2) of the toughness curve in the RCC M (Figure 11).

At the end of the assessment, AREVA also specified that it had identified three other possible situations inducing a hot shock, which are not all included in the list of situations:

- RHRS connection following a small primary break (not included in the list of situations; this situation would need to be classified category 3);
- restart of natural circulation in a small primary break situation (not included in the list of situations; this situation would need to be classified category 3);
- total loss of RHRS cooling in initial state on RHRS (included in the list of situations, classified category 4).

To ensure robustness, AREVA also identified a situation not included in the list of situation, which it considers to be highly implausible and the annual frequency of which would be about 10^{-7} per year.

For all of the last four above-mentioned situations, the maximum stress intensity factor obtained would exceed the historical asymptote. However, according to AREVA, these situations cannot lead to a risk of brittle fracture, and the hydrostatic pressure testing situations are far more severe.

To conclude, AREVA considers that the toughness is sufficient for normal, incident and accident situations, whatever the RT_{NDT} value of the material.

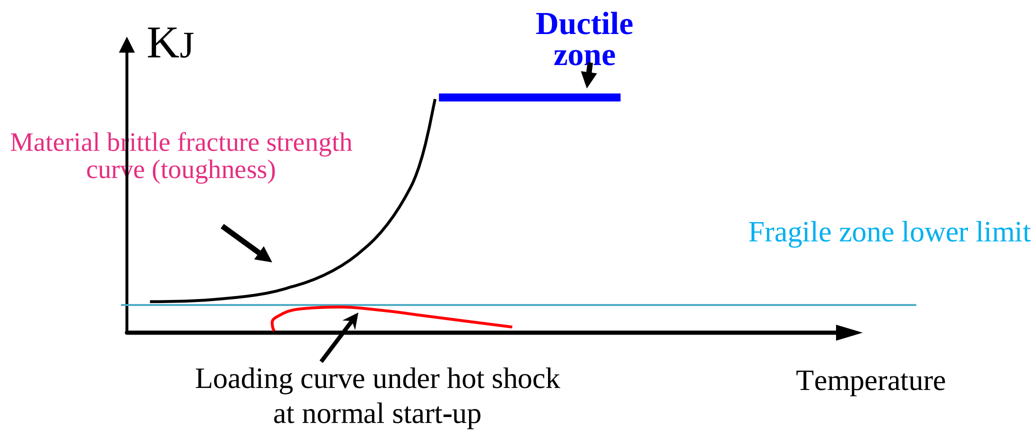


Figure 11: Positioning of the hot shock loading at normal start-up in relation to the toughness curve.

According to AREVA, the fast fracture risk analyses performed for the above-mentioned flaws show that the hydrostatic pressure tests constitute the most penalising loadings for the RPV closure head and lower head and are shown in Table 11 below.

	Pressure	**Margins coefficient according to RCC-M**	**Flaw (a x 2c in mm) / Location**		**K_{cp}(*) in $MPa.m^{1/2}$**
Initial test factory or site	1.43 * PS 250 bar	1.6	10 x 20	Vessel head – adapter corner	63.4
			10 x 60	Vessel lower head	60.0
Periodic requalification test	1.2 * PS 210 bar	1.6	10 x 20	Vessel head – adapter corner	53.2
	1.2 * PS 210 bar	1.6	10 x 20	Vessel head – adapter corner	53.2
(*) including the margin coefficient stipulated in RCC-M Appendix ZG					

Table 11: Results of mechanical fracture calculations for the test situations

4.2.3.5. Determination of acceptable RT_{NDT}

The values of the stress intensity factor Kcp make it possible to calculate the limit parameter (T-RT_{NDT}) using the minimum toughness formula of the RCC-M code Appendix ZG 6100 and then to deduce the acceptable RT_{NDT}. The calculations are detailed in Table 12 below.

	Test temperature (°C)	K_{cp} (MPa√m)	T-RT_{NDT} (ZG 6100)	$RT_{NDT\ acceptable}$ (beginning of life)
Initial test factory or site	50°C	63.4 (closure head)	+5°C	45°C
	50°C	60.0 (lower head)	0°C	50°C
Periodic requalification test	50°C	53.2 (closure head)	-7°C	43°C
	85°C	53.2 (closure head)	-7°C	78°C

Table 12: RT_{NDT} acceptable during hydrostatic pressure testing

The factory and initial site hydrostatic pressure tests are generally performed at a temperature of 35°C. To obtain a point of comparison, the calculations were performed at 50°C in both cases. According to these results, the acceptable beginning of life RT_{NDT} is 45°C for factory hydrostatic pressure testing and 43°C for periodic requalification testing, assuming that these tests take place at 50°C. AREVA thus obtains comparable acceptable RT_{NDT} for the different hydrostatic pressure test cases at 50°C. AREVA points out that the hydrostatic pressure test temperature can be increased if necessary, in particular for the periodic requalifications.

Finally, the analysis of the mechanical strength during the factory hydrostatic pressure testing of the domes in the presence of flaws with a depth equal to the mid-thickness, the tip of which would be situated outside the segregated area, concludes that there is a K_{IC}/K_{CP} ratio higher than 1, assuming local toughness properties similar to those of the acceptance zone and ignoring the margins coefficient given in the RCC-M.

4.2.3.6. Position of the rapporteur

4.2.3.6.1. Flaws analysed

The rapporteur recalls that the RCC-M (Appendix ZG 1200) requires that the manufacturer perform a conventional fast fracture analysis. This analysis method is more specifically *"dedicated:*

- *to establishing in-service allowable P-T service pressure versus temperature curves;*
- *determining the minimum hydrostatic pressure testing temperatures".*

The rapporteur notes that the manufacturer simply carried out the "detailed analysis" and not the "conventional analysis". The rapporteur considers that the "detailed analysis" is acceptable for determining adequate toughness, enabling the minimum temperature required to prevent the risk of fast fracture in a hydrostatic pressure test situation to be deduced. However, the rapporteur considers that the hydrostatic pressure test temperatures used in practice must be determined on the basis of a "conventional analysis" as required by the RCC-M code.

At the end of the assessment, AREVA made the following undertaking:

- *"For the adequate toughness justification file, AREVA will take account of the 10 mm flaw and undertakes to complete the documentation with sensitivity study assessments for a 20 mm flaw;*
- *For the on-site test cases, AREVA agrees initially to consider the 20 mm flaw to define the hydrostatic pressure test temperature and, if the analysis with conventional flaw leads to an industrially prohibitive or impossible hydrostatic pressure test temperature, consistently with the RCC-M, to:*

- *consider the beginning of life mechanical properties for the initial hydrostatic pressure test (no ageing) and end of life properties for the requalification tests;*
- *set an industrially reasonable hydrostatic pressure test temperature;*
- *determine the flaw strictly compliant with the criteria of the RCC-M code;*
- *compare it with the detection limit flaw".*

The rapporteur considers that this undertaking is satisfactory provided that the flaw strictly compliant with the criteria of the RCC-M code is greater than the detection limit flaw.

4.2.3.6.2. Situations and loads

Given the belated transmission of data concerning the exhaustiveness of the situations considered in the mechanical analyses, these data will be examined later by the rapporteur. In this respect, the rapporteur will in particular closely check that AREVA has accurately examined all the pertinent situations to ensure compliance with the criteria associated with the second barrier.
In the rest of this report, the rapporteur's analysis is based on the data transmitted by AREVA so far.

The rapporteur underlines that the limiting situations and loadings were selected assuming that the reduction in toughness in the segregated area extends from the outer surface of the dome to mid-thickness. Consequently, the situations opening any flaws situated beyond this mid-thickness are not considered, in particular cold shocks. The rapporteur considers that this hypothesis must be validated by the test programme (see §4.3).

4.2.3.6.3. Ageing

On the basis of his own evaluations, the rapporteur concurs with AREVA's position on the fact that the fluence is not such as to lead to irradiation-induced damage.

AREVA adopts a fixed RT_{NDT} offset of +15°C to take account of ageing. However, given the fixed nature of the value and the small amount of data on thermal ageing, the rapporteur considers that further justification is required to estimate the effect of thermal ageing in the case of this material for which the chemical composition is different from that of the materials previously studied.

Given the little amount of data available on the thermal ageing of heavily segregated parts over 60 years of operation, the rapporteur considers that a test programme is required to confirm the low thermal ageing of the heavily segregated areas of the 16MND5 steel used for the Flamanville 3 reactor RPV domes.

At the end of the assessment, AREVA transmitted additional data that were not in its initial file, mentioning studies previously carried out by EDF, CEA, FRAMATOME and WESTINGHOUSE. Based on these data, *"EDF and AREVA agree to provide a more complete file demonstrating that an ageing programme is not pertinent, by the end of the first quarter of 2016".*

The rapporteur considers this undertaking to be satisfactory. The new file that AREVA undertakes to provide shall make it possible to rule on the need to initiate a specific thermal ageing programme for the heavily segregated parts.

4.2.4. Analysis in the ductile zone

4.2.4.1. AREVA proposal

AREVA proposes ensuring the appropriate mechanical behaviour of the RPV domes in the ductile zone by:

- evaluating the adequate toughness to ensure the margins required by RCC-M Appendix ZG for the most unfavourable situations;
- evaluating the toughness of the material in the ductile zone based on tests on toughness test specimens.

Several toughness tests in the ductile zone will be performed to verify that the minimum toughness of the material is greater than the adequate toughness.

4.2.4.2. Position of the rapporteur

The rapporteur has no particular observation with regard to AREVA's approach.

4.3. Determination of the minimum toughness and mechanical properties of the material in the segregated area

4.3.1. AREVA proposal

The purpose of the test programme proposed by AREVA in references [13] to [17] is to evaluate:

- the extent of the segregated area;
- the mechanical properties of the heavily segregated areas, especially the toughness.

This test programme is run on a scale one replica upper dome ("UK" EPR RPV), produced by the same manufacturing process as the RPV domes at Flamanville 3 and also produced at Areva Creusot forge.

The first step in the test programme, which has already been carried out, was to determine the extent of the positive segregation area on the surface and in the thickness of the UK sacrificial upper dome, by analysis of the carbon content.

The second step in the test programme concerns the tests to characterise the mechanical properties of the localised segregated area following the first step in the test programme.

4.3.1.1. Representativeness of the UK upper dome

The production processes for the FA3, UK and UA domes were the subject of a comparative analysis by AREVA in order to ensure that the UK upper dome is representative of the FA3 domes

Chemical composition

The chemical composition of the UK upper dome is virtually identical to that of the Flamanville 3 RPV domes. The slight differences in the content of certain chemical elements are not such as to lead to significant differences in the mechanical properties (see Tableau 13 and Table 14).

	FA3		UA		UK	
	Calotte supérieure		Calotte supérieure		Calotte supérieure	
	Requis	RVR 2403	Requis	RVR 2944 RC	Requis	RVR 3365
C	0,20 maxi	0,18	0,20 maxi	0,18	0,20 maxi	0,19
Mn	1,15 - 1,55%	1,55	1,20 - 1,50%	1,46	1,15 - 1,55%	1,57
P	0,008 maxi	0,003	0,008 maxi	0,004	0,008 maxi	0,005
S	0,005 maxi%	0,001	0,005 maxi%	0,001	0,005 maxi%	0,001
Si	0,10 - 0,30%	0,17	0,15 - 0,30%	0,18	0,10 - 0,30%	0,20
Ni	0,50 - 0,80	0,72	0,50 - 0,80	0,71	0,50 - 0,80	0,71
Cr	0,25 maxi	0,17	0,25 maxi	0,18	0,25 maxi	0,16
Mo	0,45 - 0,55	0,51	0,45 - 0,55	0,49	0,45 - 0,55	0,52
V	0,01 maxi	0,001	0,01 maxi	0,005	0,01 maxi	0,001
Cu	0,10 maxi	0,04	0,10 maxi	0,04	0,10 maxi	0,06
Al	0,04 maxi	0,02	0,04 maxi	0,01	0,04 maxi	0,01
Co	0,03 maxi	0,01	0,03 maxi	0,01	0,03 maxi	0,01
H2	1,5 ppm maxi	0,95 ppm	1,5 ppm maxi	0,94 ppm	1,5 ppm maxi	1,10 ppm

Table 13: Comparison of chemical compositions of the FA3, UA and UK upper domes

	FA3		UA		UK	
	Calotte inférieure		calotte inférieure		calotte inférieure	
	Requis	RVR 2473	Requis	RVR 3195 RC	Requis	RVR 3370
C	0,20 maxi	0,18	0,20 maxi	0,18	0,20 maxi	0,18
Mn	1,15 - 1,55%	1,55	1,20 - 1,50%	1,45	1,15 - 1,55%	1,58
P	,008 maxi	0,004	,008 maxi	0,004	0,008 maxi	0,005
S	0,005 maxi%	0,001	0,005 maxi%	0,001	0,005 maxi	0,001
Si	0,10 - 0,30%	0,18	0,15 - 0,30%	0,20	0,10 - 0,30%	0,18
Ni	0,50 - 0,80	0,75	0,50 - 0,80	0,69	0,50 - 0,80	0,71
Cr	0,25 maxi	0,14	0,25 maxi	0,15	0,25 maxi	0,16
Mo	0,45 - 0,55	0,51	0,45 - 0,55	0,50	0,45 - 0,55	0,51
V	0,01 maxi	0,001	0,01 maxi	0,001	0,01 maxi	0,001
Cu	0,10 maxi	0,04	0,10 maxi	0,03	0,10 maxi	0,06
Al	0,04 maxi	0,02	0,04 maxi	0,01	0,04 maxi	0,01
Co	0,03 maxi	0,010	0,03 maxi	0,004	0,03 maxi	0,009
H2	1,5 ppm maxi	0,95 ppm	1,5 ppm maxi	0,6 ppm	1,5 ppm maxi	1,07 ppm

Table 14: Comparison of chemical compositions of the FA3, UA and UK lower domes

Manufacturing process

The manufacturing processes for the upper and lower domes are identical:

- same type and weight of ingot;
- same forging process and sequence;
- same blank dimension;
- same precautionary heat treatment instruction;
- same blank before hot forming;
- same hot forming.

The main difference in the manufacturing process between the upper and lower domes lies in their machining, owing to their final profile thickness: 232 mm for the upper dome, 147 mm for the lower dome. This difference appears as of machining of the blank before quality heat treatment (at this stage, the lower domes are 250 mm thick, while the upper domes are 290 mm thick). The outer skin machining in the centre of the domes is slightly greater for the lower dome as shown in Table 15.

Calotte supérieure		FA3	UA	UK	Calotte inférieure		FA3	UA	UK
Usinage total	Surface externe	71	65	76	Usinage total	Surface externe	108	92	115
	Surface interne	37	127	163		Surface interne	155	197	194

Table 15: Machined thickness (in mm) in the centre of the upper and lower domes

After forging and before machining, the domes undergo quality heat treatment (TTQ) consisting of quenching and tempering[12]. Quality heat treatment is comparable for the FA3 and UK upper domes (see Table 16).

	Pièces	Calottes supérieures			Calottes inférieures		
	Contrats	FA3	UA	UK	FA3	UA	UK
Paramètres Essentiels							

Table 16: Summary of the main manufacturing parameters for the FA3, UA and UK upper and lower domes

<u>Dome similarity in terms of segregation</u>

For an identical ingot, the extent of the segregated areas in the thickness of the domes depends on the forging process and the machining process.

The lower domes have the same manufacturing process as the upper domes, from ingot to rough machining for quality heat treatment. In addition, according to AREVA, the upper domes have *"greater*

12 The purpose of quality heat treatment is to obtain the required mechanical properties for the material (yield strength, ultimate tensile strength, elongation, bending rupture energy, toughness). Quenching involves three steps: heating then maintaining at a temperature slightly higher than 850°C for several hours to form fine-grain austenite (austenitisation) and finally rapid cooling with water. The purpose of quenching is to obtain a balanced material state and eliminate internal stresses of thermal or metallurgical origin. It comprises heating, maintaining at a temperature of about 650°C for several hours and cooling in air or in the oven.

thickness than the lower domes during TTQ, which on the one hand ensures that the properties of both types of parts are covered and on the other allows sampling of a large number of test specimens from the thickness of the part".

The measurements made on the UK, UA, FA3 upper domes show that the level of carbon segregation on the surface is comparable on the three upper domes, as shown in Figure 12 and in Table 17.

It should be noted that the values of 0.30 % and 0.29 % carbon were measured by sampling chips from the top (skin and quarter-thickness) of the core sampled from the centre of the UA upper dome.

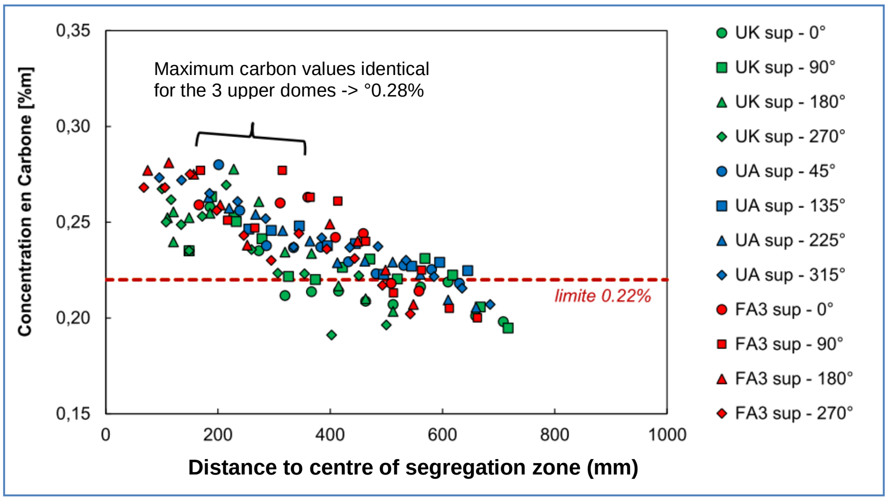


Figure 12: Evolution of the carbon content along 4 geometrical axes of the upper domes

Upper dome		**FA3**	**UA**	**UK**	**Lower dome**		**FA3**	**UA**	**UK**
maximum %C measured	Outer surface	**0.28**	**0.28**	**0.28**	maximum %C measured	Outer surface	**0.28**	**0.27**	**0.25**
	Inner surface	0.17	0.19	0.19		Inner surface	0.16	0.18	0.18

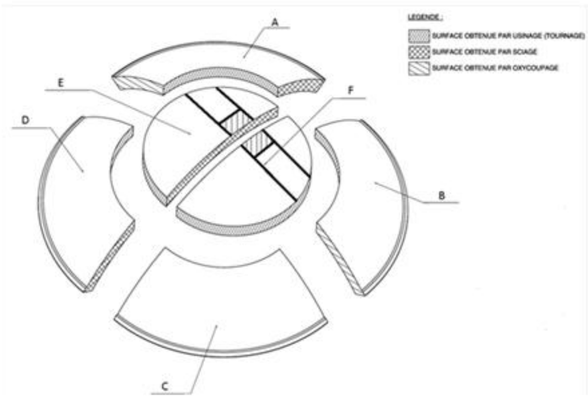
Table 17: Surface carbon content of the FA3, UK and UA domes measured by portable optical emission spectrometry for outer surfaces and by melting of the chips sampled during manufacturing for the inner surfaces

4.3.1.2. Steps already taken by AREVA

The first step in the test programme, which has already been carried out, was to determine the extent of the positive segregation zone on the surface and in the thickness of the UK sacrificial upper dome, by analysis of the carbon content using portable optical emission spectroscopy kit.

AREVA indicated that this measurement method gives results equivalent to the chip melting analysis method.

AREVA first of all determined the extent of segregation on the surface of the outer skin (which corresponds to the top of ingot side), first of all along 8 axes and then according to a mesh centred on the previously determined segregation centre. AREVA then cut the dome (see Figure 13) and carried out carbon measurements on a section passing through the segregation centre (see Figure 14).



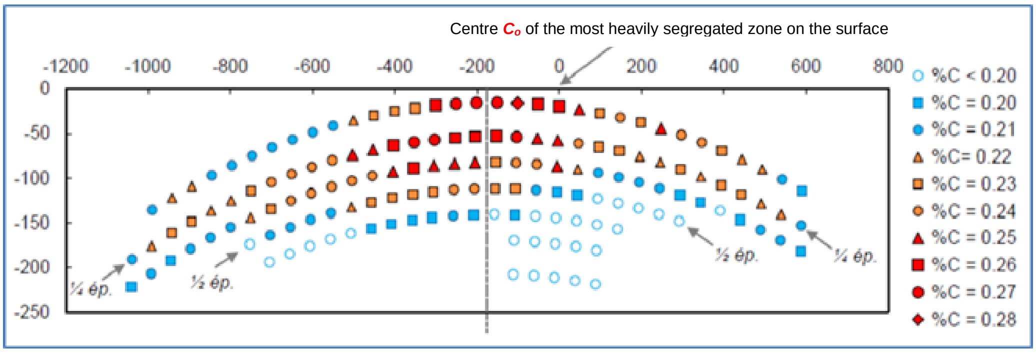


Figure 13: Map of carbon content in the thickness of the UK upper dome

These measurements enabled AREVA to characterise the segregation zone in the upper dome:

- the segregated part, that is with a carbon concentration greater than 0.22%, is situated up to mid-thickness (diameter of 1600 mm at ¼ thickness and 500 mm at ½ thickness);
- the heavily segregated part, in other words with a carbon concentration greater than 0.25%, extends up to 30 mm below the ¼ thickness (diameter of 550 mm at ¼ thickness);
- the non-segregated part, that is with a carbon concentration strictly below 0.22%, is situated as of 30 mm below the ½ thickness.

4.3.1.3. Future test programme: characterisation of the mechanical properties of the segregation zone

The test programme, the aim of which is to determine the impact of positive macrosegregation on the mechanical properties, will involve three steps:

1. evaluation of a local RT_{NDT}: the NDT of the positive macrosegregation zone will be determined using drop-weight test specimens and impact test specimens according to the protocol in the RCC-M;
2. evaluation of the toughness in the positive macrosegregation zone in the ductile zone: 5 tests on

a CT25 test specimen will be performed at 50°C (hydrostatic pressure test temperature) and one test at 330°C (operating temperature);

3. evaluation of toughness in the brittle-ductile transition zone of the positive macrosegregation: 48 CT test specimens 12.5 mm thick will be used. The tests will be performed in accordance with procedure ASTM E1921.

All the tests planned at the quarter-thickness of the UK upper dome will be performed in a similar way on the test specimens sampled from the acceptance zone of the UK upper dome and from the FA3 domes, in order to act as a reference.

Further to the questions from the rapporteur, AREVA revised its test programme in order to optimise the positioning of the test specimens according to the carbon concentrations and to perform the same test programme at both ¼ and ½ thickness.

AREVA will cut the cross-hatched area (see Figure 15) into two 800 x 400 mm pieces which will themselves be cut into two 400 x 400 mm pieces.

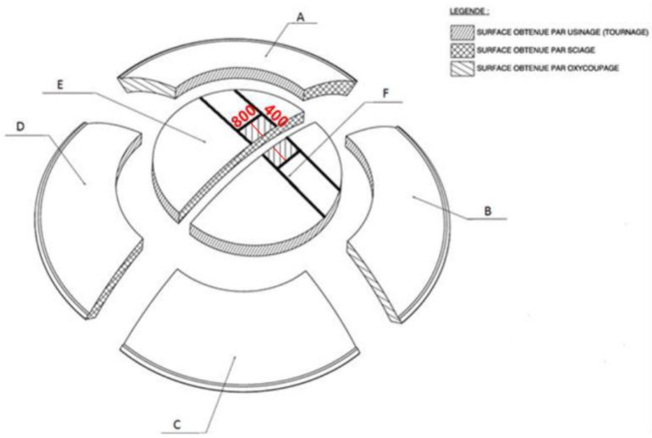


Figure 14: Positions of the 800 x 400 mm pieces

Each 400 x 400 piece will be cut as shown in the drawing in Figure 16. 7 slices will thus be sampled by wire cutting enabling the maximum amount of material to be conserved.

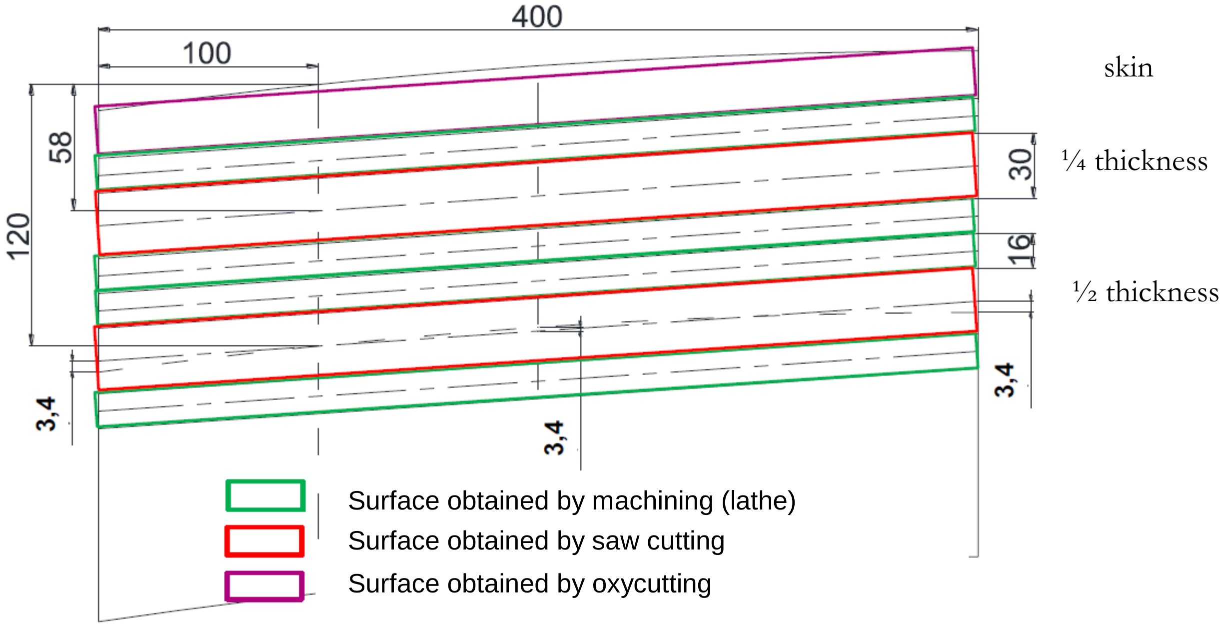


Figure 15: Cutting of various slices within the thickness

The violet upper slice will be used for 3 tensile tests at 20°C. If the fracture elongation is below 20% (values mentioned in point 4 of Appendix 1 of the order in reference [6]), 6 toughness tests in the ductile zone will be scheduled.

The two red slices reserved for the toughness tests are 30 mm thick and on average centred at ¼ and ½ thickness respectively, with a maximum variation of 3.4 mm. At each elevation (¼ and ½ thickness) the programme will comprise:

- 18 bending rupture energy test specimens;
- 48 CT12.5 type test specimens (brittle zone);
- 6 CT25 type test specimens (ductile zone);
- 8 standard tensile test specimens.

This test volume was built up from the characterisation of the segregation zone in the slice of the UK upper dome shown in Figure 14. It will be optimised in order to ensure that a maximum number of test specimens are sampled from this segregation zone, based on the chemical characterisation by portable spectrometry in accordance with the drawing in Figure 17 which will be performed on the upper surface of each of the red slices intended for the mechanical tests. Thus 8 surfaces (2 slices x 4 blocks) will be characterised.

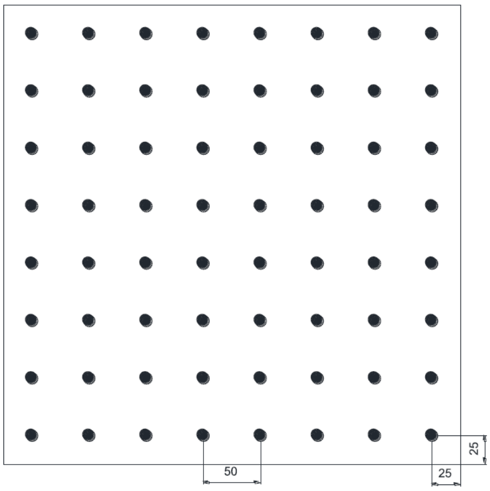


Figure 17: Carbon chemical mapping of the various slices

The green samples for the drop-weight tests are sampled from either side of the red slice:

- 12 bending rupture energy test specimens;
- 8 drop-weight test specimens.

Chemical analyses on test specimens

Chips will be taken from all the broken test specimens sampled at ¼ and ½ thickness in order to analyse the carbon and sulphur content as close as possible to the fracture zone. The samples will be taken by drilling (see Figure 18, Figure 19 and Figure 20).

In addition, a complete chemical analysis will be performed on 5 test specimens, in order to evaluate the evolution of the other segregating elements:

- the test specimen whose carbon content corresponds to the minimum value of the toughness test;
- the test specimen whose carbon content corresponds to the maximum value of the toughness test;
- 3 test specimens chosen randomly from within this range.

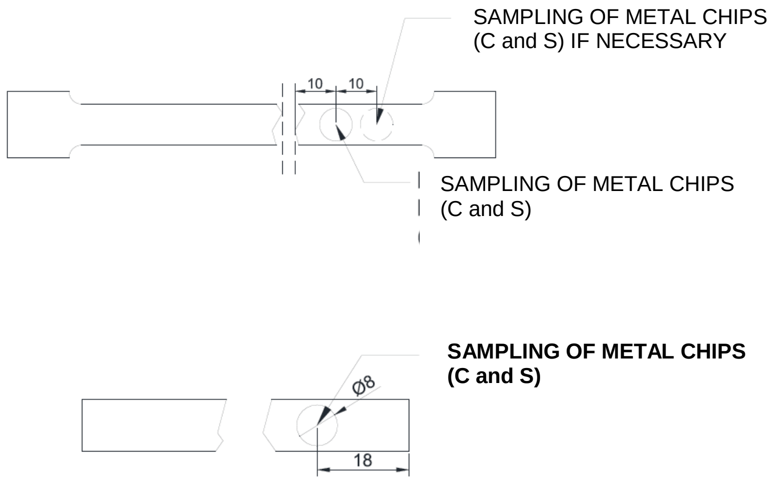


Figure 16: Sampling of chips from tensile and bending rupture energy test specimens

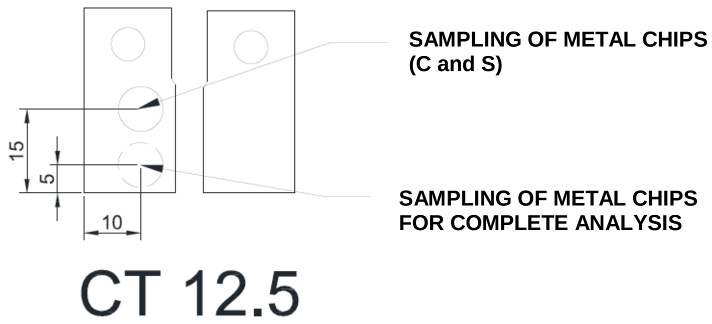


Figure 17: Sampling of chips from CT 12.5 test specimen

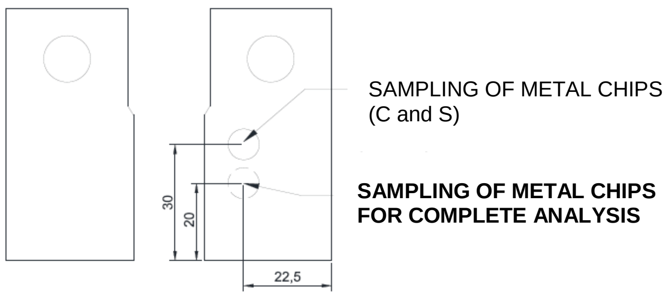


Figure 20: Sampling of chips from CT 25 test specimen

Following the carbon content measurements on the outer surface of the various domes, AREVA adopted the 0.25% threshold to define the volume of material available for the mechanical tests.

Macrography and micrography

Macrography will be carried out in order to characterise the microstructure (4% Nital etching).

Depending on the results of this macrographic examination and the available material, samples could be taken to carry out a micrographic analysis.

This sampling will only be carried out if it does not compromise the quantity of material needed to perform the mechanical tests.

4.3.1.4. Test laboratories

AREVA used the following criteria to choose the test laboratory, in order of importance:

1. technical know-how. Few laboratories have the technical expertise needed to carry out a complete test programme;
2. accreditation according to standard ISO 17025;
3. laboratory's capacity for carrying out machining and testing;
4. performance time.

AREVA thus chose the laboratories presented in Table 18.

Tests	Standard applicable (RCC-M) to the FA3 project	Latest standard in force	Laboratory
Tensile tests	**NF EN 10002-1 and 10002-5**	**ISO 6892-1 and 6892-2**	**AREVA Erlangen**
Bending rupture energy tests	**NF EN 10045-1**	**ISO 148-1**	**AREVA Erlangen**
Drop-weight tests	**ASTM E208**	**ASTM E208**	**AREVA Saint-Marcel**
Toughness tests (ductile and brittle)	**N/A**	**ASTM E1820 and 1921**	**AREVA Erlangen**
Chemistry	**MC 1350**	**-**	**AREVA Saint-Marcel and Creusot Forge**

Table 18: Applicable standards and test laboratories selected

The standards used by the Erlangen laboratory for the mechanical tests, in particular tensile and bending rupture energy, are the latest standards in force. They are also mentioned in §A1300 of the 2010 modification of the 2007 edition of the RCC-M.

The Erlangen laboratory which is to perform the tensile, bending rupture energy and toughness tests holds ISO 17025 accreditation in accordance with the latest standards in force.

For the drop-weight tests, which are industrial tests little used by research laboratories, AREVA chose the Saint-Marcel laboratory, which does not hold accreditation. AREVA will have the performance of these tests supervised by a notified approved body.

For the chemical analyses, the chips will be sampled by the Saint-Marcel plant, which regularly performs this type of sampling, in which a major challenge is to prevent the pollution of the chips. The chemical analyses will be carried out by the Creusot Forge laboratory.

Measurement uncertainties

The measurement uncertainties are quantified for the tensile, toughness and bending rupture energy tests, given that they are performed in an ISO 17025 accredited laboratory.

For the drop-weight tests, the procedures used must be able to demonstrate that the test is performed satisfactorily.

For the chemical analyses, the Creusot Forge laboratory holds no accreditation and can provide no evaluation of the measurement uncertainties.

4.3.2. Position of the rapporteur

Representativeness of the UK upper dome

The rapporteur considers that the UK upper dome is representative of the FA3 upper dome with respect to both the carbon content and the extent of the segregation zone, in the light of their chemical composition, their manufacturing process and the carbon levels recorded on the surface of the domes.

The rapporteur notes that despite greater machining on the outer skin on the lower domes, the maximum carbon concentration values on the outer skin of the lower and upper domes are similar. These values cannot be explained simply by geometrical considerations (machining thickness, thickness of the lower dome, etc.) and do not therefore allow the depth of the segregation zone of the lower dome to be assessed, more specifically at the ½ thickness of this dome. Consequently, the rapporteur considers that additional investigations are required with regard to the extent and depth of the segregation zone in a lower dome.

The rapporteur also considers that the programme to characterise the mechanical properties cannot simply be limited to determining the properties of a material from a single pouring of steel. Mechanical properties measurements on a dome from a pouring of steel other than that used for the UK upper dome are thus necessary in order to enhance confidence in the results obtained.

At the end of the assessment, AREVA therefore undertook to perform a chemical characterisation and mechanical test programme on the UA lower dome that is identical to that performed on the UK upper dome. AREVA however pointed out that as these lower domes are not as thick as the upper domes, certain tests could not be carried out. AREVA thus proposes not performing the drop-weight tests and determining the local RT_{NDT} at ¼ and ½ thickness of the UA lower dome by another method:

- if the results obtained on the UK upper dome confirm that in the segregation zone the RT_{NDT} is fixed by the TCV temperature of chapter MC1240 of the RCC-M code, AREVA proposes using this temperature to determine the local RT_{NDT};
- if the RT_{NDT} is not fixed by the TCV temperature in chapter MC1240 of the RCC-M code, and depending on the carbon mapping to be performed on the slices, AREVA proposes examining the possibility of machining a few drop-weight test pieces;
- if it is not possible to machine these drop-weight test pieces, AREVA proposes estimating the offset between the acceptance RT_{NDT} and the NDT of the macro-segregation zone on the UK upper dome and transposing this offset to the RT_{NDT} of the acceptance zone of the UA dome. AREVA also proposes performing bending rupture energy tests using the approach in chapter MC1240 of the RCC-CM code to finalise the estimation of the local RT_{NDT}.

The rapporteur considers this undertaking to be satisfactory.

Heat treatment

The FA3 and UK domes underwent the same quality heat treatment (TTQ). The FA3 domes also underwent various stress-relieving heat treatments (TTD) following the welding operations. These heat treatments have an influence on the mechanical properties of 16MND5 steel, its toughness in particular, as shown by the bending rupture energy values measured on the test specimens taken after TTQ and after TTQ plus TTD. Insofar as AREVA's objective is to determine the properties of the material of the Flamanville 3 EPR RPV during its operation, the same heat treatment as that carried out on this RPV must necessarily be applied to the test specimens taken from the sacrificial domes.

At the end of the assessment, AREVA undertook to perform stress-releaving heat treatment on the 800 x 400 mm blocks, as required in the procurement specifications, that is maintaining at 620°C +/- 5°C for 16h to 16h30, with a maximum rise and fall gradient of 55°C/h between 400°C and 620 °C.

The rapporteur considers this undertaking to be satisfactory.

Sufficiency of number of tests

A large number of toughness tests is scheduled by AREVA on test specimen pieces sampled at quarter and half-thickness in the most heavily segregation zone of the UK upper dome.

For the rapporteur, the volume of tests would appear to be sufficient, but during the assessment he underlined that given the variability of the carbon concentration in the sample zone, the sample for a given carbon concentration could be low. Consequently, the adequacy of the test programme could only be assessed subsequently, after analysis and interpretation of the test results. The rapporteur considers that as many verifications as possible must be performed to characterise the segregation zone, which has no equivalent on the EDF fleet, because it is hard to predict the influence of all the parameters on toughness. The rapporteur also considers that all the material (test specimen, discards, etc.) taken from the UA, UK upper and UK lower domes should be identified and kept for any further investigations.

The rapporteur underlines that the limiting situations and loadings were selected assuming that the reduction in toughness in the segregation zone would stop at mid-thickness. The rapporteur notes that the test programme now includes tests at ½ thickness, which would validate this core hypothesis of the AREVA dossier. The rapporteur however points out that the results presented in Figure 14 show that the segregation zone exceeds ½ thickness.

Positioning of test specimens

The rapporteur notes that the positioning of the test specimens in the 28 slices (7 slices per part) will take account of the results of the surface spectrometry chemical mapping of the 8 slices intended for the mechanical tests (tensile, bending rupture energy and toughness).

The rapporteur considers that this arrangement would be such as to intercept the zones with the highest carbon content.

Interpretation of test results

The rapporteur considers that the carbon and sulphur chemical analyses planned on each broken test specimen as close as possible to the fracture zone, will ensure that the test programme characterises the segregation zone.

The rapporteur considers that the macrographic and micrographic analyses should be able to characterise the structure of the segregated material and that the fracture surface of the test specimens will have to be analysed.

Recommandation 2

The rapporteur recommends that prior to initiating the test programme and after characterising the extent of the segregation zone, AREVA specify the location of the macrographic and micrographic examinations. The rapporteur also recommends that AREVA analyse the fracture surfaces of the test specimens.

The rapporteur considers that all the data from the test programme must be analysed after they are classified according to the level of segregation of the test specimens from which they come. However, the rapporteur considers that only the test results corresponding to test specimens with a carbon concentration of 0.25% or more must be considered when the test results are statistically processed.

The rapporteur notes that the entire approach is based on the hypothesis that low bending rupture energy values are linked to the presence of positive macrosegregations and that the various domes are representative with respect to this phenomenon, which will need to be confirmed by the test results. If the test results reveal that the mechanical properties are degraded by another phenomenon, the rapporteur considers that AREVA will need to demonstrate the representativeness of the UK, UA and FA3 domes with respect to the new phenomenon brought to light.

Skin elongation

The rapporteur recalls that in the frame of the technical qualification file for the elliptical domes of the replacement steam generators for the 900 MWe reactors, the tests performed on the skin of the segregation zones showed elongation values lower than the 20% mentioned in point 4 of appendix 1 in the order in reference [6] (see Table 19).

ref.	location	Rp 0.2%	Rm	A%	C%
8T1	segregation zone in reinforcement	506	653	24.4	0.23
8T1	Flow limiter zone	577	736	20.3	0.26
T23	Top of central core sample	574	732	18.4	0.25

Table 19: Results obtained on the sacrificial elliptical domes of the 900 MWe reactor replacement steam generators

The rapporteur notes that three tensile strength tests will be performed on the outer skin of the UK upper dome. The rapporteur notes that in the case of elongation not compliant with the value in the order in reference [6] (greater than or equal to 20%), AREVA plans to perform 6 toughness tests in the ductile zone.

The rapporteur considers that in the case of skin elongation values below that mentioned in point 4 of Appendix 1 to order [6], AREVA shall give a detailed demonstration, in particular taking account of the mechanical properties measured in the segregation zones of the UK upper and UA lower domes, that the material offers ductile behaviour compatible with the design rules used for the domes of the Flamanville 3 EPR RPV.

Choice of laboratory

The rapporteur considers that the ISO 17025 accreditation of the Erlangen laboratory selected by AREVA for the mechanical tests, with the exception of the drop-weight tests, offers sufficient guarantees in terms of technical know-how, quantification of uncertainties and impartiality. The rapporteur also notes that this laboratory is involved in the assessment and research programmes for nuclear reactors in other countries (Doel 3, Tihange 2 and Olkiluoto 3).

The rapporteur duly notes that a quantification of the uncertainties concerning the results of the tests performed in this accredited laboratory (mechanical tests except for the drop-weight tests) will be transmitted by AREVA. He considers that they will be low enough to be considered covered by the appropriate safety factors.

The rapporteur considers that the technical specificity of the drop-weight tests justifies their performance in a laboratory with experience of this type of test.

The rapporteur considers that the chemical analyses, which will not be performed by an accredited laboratory, do not constitute a major issue other than the guaranteed traceability of the chips sampled. In this respect, the rapporteur considers that the analyses already performed by the Creusot Forge laboratory for similar projects in the past have demonstrated this capability. However, the rapporteur considers that the measurement uncertainties of these chemical analyses must be evaluated.

Given the lack of accreditation of the laboratories chosen for the chemical analyses and drop-weight tests, the rapporteur also considers that these chemical analyses and the drop-weight tests must be specifically monitored by an notified approved body in order to provide the necessary technical and impartiality guarantees of compliance with regard to test procedures, traceability and results interpretation.

At the end of the assessment, AREVA has undertaken to draft a specific protocol to assess the uncertainties related to the chemical analyses. AREVA has also agreed to perform all the tests (preparation of test specimens, sampling and testing), under 100% monitoring by a notified approved body assigned by ASN.

The rapporteur considers this undertaking to be satisfactory. However, the rapporteur points out that an accredited laboratory independent of the AREVA group would provide a stronger guarantee of impartiality.

Test standards applied

The rapporteur notes that the standards to be used for the tests are not those applicable to the FA3 project. This change in standards could have an impact on the results and the conditions for invalidating and the interpretation of the results. AREVA conducted an initial partial analysis which shows that with regard to the tensile standard, this change has no effect.

At the end of the assessment, AREVA has undertaken to perform a complete assessment of the impact of the change in the standards on the test results.

The rapporteur considers this undertaking to be satisfactory. The rapporteur however considers that this assessment must be performed before the tests are carried out and that it should more specifically cover the criteria concerning the nonconforming tests.

4.4. Comparison between the minimum toughness of the material and the adequate toughness

4.4.1. AREVA proposal

AREVA makes a distinction between:

- normal, incident and accident operating situations, which are assessed in the safety case;
- hydrostatic pressure testing, which is assessed with regard to safety, because the core is unloaded during the hydrostatic pressure tests.

For normal, incident and accident situations, AREVA selected limiting situations and loadings assuming that the reduction in toughness due to the segregation zone would stop at mid-thickness. AREVA has consequently scheduled mid-thickness bending rupture energy tests to verify this hypothesis.

For the hydrostatic pressure tests, AREVA proposes positioning the toughness values measured in the segregation zone, as a result of the test programme, with respect to RCC-M curve ZG 6110 (see Figure 8), indexed on either:

1. the acceptance RT_{NDT} for the tested dome;
2. the local RT_{NDT} determined by the test programme;
3. the RT_{T0} (master curve approach – see Appendix 5) determined by the test programme.

The flowchart in Figure 21 summarises the sequence of tests included in the approach proposed by AREVA.

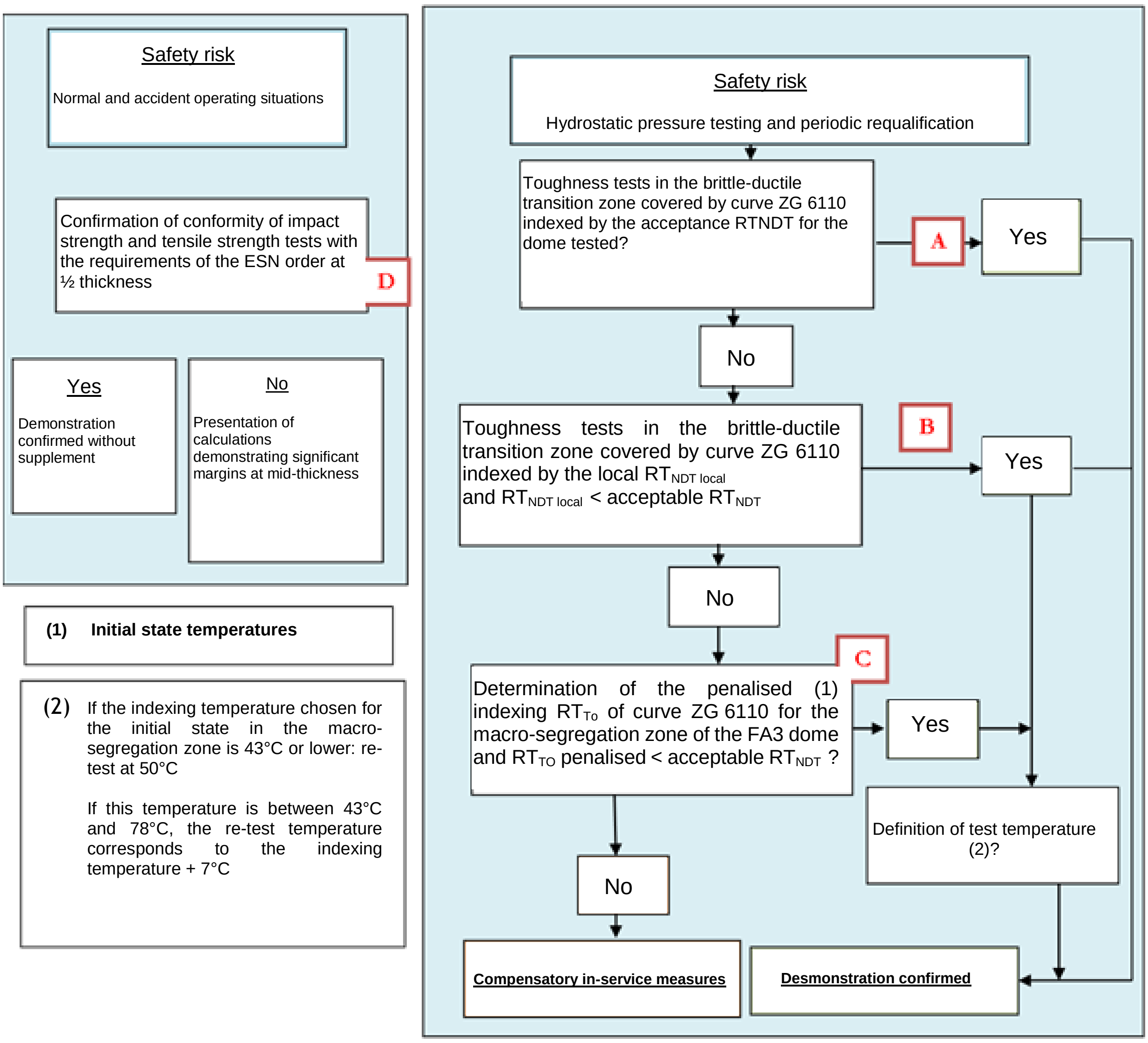


Figure 21: Detailed demonstration approach – Test sequence

In the case (marked A on the flowchart in Figure 21) for which the toughness values measured in the segregation zone are bounded (lower value) by RCC-M curve ZG6110 indexed on the acceptance RT_{NDT} (test reference A on the flowchart), the design file remains applicable.

If test A is not validated, in the case (marked B on the flowchart) in which the toughness values measured in the segregation zone are bounded (lower value) by RCC-M curve ZG6110 indexed on the local RT_{NDT} and in which it is also proven that the local RT_{NDT} is lower than the acceptable RT_{NDT} (which depends on the test temperature as shown in Table 12 of § 4.2.3.4), the toughness of the material determined by the test programme is higher than the adequate toughness value. In this case, the demonstration is conclusive, although with a potential redefinition of the test temperature.

If test B is not validated (marked C on the flowchart) the toughness values measured in the segregation zone are bounded (lower value) by RCC-M curve ZG6110 indexed on the RT_{T0} and a test is performed to verify that the RT_{T0}[13] is lower than the acceptable RT_{NDT} (which depends on the test temperature as shown in Table 12 of § 4.2.3.4). In this case, the toughness of the material determined by the test programme is higher than the adequate toughness value. This test C is proposed by AREVA if the curve indexed on the local RT_{NDT} were to prove too conservative and would lead to an excessively high hydrostatic pressure test temperature (excessive offset of the RT_{NDT}). If not, AREVA makes provision for in-service mitigation measures aimed at demonstrating the absence of damaging flaws.

4.4.2. Position of the rapporteur

With regard to the situations analysed for the purposes of safety, the rapporteur points out that AREVA selected the loadings based on the assumption that the drop in toughness due to the segregation zone stopped at mid-thickness and that it was therefore unnecessary to study the cold shock situations. This hypothesis implies that as of mid-thickness, the toughness is similar to that of the acceptance zone (compliance with bending rupture energy criterion) and that for flaws situated in the inner part, the initial design file is therefore applicable.

The rapporteur notes that the test programme includes tests at mid-thickness, which would validate this core hypothesis of the AREVA dossier. However, for this bending rupture energy test criterion, AREVA uses the bending rupture energy value mentioned in the order in reference [6], that is 60 J at 0°C. The rapporteur considers that this is not appropriate because in order to demonstrate that the design file remains applicable, AREVA must use the criteria adopted in the design file, which is based on application of the RCC-M code (procurement according to the specifications of this code). It is therefore necessary to use the same mid-thickness acceptability criteria as those of the acceptance zone, or more specifically an average bending rupture energy of 80 J.

At the end of the assessment, AREVA specified that at mid-thickness, there was no need to meet the criteria defined in the acceptance zone in order to ensure that the design hypotheses were applicable at mid-thickness. The rapporteur considers that this position consists in defining the expected quality at mid-thickness with an average bending rupture energy of 60 J, which is felt to be acceptable.

At the end of the assessment, AREVA also stated that if the mid-thickness bending rupture energy value was not met (marked D on the flowchart) the test programme planned at mid-thickness would be able to demonstrate adequate toughness, in the same way as the approach proposed for the hydrostatic pressure tests.

The rapporteur points out that this calls into question the determination of adequate toughness proposed by AREVA (paragraph 4.2) and thus the associated demonstration approach.

With regard to the hydrostatic pressure test situations, AREVA considers that the design file rules out the risk of fast fracture provided that the result of test A is satisfactory. The rapporteur points out that according to AREVA, the result of test A is satisfactory once the toughness measurements obtained are all above the ZG 6110 curve indexed on the acceptance RT_{NDT} value for the tested dome.

The rapporteur considers that this test satisfactorily verifies that the ZG 6110 curve indexed on the acceptance RT_{NDT} value of the tested dome encompasses the toughness measurements made in the

[13] The RT_{T0} temperature is the reference temperature of the segregation zone according to standard ASTM E1921 plus 19.4 + 20°C that is 39.4°C in order to cover all the experimental points of the reference toughness curve in the RCC-M.

positive macrosegregation zone. However, this does not allow a conservative estimate of the mechanical margins to be made. AREVA estimated that in theory the local RT_{NDT} of the segregation zone would be higher than the acceptance RT_{NDT} (offset between 35 and 70°C). The rapporteur points out that the criterion used in the fast fracture analyses (stress intensity factor lower than the toughness given by the indexed ZG curve) associated with the acceptance RT_{NDT} is less conservative than that which would be associated with the local RT_{NDT} (Figure 22).

Consequently, test A is only acceptable if supplemented by a verification of the margins with respect to the fast fracture risk, considering the curve of appendix ZG indexed on the local RT_{NDT} and not on the acceptance RT_{NDT}.

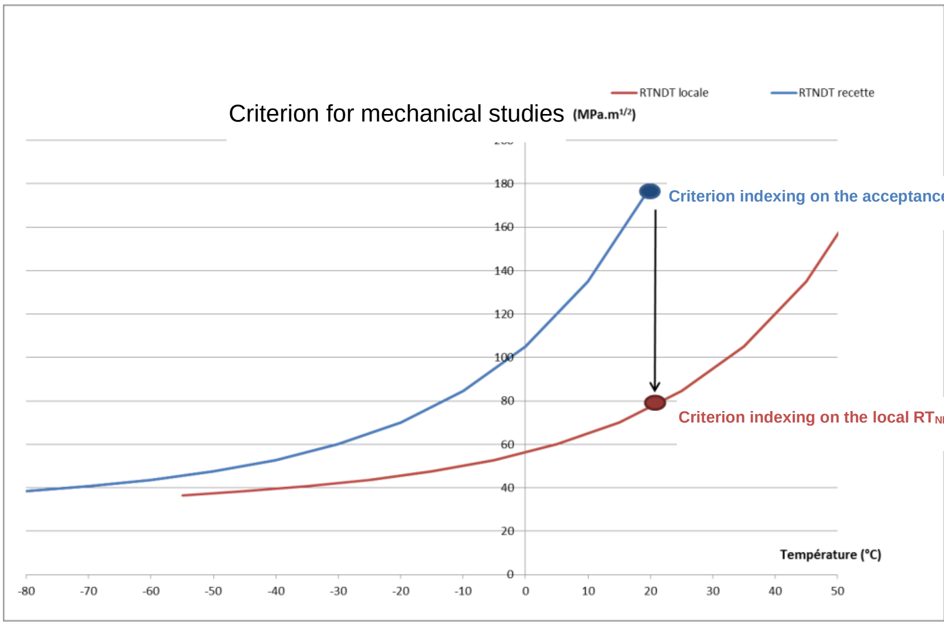
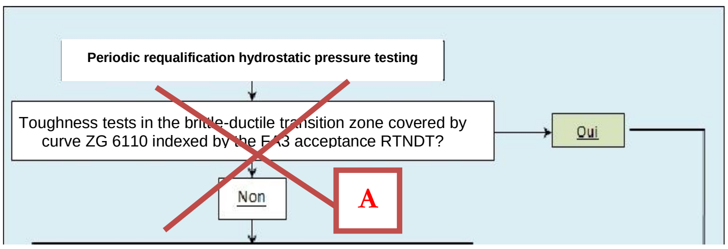


Figure 18: Reduction in K_{IC} depending on the indexing of the curve in appendix ZG 6110.



With regard to test B proposed by AREVA, the rapporteur has no particular comments. This concerns an adaptation to the segregation zone of the demonstration approach for the fast fracture of the irradiated RPV shells. The ΔRT_{NDT} due to irradiation is simply replaced by an ΔRT_{NDT} due to the segregation zone. It is thus considered to be acceptable by the rapporteur.

With regard to test C proposed by AREVA, the rapporteur points out that AREVA proposes a new approach (such as Master-curve) which entails the use of non-approved methods, as part of a specific file and following the failure of the usual approach. The rapporteur considers that a material nonconformity file is not a suitable framework for investigating new demonstration methods. The rapporteur also points out that resorting to this new approach would result from a significant overshoot, in the segregation zone, of the design RT_{NDT} adopted for the end-of-life core shells (30°C). This new approach could shed additional light through the data interpretation that it proposes, but cannot in itself constitute a means of demonstrating adequate toughness.

Finally, the rapporteur points out that, neither in its file nor during the assessment has AREVA defined the in-service mitigation measures aimed at demonstrating the absence of damaging flaws.

Recommandation 3

The rapporteur recommends that the AREVA justification approach be based on:

- **verification that the ZG 6110 curve in RCC-M indexed on the RT_{NDT} measured in the segregation zone indeed constitutes the lower envelope of the toughness measurements taken on the material in the segregation zone;**
- **incorporation of the RT_{NDT} measured in the segregation zone, to compare it with the acceptable RT_{NDT}, representative of the adequate toughness of the material.**

Recommandation 4

The rapporteur recommends limiting the use of the Master-curve type approach, proposed by AREVA for indexing the RCC-M ZG 6110 curve, to a supplementary interpretation of the results of the mechanical tests.

The rapporteur notes that the approach proposed by AREVA can lead to an adjustment in the hydrostatic pressure test temperature, as follows:

- if the local RT_{NDT} in the segregation zone is 43°C or less, AREVA adopts a test temperature of 50°C;
- if the local RT_{NDT} in the segregation zone is between 43 and 78°C [14], AREVA adopts a hydrostatic pressure test temperature adjusted to the local RT_{NDT} + 7°C.

The rapporteur has no particular remarks regarding the definition of the hydrostatic pressure test temperature according to the local RT_{NDT} measured.

4.5. Consequences of the demonstration approach on the implementation of the defence in depth principle

The demonstration approach proposed by AREVA is an analysis of the mechanical fracture behaviour of the Flamanville 3 RPV closure head and lower head domes, based on tests conducted on a representative scale one replica. This approach may reveal significant margins with respect to the possible risks, which would thus enable us to conclude that the manufacturing process gives the material sufficient mechanical properties to rule out these risks. However, this would not guarantee the high quality of manufacturing that can be offered by the use of the best available techniques and satisfactory technical qualification, expected for a break preclusion component such as the RPV.

Adopting the break preclusion hypothesis in the RPV design means that its failure is not postulated in the safety case. Thus there is nothing in the third line of defence to mitigate the consequences of its

[14] A maximum of 85°C is set for performance of the hydrostatic pressure tests

failure. Consequently, this hypothesis requires reinforcement of the first two levels of defence in depth in order to attain a satisfactory level of safety.

Insofar as the first level of defence in depth is affected, the rapporteur considers that the demonstration approach proposed by AREVA needs to be supplemented by operational provisions on the Flamanville 3 RPV closure head and lower head domes such as to reinforce the second level of defence in depth. These operational provisions shall include reinforced checks to ensure the absence of flaws following manufacturing, as well as periodic inspections during operation.

Recommandation 5

Given the statements regarding the first level of defence in depth, the rapporteur considers that a demonstration approach without provision for reinforcement of the second level of defence in depth would not be sufficient to justify the nuclear use of the Flamanville RPV domes.

The rapporteur therefore recommends that reinforced measures for commissioning, in-service, maintenance and operating inspections be defined and implemented.

5. General conclusion

In late 2014, AREVA informed ASN of the results of the bending rupture energy tests - performed for technical qualification of the manufacturing operations on the Flamanville EPR RPV domes - which were lower than expected. The values measured on two series of three test specimens taken from a dome representative of those intended for Flamanville 3, were on average 52 joules meaning that the quality expected by AREVA was not reached and they were also below the 60 joules bending rupture energy value mentioned in point 4 of Appendix 1 of the nuclear pressure equipment order of 12 December 2005 in reference [6], known as the "ESPN order". Failure to comply with the bending rupture energy criteria means that the toughness of the material cannot be confirmed as adequate.

AREVA carried out investigations to determine the origin of these non-conforming values. The carbon measurements made on the surface of the dome by portable spectrometry showed the presence of a positive macrosegregation zone over a diameter of about one metre. The metallographic examinations of the test specimens also showed the presence of these segregations at one-quarter thickness. AREVA ascribes the low bending rupture energy values to the presence of this zone taken from the ingot used for forging and not totally eliminated during the cropping operations.

In the light of this deviation, AREVA proposed running a test programme on a scale one replica representative of the Flamanville EPR reactor lower and upper domes, in order to demonstrate the adequate toughness of the material of these domes.

Regulatory requirements applicable to the design and manufacture of the Flamanville 3 EPR RPV

The design of nuclear facilities is based on the principle of defence in depth which leads to the implementation of successive levels of defence (intrinsic properties, material provisions and procedures), designed to prevent incidents and accidents and then, if this prevention fails, to mitigate their consequences. Application of the principle of defence in depth is required by Article 1.3 of the order of 7 February 2012 setting out the general rules for BNIs.

The purpose of the *first level of defence* is to prevent incidents: for equipment, provisions are defined to ensure a high level of quality in design and manufacture. The requirement for the use of the best available techniques e, mentioned in Appendix 1 of the pressure equipment decree of 13 December 1999, contributes in particular to the first level of defence in depth. In addition, to ensure a high level of quality, special requirements are defined for material properties, in order to guarantee that it is sufficiently ductile and tough. Finally, the production of a material with a risk of heterogeneous properties must lead to technical qualification with the aim of ensuring that the components manufactured in the qualification conditions and according to the qualification procedures will have the required properties.

Vessel fracture is precluded in the design stage: precluding the fracture of a component means that its failure is not postulated in the safety case. Thus there is nothing in the third line of defence to mitigate the consequences of its failure. Consequently, the break preclusion hypothesis requires reinforcement of the first two levels of defence in depth in order to attain a satisfactory level of safety.

The technical qualification file presented by AREVA for the Flamanville 3 RPV closure head and lower head domes shows that the risk of heterogeneity due to positive residual segregations was incorrectly analysed and its consequences inadequately quantified. The rapporteur considers that the technical qualification requirement is therefore not met for the RPV closure head and lower head domes intended for Flamanville 3. The rapporteur also points out that AREVA did not choose the best available techniques for the production of the Flamanville 3 EPR RPV domes.

The rapporteur considers that the manufacturing process adopted for the Flamanville EPR RPV does not give the same guarantee of quality as would have been the case with the best available techniques and satisfactory technical qualification: these conclusions call into question the first level of defence in depth which aims to obtain a high level of quality in design and manufacture, owing to the failure to comply with the requirements recalled above.

Approach to confirm the adequate toughness of the RPV domes

Given the non-compliance with the minimum bending rupture energy values specified by the order in reference [6] for a material with a ferritic structure, AREVA proposed an approach aiming to demonstrate the adequate toughness of the material of the Flamanville 3 EPR domes. This approach is focused on the prevention of the fast fracture risk, with AREVA considering that the presence of positive macrosegregations does not call into question the absence of the risk of excessive deformation and plastic instability of the RPV domes, confirmed in the design file.

The demonstration approach adopted by AREVA comprises 3 main steps:

1. the determination (by calculation) of adequate toughness to prevent the risk of fast fracture;
2. the evaluation (by testing) of the minimum toughness in the positive macrosegregation zone of the material;
3. the comparison between the minimum toughness of the material and the adequate toughness.

With regard to the **determination of adequate toughness**, the rapporteur points out that this was defined in the AREVA file on the basis of a list of situations - which could not be assessed in this report, given the late transmission of the data - and assuming one fundamental hypothesis: AREVA considers that the positive macrosegregation is situated on the outer skin of the domes manufactured and therefore limits its fast fracture risk assessment to flaws located on the outer skin. AREVA deduces that there is no need to examine the cold shock situations, which are only liable to stress flaws located on the inner skin. The rapporteur notes that the test programme includes tests at mid-thickness, which would validate this core hypothesis of the AREVA dossier. Finally, the rapporteur points out that the exhaustive and conservative nature of the situations will be assessed at a later date.

With regard to the **assessment of the minimum toughness by means of testing**, the rapporteur notes that the test programme was notably revised by AREVA during the assessment. The positioning of the test specimens will in particular be optimised according to the results of the chemical mapping performed by surface spectrometry of the slices cut at various depths of the dome intended for the mechanical tests (¼ thickness and ½ thickness): this arrangement is such as to obtain test results in the zones with the highest carbon content.

The test programme will in the end be performed on two domes – one upper dome from the UK project and one lower dome from the UA project – which will make it possible to assess the extent and depth of the segregation zone in these two domes with different machined thicknesses. The rapporteur also considers that the mechanical properties measurements on a dome from a pouring of steel other than that of the UK upper dome would enhance confidence in the results obtained.

With regard to the **comparison between the minimum toughness of the material and the adequate toughness**, the rapporteur points out that the AREVA approach differs according to the situations:

- for the hydrostatic pressure tests, AREVA proposes positioning the toughness values measured in the segregation zone, based on the results of the test programme, opposite RCC-M curve ZG 6110, indexed on three distinct reference temperatures, considered in turn. The comparison consists in verifying that the toughness values measured are higher than the indexed curve values and that the minimum toughness, deduced from the curve at the test temperature, is higher than the adequate toughness. The rapporteur considers that only the approach based on indexing of the curve on the RT_{NDT} measured in the positive macrosegregation zone is acceptable;
- for the operating situations in the safety case, AREVA proposes verifying a bending rupture energy criterion at mid-thickness in order to validate the hypothesis adopted for selection of the limiting situations. However, at the end of the assessment, AREVA indicated that if the bending rupture energy measured at mid-thickness did not meet the chosen criterion, the toughness measurements also planned for mid-thickness would enable it to demonstrate that the toughness of the material there is adequate. The rapporteur points out that this calls into question the definition of adequate toughness proposed by AREVA and thus the associated demonstration approach.

The demonstration approach proposed by AREVA is an analysis of the mechanical fracture behaviour of the Flamanville 3 RPV closure head and lower head domes, based on tests conducted on a representative scale one replica. As applicable, this approach could reveal significant margins with respect to the possible risks, which would thus enable us to conclude that the manufacturing process gives the material sufficient mechanical properties to rule out these risks. However, this would not guarantee the high quality of manufacturing that can be offered by the use of the best available techniques and satisfactory technical qualification, expected for a break preclusion component such as the RPV.

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Annexe 2 : Previous regulatory requirements

- **Order of 26 February 1974 reference [5]**

The order of 26 February 1974 was applicable to the construction of all the main primary systems of the French reactors currently in operation in France.

Qualification requirement

This order did not prescribe a materials qualification procedure.

Essential requirements concerning the properties of materials

Article 16 of this order imposed requirements on the mechanical characteristics of the materials:

"§ 1. - The materials shall be chosen so as to avoid any risk of fast fracture in operation.

§ 2. - The materials intended to be assembled by welded joints shall display satisfactory weldability under the planned conditions and which can moreover satisfy the provisions of article 23.

§ 3. - With the exception of the case provided for in article 17, the following shall in principle be considered not to satisfy the above conditions:

- steels whose maximum tensile strength at 20°C, exceeds 70 hbar (1) or whose percentage elongation at break is less than 18;

- steels whose mean bending rupture energy value at 0°C, called KCV, measured on three test specimens is less than 5 daJ/cm2 for a maximum tensile strength of less than 60 hbar or less than 7 daJ/cm² for a maximum tensile strength of between 60 and 70 hbar.

§ 4. - The manufacturer may nevertheless use, subject to the observations of the head of the mineralogical division responsible for inspection, a steel that does not meet the requirements of paragraph 3 if it can conclusively justify this choice with regard to the weldability of this steel and the risk of fast fracture, in both the base metal and the areas concerned by the weld. To this end the manufacturer shall enclose a supporting report with the file provided for in article 14."

The bending rupture energy value to retain for the RPV material is 7 daJ/cm². The physical value is an energy level times a surface area. However, the value measured in the Charpy tests depends not only on the surface area but also on the geometry of the test specimen and of the notch. Consequently, this value cannot be used to calculate the rupture energy for a sample of another cross-sectional area (CSA) by simply multiplying with the new CSA. To be able to compare measurements from different experiments, it became absolutely necessary to standardize the CSA and the size of the test specimens. This was done through an ISO standard. The size of the most common test specimen is 10x10 mm² with a 2-mm deep V-notch. This corresponds to a working area of 8x10 mm². The value in the order of 26 February 1974 for the RPV steel thus corresponds to a value of 70 x 0.8 = 56 J. This value is comparable with those specified in the technical rules in reference [8] and the order reference [6] because the test specimen is the same.

It is to be noted that under §4 of article 16, the manufacturer is not required to comply with this value if it can conclusively justify this choice, more specifically with regard to the risk of fast fracture in the base metal.

- **Technical rules of 1999 in reference [8]**

In 1999, it was found to be necessary to clarify the technical rules for the construction of the new main primary and secondary cooling systems. These rules are the forerunners of the essential requirements of the ESPN order reference [6]. They formed the subject of several sessions of the SPN (advisory nuclear section) of the CCAP.

<u>Qualification requirement</u>

These rules institute the qualification of certain manufacturing operations: *"The manufacturing operations that have to undergo a qualification are defined. More specifically, cladding, welding and casting operations are subject to qualification"*.

<u>Requirements concerning the properties of materials</u>

Furthermore, these rules impose minimum characteristics for the materials: *"Save particular justifications, the chosen materials shall display characteristics in qualification and acceptance testing whose individual values comply with the rules of points 2 to 4 below. […]*
3. Materials with a ferritic structure other than bolting materials shall present, including in the welds (acceptance testing and test coupons), an elongation at break at ambient temperature of 20% or more, a bending rupture energy on ISO V test specimen at 0°C greater than or equal to 40 J and a tensile strength at ambient temperature not exceeding 800 MPa. The 40 J limit is increased to 60 J for materials whose tensile strength at ambient temperature is 600 MPa or more.

For the acceptance tests and qualification of the RPV steel, the minimum individual bending rupture energy value is 60 J.

Annexe 3 : Inspection performance levels

<u>Input parameters for estimating performance by simulating the 45° shear wave (OT 45°) inspection</u>

The assessment of these performance levels was the subject of a simulation by IRSN using the latest version of the CIVA software; this simulation takes into account all the input data from the ultrasonic inspection procedure described in the note reference [11]. The input data are nevertheless adapted to limit the simulations in the depth of the core situated between mid-thickness and the bottom of the dome, that is to say 145 mm. The input data concerned are:

- OT 45° sensor type WB45-N2;
- four "generating surface" calibration holes of 2 mm diameter, similar to those used to calibrate the OT 45° sensor, positioned in the external mid-thickness of the RPV lower head core concerned by the material anomalies; they are distributed between 70 mm and 145 mm (total thickness of the PRV lower head dome);
- <u>application of a distance amplitude correction (DAC) curve to the four holes</u> in order to have a reference at 0 dB on each of the 4 holes when analysing the simulation results;
- choice of a flat simulation model: given the large bend radius of the RPV lower head (2695 mm inside radius), it is neither necessary nor worthwhile using a curved model, given the very small influence of the depth of layer of water present beneath the sensor;
- installation of flat reflectors in the simulated part, adapted to the verification of the planar flaw detection performance in the two sensing directions - circumferential and axial - mentioned in Figure 10 ;
- choice of flat reflectors, the detection of which is simulated:
    - planar flaws with dimension 5 x 20, 10 x 20, with a very smooth fracture surface, at different depths, perpendicular and slightly skewed;
    - planar flaws with dimension 5 x 20, 10 x 20, with a rough fracture surface, at different depths, perpendicular and slightly skewed.

The simulations were carried out for rough planar flaws (Figure 24) and for hypothetically perfectly smooth planar flaws (Figure 25).

<u>Results of the IRSN simulation for the OT 45° inspection</u>

The results of the simulations carried out on hypothetical flaws with both rough and smooth fracture surfaces do indeed confirm the performance levels given by the manufacturer.
According to the provisions of the RCC-M code, planar flaws of 5 and 10 mm height with rough fracture surfaces, surface breaking or at a distance of 20 mm with respect to the external surface, are all recorded and unacceptable in the cases retained for the simulations when they are perpendicular or slightly misoriented in "tilt" (see Figure 23 for the definition of the "tilt" and "skew" angles).

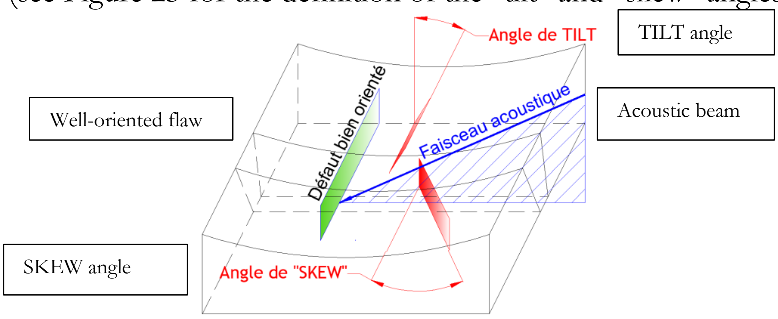

Figure 23: Misoriented flaws: tilt and skew

The rough fracture surface flaws very far from the external skin (more than 20 mm) would also be recorded and rejected if they remain perpendicular. The misoriented flaws with a slight skew of 5° appear to be recordable and even rejectable if they are surface breaking or have a small ligament (about 10 mm). These same "skew" flaws would nevertheless not necessarily be recordable and rejected according to the criteria of the RCC-M when they are very far from the external skin (more than 20mm). This is directly visible on the mappings which show that the flaws which are predominantly red in colour are flaws whose amplitude is greater than the 0 dB amplitude of the 2-mm diameter generating surface hole, which leads to the rejection of the flaws.

According to the provisions of the RCC-M code, planar flaws of 5 and 10 mm height with very smooth fracture surfaces are also all recorded and are rejected if they are surface breaking flaws or at a distance of 20 mm with respect to the external surface, in the cases retained for the simulations when they are perpendicular or slightly misoriented in tilt. These same perpendicular flaws would be recorded but not necessarily rejected if they are very far from the external skin (more than 20 mm).

The misoriented flaws with a slight skew of 5° appear to be recordable and even rejectable when surface breaking or with a small ligament (about 10 mm). These same flaws with a very slight skew are more difficult to record than rough flaws when the ligament exceeds 10 mm.

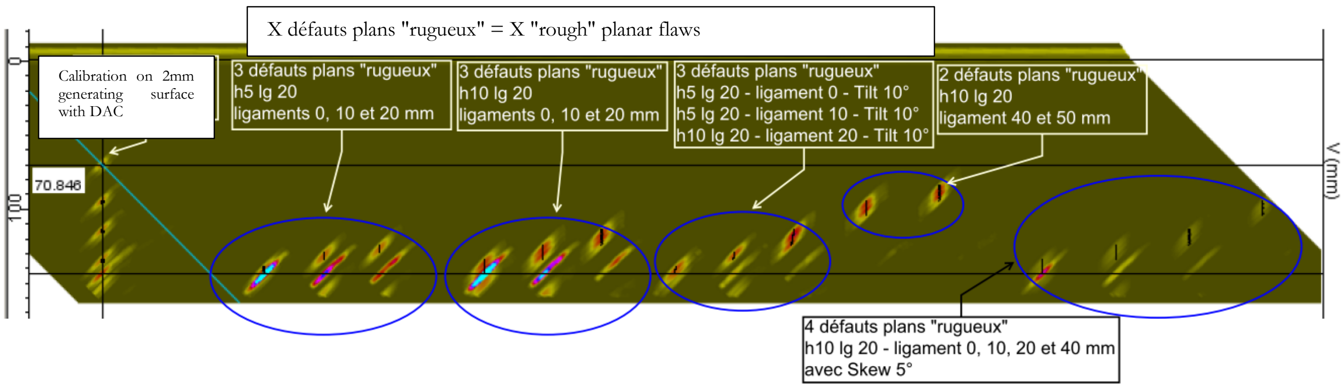

Figure 24: Evaluation by simulation of the detection of rough fracture surface flaws of dimensions 5 x 20 and 10 x 20, perpendicular to the external skin or slightly misoriented

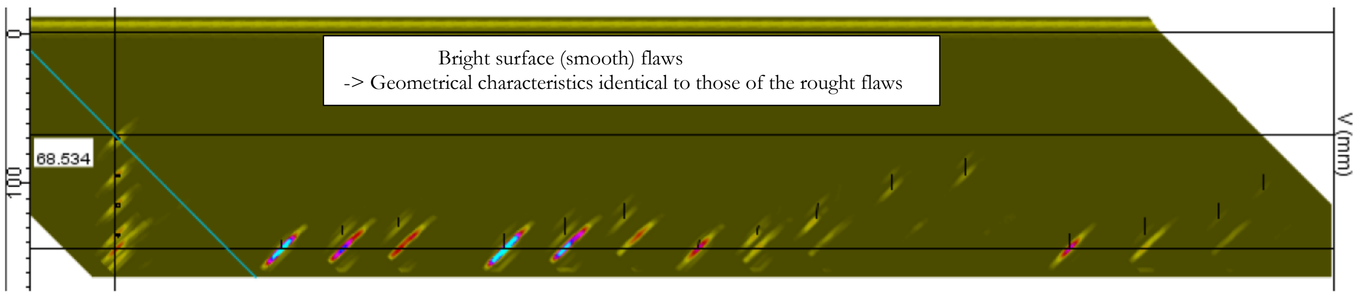

Figure 25: Evaluation by simulation of the detection of perfectly smooth fracture surface flaws of dimensions 5 x 20 and 10 x 20, perpendicular to the external skin or slightly misoriented

Annexe 4 : A priori estimation of the RT_{NDT} shift in the area of positive major segregation

Initially, AREVA used the results of bending rupture energy tests performed on the UA upper dome to estimate the shift in temperature of the RT_{NDT} of the segregation zones of the UA upper dome with respect to the acceptance test zone by considering two approaches:

- **a realistic approach**: the RT_{NDT} determined using the procedure codified in the RCC-M is imposed by the Charpy tests (temperature at which the minimum individual bending rupture energy value is greater than 68 J) and not by the Pellini tests. Working from the bending rupture energy results at 0°C in the UA dome it is possible to estimate the impact of the segregation on the RT_{NDT}. The values obtained from the 6 Charpy tests in the ¼ upper thickness of the UA upper dome lead to an average bending rupture energy Kv_{moy} at 0°C of 52 J and a minimum value Kv_{min} of 36 J.

  By taking a change in the impact energy with temperature in the transition zone of 1.5 J per °C and a value of 0.7 for the ratio of the mean bending rupture energy to minimum bending rupture energy, one obtains:

  $\Delta RT_{NDT} = (68/0.7 - Kv_{moy})/1.5 = 30$ °C

  $\Delta RT_{NDT} = (68 - Kv_{min})/1.5 = 21$ °C

- **a more conservative approach**: working from the Charpy tests performed on the acceptance test zone and on the central zone at a quarter thickness, on the top side of the UA dome, it is possible

- to approximately index a bending rupture energy curve for each zone. The distance between these two curves enables a conservative measurement of the temperature shift to be determined. Figure 26 below shows this construction leading to an estimate of the shift of the bending rupture energy curves of about 70°C

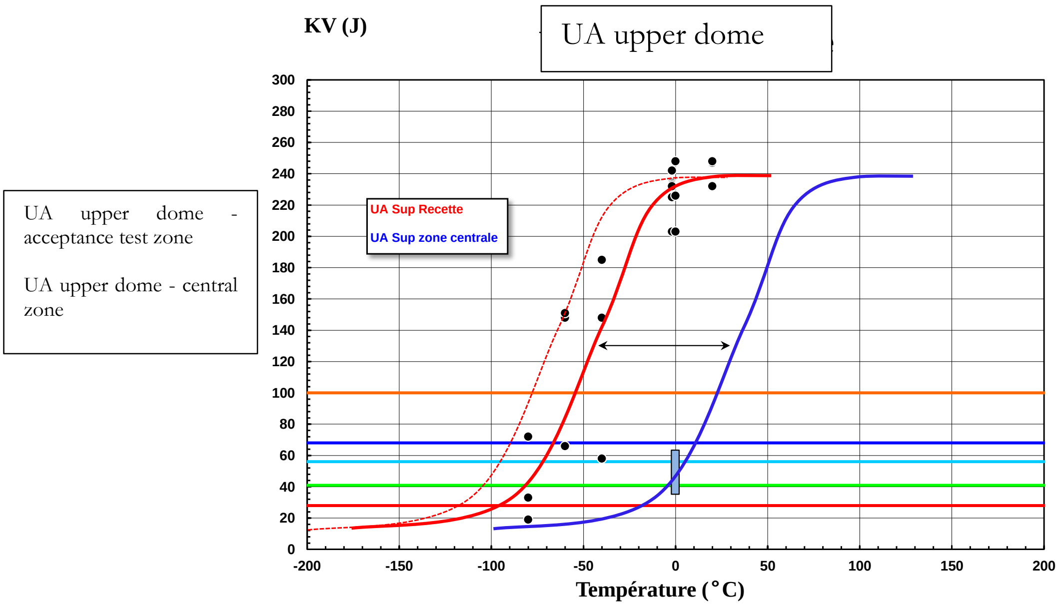

Figure 26: UA dome Evaluation of bending rupture energy transition between acceptance test zone and ¼ thickness zone on top side

AREVA deduced from this that the expected shift in transition temperature between the acceptance test zone and the ¼ thickness zone on the head side in the axis should be very much lower than 70°C and probably much closer to 35°C.

Annexe 5 : Reference temperature T_0

The reference temperature T_0 is used for the indexing of the "MASTER_CURVE" curve introduced in standard ASTM E1921, describing the development of ferritic steels in the brittle-ductile transition zone, like the RT_{NDT} used for the indexing of the ZG 6110 curve of the RCC-M. T_0 is determined by toughness tests on test specimens which can be small in size (12.5 mm thickness for example). A small number of tests are required. For a homogeneous material, about ten tests will suffice to determine T_0 with a good level of precision.

For information, the transition temperature (RT_{NDT}) on which the toughness curve of the RCC-M is indexed is characterised by impact tests (Pellini tests associated with Charpy tests). These dynamic tests are very different from the toughness tests which are crack-initiation tests conducted under virtually static loading.

Thus, the RT_{NDT} is a reference temperature deduced from the characterisation tests for fracture initiation, tearing and crack stopping, whereas the reference temperature T_0 is deduced from tests dedicated to fracture initiation.

In its file, as an alternative to indexing the ZG 6110 curve of the RCC-M on the RT_{NDT} determined in accordance with the protocol defined by the code, AREVA proposes indexing the curve on the temperature RT_{T0} introduced by the EPRI and equal to T_0+19.4°C. AREVA takes into consideration an additional penalisation of 20°C on the RT_{T0} temperature to ensure that the thus indexed curve of appendix ZG 6110 remains a minimum envelope curve of the experimental toughness data from which the RCC-M curve originated.

Annexe 6 : Assessment of uncertainties, safety factors and margins

1. Uncertainties and safety factors

The decree reference [3] imposes*"the application of safety factors that entirely eliminate all the uncertainties resulting from the manufacturing process, the actual conditions of use, the constraints, the calculation models and the properties and behaviour of the material."*

Difficulties have been observed in the general context of proving compliance with the requirements of the regulations relative to nuclear pressure equipment, and they must be addressed by an action programme which is currently being defined by the manufacturers.
For this file concerning the FA3 RPV domes, AREVA has presented the elements at its disposal to date concerning this matter.

The sources of uncertainties associated with the choice of the UK dome for the performance of the tests are addressed along with the question of its representativeness (see §4.3).

The other sources of uncertainties concern the determining of the mechanical characteristics, the defining of the flaw and the calculation models.

With regard to the determining of the mechanical characteristics, consideration of the following safety factors is indicated by AREVA:

- the standards in effect for the mechanical tests, with the exception of the Pellini tests, encompass safety factors through requirements concerning the precision of the measuring means (force, opening sensor, temperature measurement). Consequently, AREVA considers the impact of the uncertainties to be negligible. These tests shall be carried out by an accredited ISO 17025 laboratory (see §4.3). AREVA indicates that for information and as a complement, the uncertainties shall be quantified;
- the toughness curve of appendix ZG 6110 of the RCC-M is a minimum envelope curve determined to cover the large variability in test results in the brittle domain, caused by the distribution of microstructural flaws within the matrix;
- the effects of thermal ageing, and after strain, are encompassed by an envelope shift of +15°C.

With regard to the dimension of the flaw, AREVA has taken into account an envelope value deduced from an analysis of the performance of the non-destructive tests implemented (see § 4.2.2).

As far as the calculation models are concerned, AREVA indicates that it has used qualified software applications and envelope calculation hypotheses comparable with the means implemented for the file covering the in-service behaviour of the vessels of the French reactors operated by EDF.

<u>Position of the rapporteur</u>

The uncertainties concerning the tests are addressed in §4.3.

The rapporteur reiterates the reservation and recommendation it issued with regard to the chosen ageing hypothesis (see § 4.2.3.3).

2. Implicit margins resulting from the adopted envelope hypotheses

For convenience of calculation, AREVA has adopted a number of simplifying envelope hypotheses. According to AREVA they provide implicit margins that it has tried to explain and quantify.

The procedure aiming at defining an indexing temperature for the envelope toughness curve integrates an implicit margin that depends on the indexing method. According to AREVA, indexing on the local RT_{NDT} deduced from the tests will be more penalising than indexing on RT_{T0}, which will nevertheless be penalised by 20°C to ensure its envelope role.

With regard to the situations, AREVA indicates that a number of physical parameters have been ignored.

As regards the orientation and location chosen for the analysed flaws, AREVA states that they integrate an implicit margin. The flaw is considered to be surface breaking and perpendicular to the skin, whereas the manufacturing process on the contrary favours the orientation of potential flaws parallel to the skins and aims at eliminating the planar flaws perpendicular to the surface, which are moreover detected by the non-destructive tests implemented, and even more so if they are surface breaking.

AREVA has carried out simplified calculations comparing, for different angles, the stress intensity factor of a tilted internal flaw with that of a perpendicular surface breaking flaw. The ratio of these stress intensity factors varies from 2 to 6 for a flaw angled at 60 to 75 degrees with respect to the perpendicular to the skin.

<u>Position of the rapporteur</u>

As the rapporteur indicates in § 4.2.3.6.2, the situations and loads considered shall be examined later on by the rapporteur.

The rapporteur agrees with the fact that the orientation and location chosen for the flaws analysed by AREVA incorporate implicit margins. The rapporteur considers that these implicit margins can be taken into account in the assessment of the results of the approach as from a large angle (60 degrees) of the flaw with respect to the normal to the wall.

3. Assessment of the effect of the segregation zone on the margins with respect to the criteria

The rapporteur considers that it is worthwhile providing an overall clarification of the application of the entire procedure for proving adequate toughness in terms of effects of the segregation zone on the margins with respect to the criteria.

To meet this demand, at the end of the assessment, AREVA undertook:

"to provide, before the GP ESPN of 30 September 2015, a study of sensitivity to the margin factors covering the impact of a shift in the RT_{NDT}, in the macro-segregation zone, with respect to the specified RT_{NDT} and that of the conventional flaw in comparison with the reference flaw of 10 mm adopted for the justification file.

This study shall be carried out on all the situations and loads of the design file relative to in-service operations, supplemented by the hot shock transients identified for categories 3 and 4 in the letter [reference].

The chosen shifts in RT_{NDT}*, equal to +35°C and +70°C, correspond respectively to the probable shift and the envelope shift, identified from the interpretation of the results obtained on the UA core sample.*

For each flaw category and dimension, the minimum margins shall be specified along with the associated stress level (K_{cp}*) and the temperature at which this minimum margin is obtained. These data will be evaluated:*

- *in the macro-segregation zone, considering the* RT_{NDT}*, specified at design (-20°C), and a shift in this* RT_{NDT} *of +35°C and +70°C,*
- *in the* R/P *joint, considering the* RT_{NDT} *specified at design (-20°C),*
- *in the core shell, considering the* RT_{NDT} *specified at design (-20°C), and an internal surface breaking flaw."*

The rapporteur considers that this undertaking corresponds to the demand it has expressed.