Summary report
for the Advisory Committee of experts
for nuclear pressure equipment

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English translation

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Procedure proposed by Areva to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel bottom head and closure head

Interim review

Date	ASN Director of Nuclear Pressure Equipment	IRSN Director of Systems, New Reactors and Safety Procedures
17/06/2016	This is a translation in English. Please refer to the original version in French for guaranteed content.	

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References

[1] Order of 12th December 2005 relative to nuclear pressure equipment (called the "ESPN order").

[2] ASN/IRSN report reference CODEP-DEP-2015-037971 – IRSN/2015-00010 – Report to the Advisory committee for nuclear pressure equipment of 30th September 2015 - Analysis of the procedure proposed by AREVA to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel lower head and closure head

[3] ESPN Advisory Committee opinion and recommendations of 30th September 2015, reference CODEP-MEA-2015-040055 of 1st October 2015

[4] ASN letter to AREVA reference CODEP-DEP-2015-043888 of 14th December 2015 – ASN position statement on the procedure to prove adequate toughness of the domes of the Flamanville 3 EPR reactor pressure vessel lower head and closure head

[5] AREVA letter to ASN reference ARV-DEP-00461 of 7th April 2016 – FA3 vessel head domes – supplementary test programme on the upper UA dome

[6] AREVA notice reference D02-PEEM-F-16-0260 revision A of 20th May 2016 – General methodology to demonstrate compliance with the mechanical criteria for the FA3 vessel closure head domes

1. Introduction

For the purposes of technical qualification of the Flamanville 3 EPR reactor pressure vessel (RPV) closure head and bottom head domes, the toughness values obtained, that were below the criteria set in point 4 of appendix 1 to the order in reference [1], led AREVA in 2015 to propose a procedure to ASN designed to demonstrate the adequate toughness of the material of these components.

This procedure was reviewed by ASN and IRSN, as written up in the report in reference [2] and was examined by the Advisory Committee for nuclear pressure equipment (GP ESPN) on 30th September 2015, which issued an opinion in reference [3] on the following points:

- the acceptability in principle of a procedure to demonstrate the adequate toughness of the Flamanville 3 EPR RPV closure head and bottom head domes;
- the notion of adequate material toughness proposed by AREVA and its method of determination;
- the method of determination of minimum material toughness, which is mainly based on a test programme, in particular the transposability to the Flamanville 3 EPR RPV domes of the results obtained on other domes;
- the comparison between the minimum toughness of the material and the adequate toughness, in particular the associated criteria.

On the basis of this review and this opinion, ASN issued a position statement regarding this procedure and made known its requirements in the letter of 14th December 2015 in reference [4] sent to AREVA. This letter is provided in Appendix 6 to this report.

Provided that its comments and requests are taken into consideration, ASN informed AREVA that it considered the demonstration procedure to be appropriate, on condition that the phenomenon concerned is identified and explained and that the mechanical properties are sufficiently well understood. This procedure was based on an experimental programme performed on scale-one replica domes (UK upper dome and UA lower dome).

ASN also underlined that this demonstration procedure was based on the assumption of satisfactory mechanical properties at mid-thickness, notably in terms of toughness, and that if this hypothesis were not to be confirmed by the results of the tests performed on the scale-one replica domes, the demonstration file would need to be revised.

The initial test results in early April 2016 led AREVA to modify four aspects of its demonstration procedure:

- extension of the test programme to a third scale-one replica dome (UA upper dome);
- extension of the tests to three-quarters of the thickness of the UA lower and upper scale-one replica domes;
- the situation and loading conditions to be taken into account in the demonstration procedure;
- the demonstration of the representativeness of the scale-one replica domes with respect to those of the Flamanville 3 EPR RPV.

The purpose of this notice is to

- present the progress of the file since the ESPN Advisory Committee session of 30th September 2015;
- present the changes AREVA proposes making to its demonstration procedure, along with the reasons for doing so.

The aim is not to present the results of the IRSN and ASN review currently in progress, nor to adopt a stance on the changes to the procedure proposed by AREVA.

2. Changes since the ESPN Advisory Committee meeting of 30th September 2015

2.1. Procedure presented at the ESPN Advisory Committee meeting of 30th September 2015

The procedure proposed by AREVA is based on an assessment of the risk of fast fracture and comprises three main steps:

1. determination (by calculation) of adequate toughness to preclude the risk of fast fracture (or a maximum allowable RT_{NDT}[1] brittle-ductile transition temperature);
2. an evaluation (by testing) of the minimum toughness in the positive macrosegregation zone of the material (or an equivalent RT_{NDT} in the segregated zone);
3. comparison between the minimum toughness of the material and the adequate toughness (or the RT_{NDT} of the segregated zone and the maximum allowable RT_{NDT}).

This procedure is schematically represented in

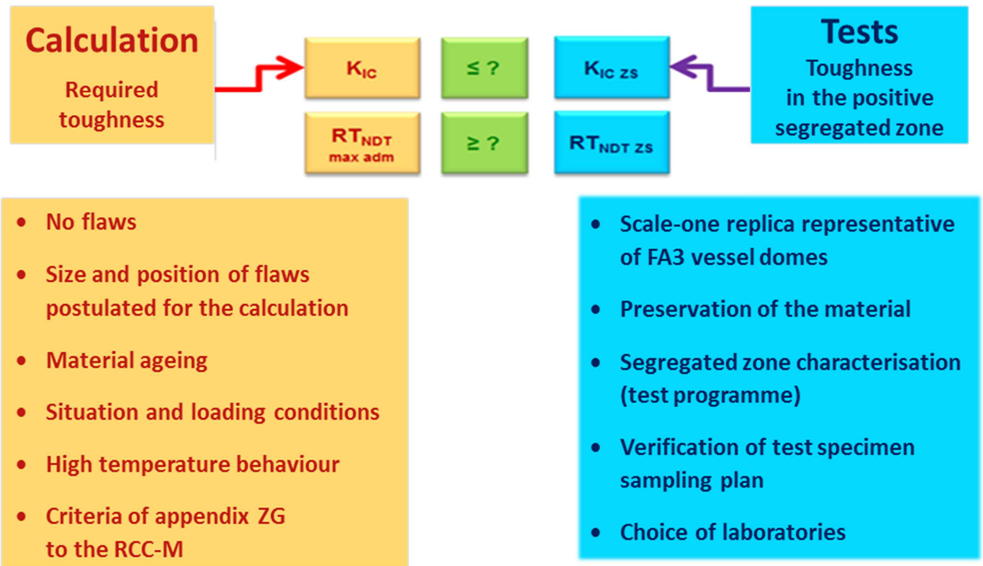


Figure *1*.

2.2. Requests made in the ASN position letter

The ASN letter in reference [4], which followed the ESPN Advisory Committee's opinion of 30th September 2015, comprises 15 requests relating either to the determination by calculation of the allowable properties of the material (in orange in

[1] The RCC-M defines the RT_{NDT} as the temperature which, when increased by 33°C, corresponds to a value of at least 68 J for the Charpy V-notch test.

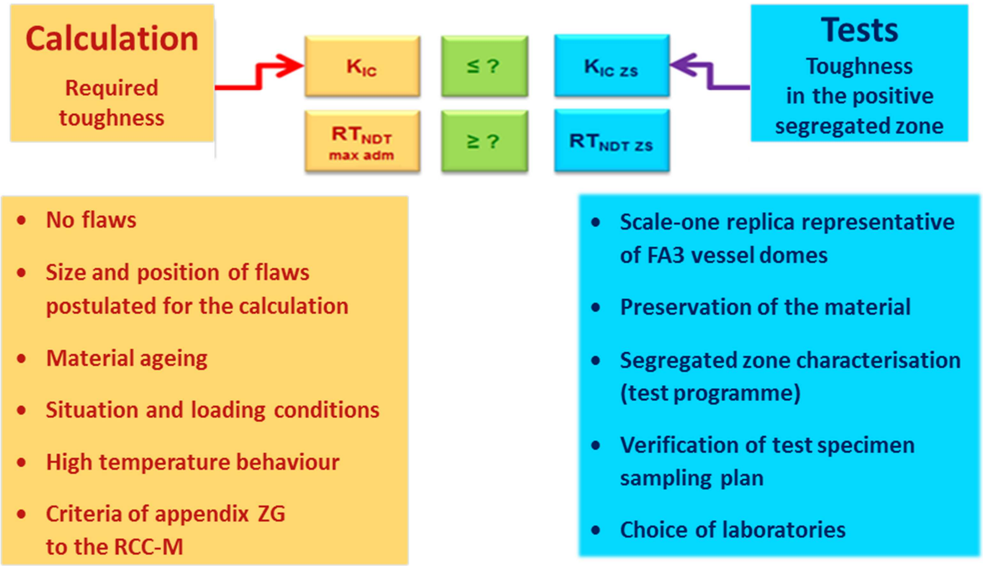


Figure 1), or to the experimental determination of the mechanical properties in the segregated zone (ZS, in blue), or to their comparison (in green).

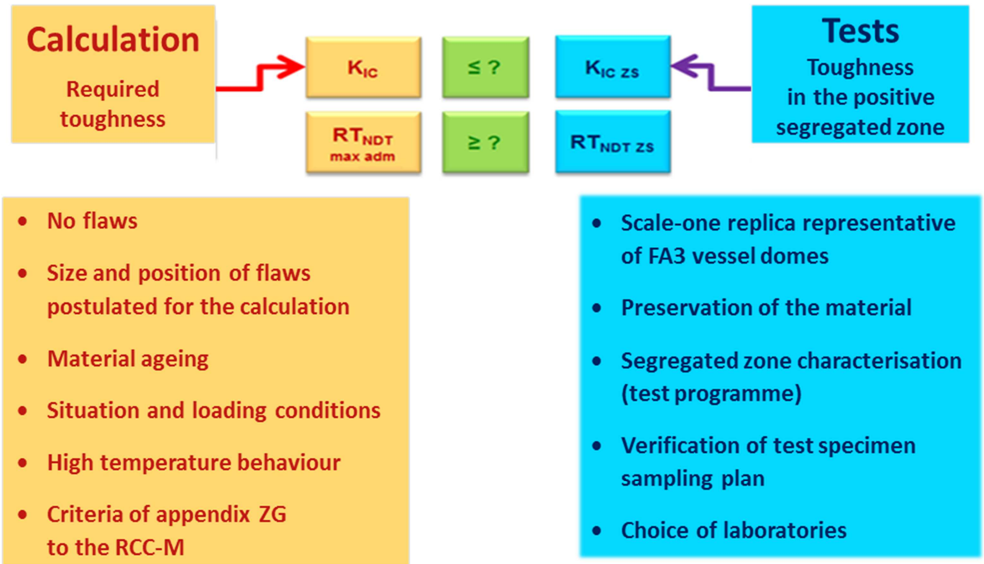


Figure 1: demonstration procedure and subjects of requests contained in letter in reference [4]. ZS: segregated zone

Additional requests concerning the possibility of replacing the domes were also made.

The table in Appendix 1 contains the 15 requests made in the letter in reference [4], along with the progress made concerning the answers provided by AREVA. This letter is provided in Appendix 6 to this report.

2.3. Implementation of the experimental programme

Characterisation of the segregated zones of each investigated dome continued at the end of 2015 and the mechanical tests started in several laboratories in 2016, as shown in the breakdown described in Appendix 2.

AREVA is currently characterising the segregated zone of the UK upper dome. The tests should shortly be completed in the AREVA technical centre laboratory in Erlangen, Germany. AREVA is also beginning to implement the test specimens sampling plan in the segregated zone of the UA lower dome. The tests will be performed in the SCK.CEN laboratory in Mol, Belgium.

The files presenting the results in the segregated zone of the UK upper dome and at mid and quarter thickness in the segregated zone of the UA lower dome are expected for September 2016.

AREVA envisages calling on a third laboratory (selection currently in progress) to run tests in the acceptance zone and at three-quarters thickness of the UA upper dome.

ASN delegated BUREAU VERITAS to monitor the implementation of the experimental programme as a whole.

2.4. New technical information since early 2016

2.4.1. Results of toughness tests on the UA upper dome

The UA upper dome, where the anomaly was discovered in 2014, leading to the demonstration file proposed by AREVA, underwent additional investigations at the beginning of 2016. The entire thickness of a core sample taken from the centre of the dome was characterised by measuring the carbon content from sampled chips and by Charpy V-notch tests (Figure 2).

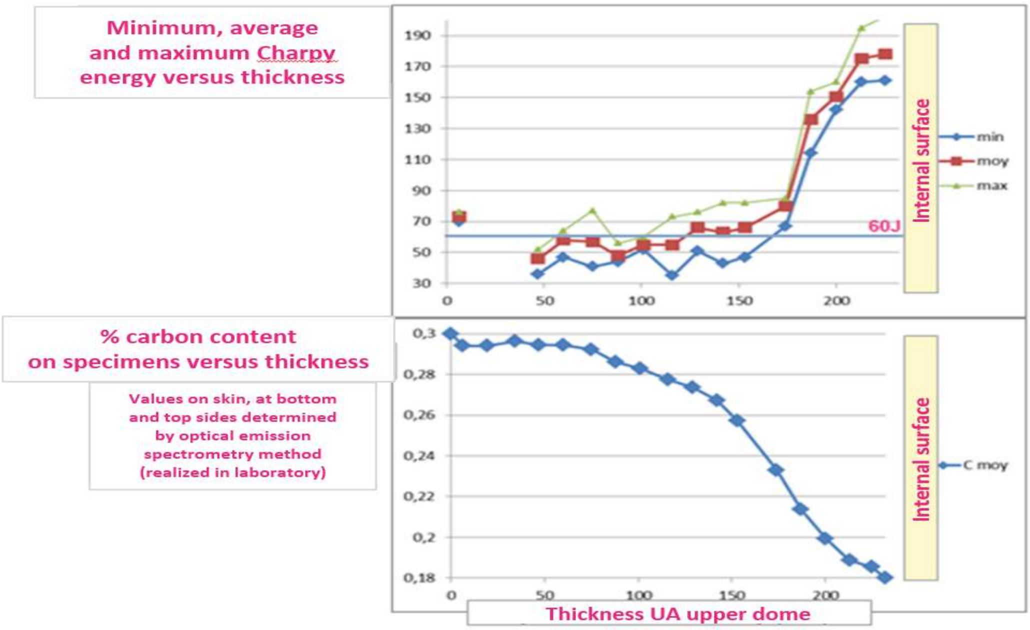


Figure 2: Charpy energy at 0°C (in J) and carbon content versus position in thickness from the outer skin on the central core sample of the UA upper dome

At mid-thickness on the central core sample of the UA upper dome, it was found on the one hand that the Charpy energy is below 60 J at 0°C and, on the other, that the elongation value at ambient temperature is less than 20% (elongation of 18.4% obtained on a small test specimen), which called into question the AREVA hypothesis in which the effect of carbon positive macrosegregation is limited to the outer half-thickness.

AREVA therefore revised the list of situation and loading conditions to be considered in the demonstration file and its file on the sufficiently ductile behaviour of the material.

With regard to the situation and loading conditions to be considered, AREVA no longer restricts its analysis to hot shocks loading the hypothetical defects situated on the outer skin, but also considers cold shocks loading the hypothetical defects positioned at three-quarters thickness starting from the external skin.

It should be noted that in its letter in reference [4] ASN has asked AREVA to check that the mechanical toughness properties of the domes, from mid-thickness towards the interior of the vessel are higher than 60 joules at 0°C.

2.4.2. Uncertainties in the carbon content measurement methods

The carbon content measurements used in AREVA's procedure are based on two techniques entailing uncertainties that need to be taken into consideration:

- portable spark optical emission spectrometry (OES);
- chemical analysis by inductively coupled plasma mass spectroscopy (ICP-MS) on material chips.

For the portable OES measurements, the uncertainty was evaluated by AREVA at ± 15%. AREVA wishes to refine the process in order to reduce the uncertainty to about ± 10%. In 2015, AREVA mentioned measurement precision of 4%, obtained from 3 measurements on a same point.

With regard to the ICP-MS measurements, the uncertainty was re-evaluated at ± 5%.

The consequences of these uncertainties are illustrated in figure 3, which presents maps produced on the same zone with the two methods at mid-thickness of the UK upper dome. However, this example shows that the two methods enable the segregated zone to be positioned in ways that are very similar.

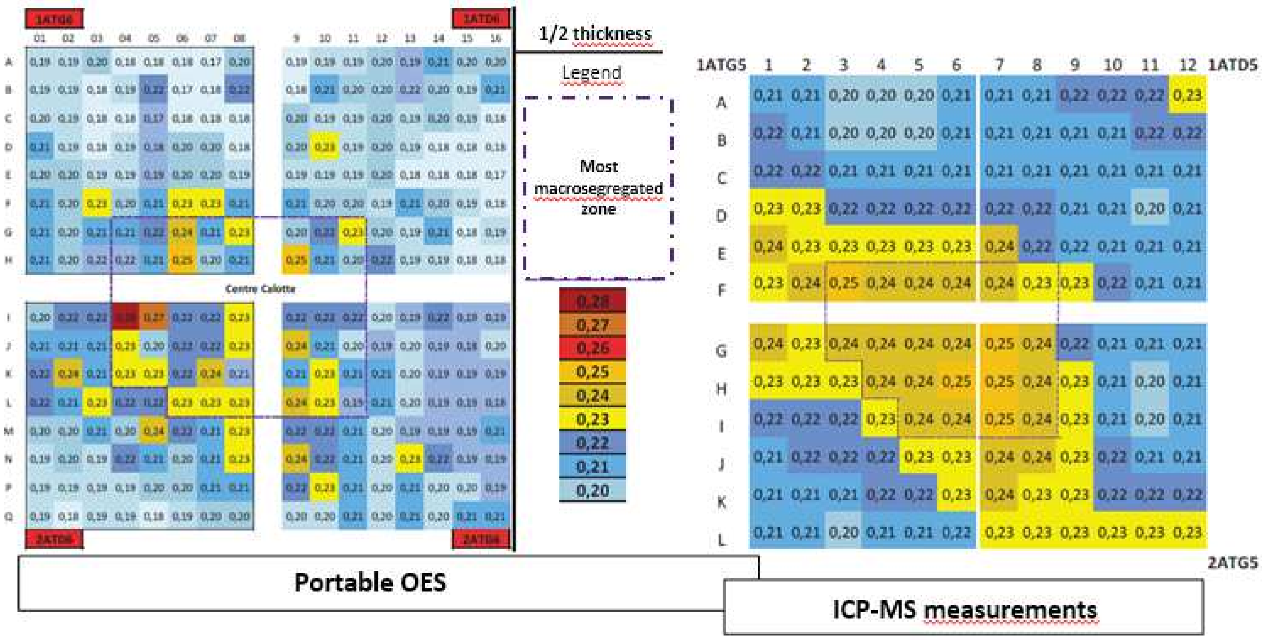


Figure 3: carbon content measurements at mid-thickness of the UK upper dome by portable OES and ICP-MS. The measurement pitch is different, but the block sizes are identical.

AREVA is currently working on characterising and optimising the uncertainties of these two measurement methods.

The carbon content maps obtained by ICP-MS measurements at different depths in the segregated zone of the UK upper and UA lower domes are presented in Appendix 3 (the maps at the different depths of the UA upper dome are currently being produced).

It should be noted that only portable OES measurements will be possible on the Flamanville 3 vessel domes, because they have already been machined to the final dimensions.

2.4.3. Results of carbon content measurements on the scale-one replica parts

AREVA positioned the carbon content measurement results in the thickness of the segregated zone of the UK upper and UA lower domes, as well as in the central core sample of the UA upper dome, in relation to a reference bloom[2], the MOPPEC[3] bloom.

The carbon content maps obtained by portable OES in the thickness of the UK upper and UA lower domes are presented in Appendix 4.

These new results led AREVA to query the extent to which the scale-one replica domes were representative of the Flamanville 3 reactor vessel domes. AREVA thus supplemented its procedure to clarify the uncertainties regarding the positioning and intensity of segregation in the ingots. This point is detailed in section 3.2.

2.5. Progress of the review of the situation and loading conditions file

The file demonstrating the design-basis situation and loading conditions initially presented by AREVA used the initiators analysed in the situations files and the initiators leading to cold overpressure.

During the review, AREVA supplemented its file with an identification of the transients which could lead to hot shock on the domes, in particular analysing the situations with a low initial metal temperature (initial or following cooling) followed by a rise in the fluid temperature during the transient. These transients were studied in order to evaluate the worst-case thermohydraulic conditions (pressure, temperature, flow).

This procedure was used for the lower and upper domes. The hypotheses used for these transients are currently being examined. At this stage, the limit situations identified correspond to:

- for the lower dome, a restart of natural circulation during a small primary break transient;
- for the upper dome, total loss of coolant from the residual heat removal system (RRA [RHRS]) in the normal cold shutdown state.

In addition, in the light of the initial test results, AREVA supplemented its file with an analysis of cold shock transients. AREVA identified the following limit transients:

- for the upper dome, inadvertent opening of a pressuriser relief valve;
- for the lower dome, rupture of a steam generator tube.

The review of the cold shocks file began in June 2016.

[2] A bloom is an intermediate part state, between the ingot (after pouring) and the as-forged part, obtained after a forging operation designed to obtain a constant diameter over its entire height.

[3] "MOPPEC" (prediction model for properties of large forgings hot formed by upsetting operation) is an R&D programme run by AREVA between 2010 and 2015 based on a scale-one replica "MOPPEC bloom", obtained from an ingot similar to that of the vessel domes being investigated.

3. Changes to the demonstration procedure proposed by AREVA

The findings presented in Chapter 2 and the ASN requests presented in section 2.2, led AREVA to make changes to its demonstration procedure on the following points at the beginning of April 2016:

- addition of a third scale-one replica dome;
- extension of the tests to three-quarters of the thickness of the UA domes;
- the situation and loading conditions to be taken into account in the demonstration procedure;
- the demonstration of the representativeness of the results obtained on the other domes with respect to the domes of the Flamanville 3 EPR RPV domes.

At ASN's request, AREVA explained a part of the changes made in the letter in reference [5] and the notice in reference [6], and incorporated them into the documentary architecture of the demonstration file (see Appendix 5).

At this stage, AREVA still needs to explain in detail the changes it proposes, which will be reviewed by ASN and IRSN.

3.1. Impact of the results of Charpy V-notch tests on the UA upper dome

To take account of the first experimental results obtained on the central core sample of the UA upper dome (Charpy energy and elongation at mid-thickness, see section 2.4.1), AREVA proposed:

- adding the UA upper dome to the test programme, defining a sampling plan with objectives similar to those of the other two scale-one replica domes (UK upper and UA lower domes);
- extending the tests to three-quarters of the thickness of the upper and lower UA[4] domes, following the same sampling plan as at half and one quarter thickness;
- providing a file on ductile tearing and carrying out additional tensile tests in the segregated zone at ambient temperature;
- completing the situation and loading conditions file, studying cold shocks with a defect at three-quarters thickness.

3.2. Impact of results of carbon content measurements on the scale-one replica parts

The results of the carbon content measurements on the scale-one replica domes enlighten about the representativeness of the results obtained on these domes with respect to those of the Flamanville 3 EPR reactor vessel.

AREVA thus proposes supplementing its demonstration procedure by:

- providing additional information to more accurately specify the characteristics of the domes of the Flamanville 3 EPR reactor by comparison with the characteristics of the scale-one replica domes, in particular regarding the positioning of the domes in the initial bloom, the uncertainty and the variability of the segregations and the quenching effects;
- taking new carbon content measurements, using the portable OES method, on the upper and lower domes of the Flamanville 3 vessel.

[4] The UK upper dome is not included owing to the carbon content at three-quarters thickness lower than that of the UA domes.

In order to evaluate and demonstrate the representativeness of the one-scale replica domes with respect to those of the Flamanville 3 EPR reactor, AREVA more specifically introduced the notion of component families. A component family is characterised by:

- coherent ladle chemical parameters;
- identical forging sequences;
- a similar segregation range;
- similar relative positioning of the parts in the initial bloom;
- similar surface carbon contents;
- an equivalent quench profile.

The notion of component family is based on:

- characterisation using the tests performed as part of the MOPPEC programme;
- characterisation of the variability of segregations and of the sources of uncertainty;
- the demonstration that each of the domes studied is part of this family.

The family of vessel domes is thus characterised by:

- ingots weighing close to 157 tonnes, poured in a type 2550 ingot mould;
- ladle carbon contents close to 0.18%;
- comparable forging sequences leading to reproducible carbon[5] positive macrosegregation levels of about 40% to 65% in the final part;
- similar quench effects, associated with machining of similar dimensions performed after quality heat treatment.

Using the manufacturing records, AREVA reconstituted the theoretical positioning of the various domes in their blooms, with a reassessment of the discard rates, fire losses and machined thicknesses. AREVA then superimposed each component over the representation of the MOPPEC bloom, on the assumption that this bloom is representative.

To evaluate the representativeness of the scale-one replica domes using the notion of family, AREVA took the carbon contents characterised in 2015 on the MOPPEC bloom (*Figure 4: Graphic representation of the ΔC/C carbon segregation level in the MOPPEC bloom*) and defined a lower and upper bound by applying coefficients to the segregation rates of the MOPPEC programme. *Figure 5: representation of the notion of component family* represents the positioning of the vessel domes in this family, incorporating the uncertainties on the determination of the carbon content (X axis) and on the positioning in the MOPPEC reference bloom (Y axis).

[5] For a steel, the carbon content measured at pouring in liquid steel (C) reflects the average carbon composition of an entire part. The difference with the local carbon content measured at a location on the part (ΔC) is a means of quantifying the positive macrosegregation rate (ΔC/C).

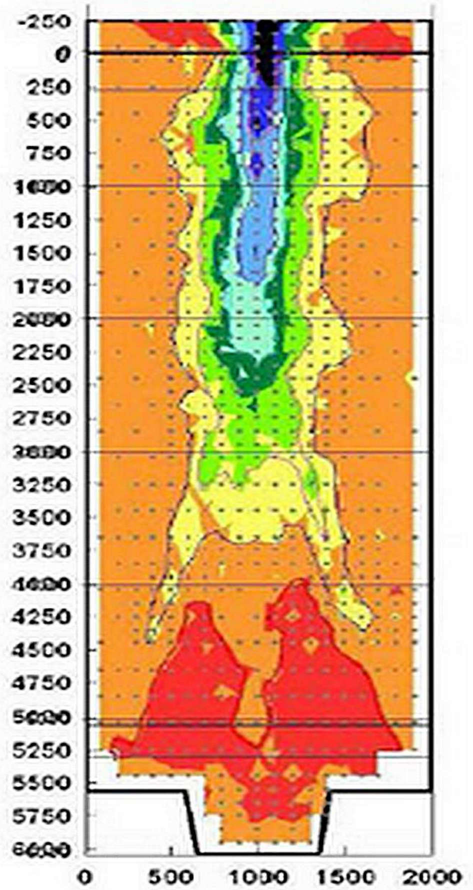


Figure 4: Graphic representation of the ⊿C/C carbon segregation level in the MOPPEC bloom

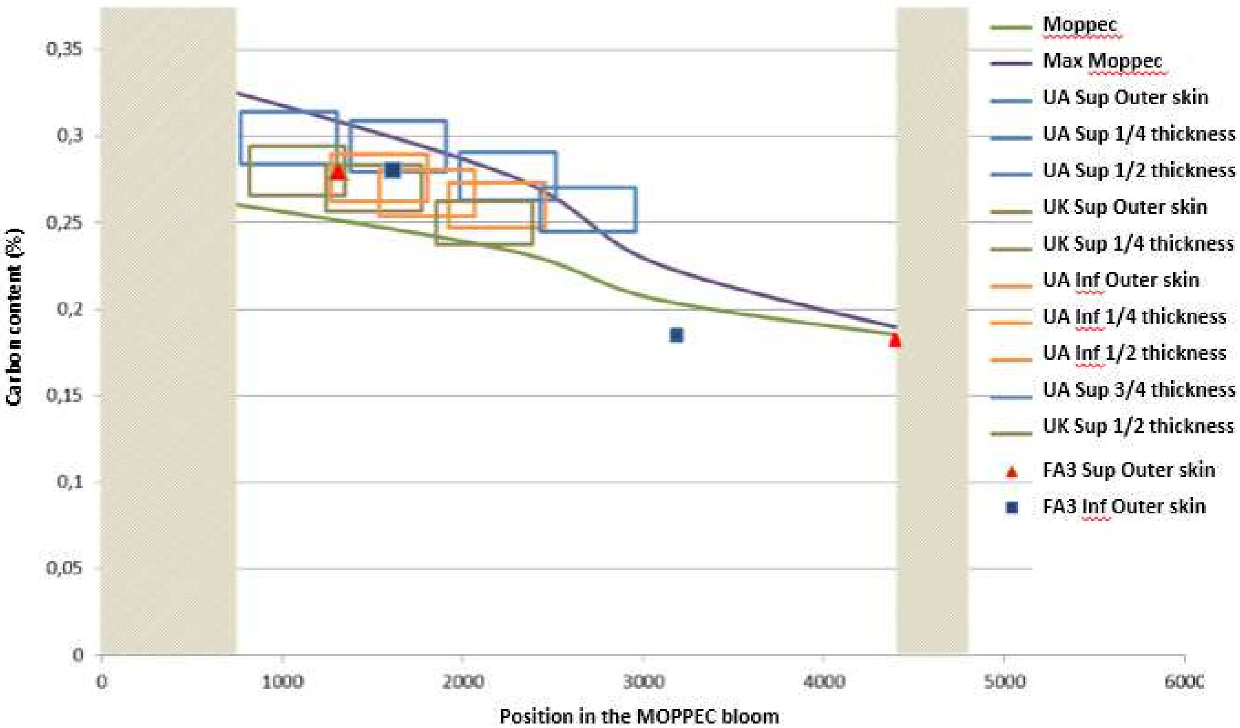


Figure 5: representation of the notion of component family

AREVA has scheduled the submission of the files for all these changes, ending in late November 2016.

These files, which are to be reviewed by ASN and IRSN, are integrated into the documentary architecture of the demonstration file presented in Appendix 5.

APPENDIX 1: Requests in ASN position statement letter of 14th December 2015

No.	Requests	AREVA answers
1	ASN asks you to perform non-destructive surface testing on the Flamanville 3 RPV bottom head, other than dye penetration, supplementing those already performed during manufacturing, to confirm the absence of flawss, using a conventional non-destructive testing procedure with conventional qualification approach.	In progress (infrared thermography method undergoing qualification)
2	By means of a test programme, ASN asks you to validate the hypothesis whereby the mechanical toughness properties of the domes, from mid-thickness towards the interior of the RPV, are higher than 60 joules at 0°C. Failing which, ASN asks you to complete the list of situations and the demonstration file, more specifically by analysing other transients.	Undergoing review by IRSN
3	By means of the test results, ASN asks you to demonstrate that in the ductile zone the material has sufficiently ductile and tough behaviour that is compatible with the design rules used.	In progress (file to be provided by AREVA)
4	ASN asks you to identify and conserve all the material (test specimens, discards, etc.) taken from the domes for possible further investigations.	Point monitored by BUREAU VERITAS
5	Before starting the test programme and after characterising the extent of the segregated zone, ASN asks you to specify the location of the macrographic and micrographic examinations. ASN also asks you to analyse the fracture surfaces of the test specimens.	1st part of the request met for upper UK and lower UA 2nd part in progress
6	Before implementing, ASN asks you to present the sampling plan you envisage further to chemical mapping.	Request met for upper UK and lower UA
7	ASN asks you to have the chemical analyses carried out by a laboratory accredited in accordance with standard NF EN ISO 17025.	Request met
8	ASN asks you to have part of the mechanical tests, except the drop-weight tests, carried out by a laboratory accredited according to standard NF EN ISO 17025 and independent of the AREVA group.	Request met
9	ASN asks you to assess: - the conservative nature of the ZG6110 curve in the RCC-M indexed on the end-of-service RT_{NDT} adopted in the design, minus the shift linked to thermal and stress ageing as well as the maximum difference between the acceptance RT_{NDT} for the Flamanville 3 RPV domes and that of each of the two scale-one replica domes with regard to the measured toughness values; - the consistency of the local T_{NDT} with the design value.	In progress (following the experimental programme)
10	ASN asks you to determine: - the indexing temperature encompassing the toughness measurements in the segregated zone; - the indexing temperature resulting from the drop-weight tests in the segregated zone; - the indexing temperature resulting from the Charpy V-notch tests in the segregated zone, if the local RT_{NDT} is not equal to the local T_{NDT}. As applicable, ASN asks you to provide elements for interpreting the difference between the local T_{NDT} and the local RT_{NDT}.	In progress (following the experimental programme)

No.	Requests	AREVA answers
11	ASN asks you to check that the indexing temperature encompassing the toughness measurements in the segregated zone is lower than the two other indexing temperatures mentioned in request n° 10.	In progress (following the experimental programme)
12	ASN asks you to check that the indexing temperatures determined by the test programme remain below the maximum allowable indexing temperature resulting from the fracture mechanics analyses.	In progress (following the experimental programme)
13	ASN asks you to propose reinforced oversight, for commissioning, operation and in-service monitoring appropriate to the situation encountered and to incorporate them into the equipment operating instruction manual.	In progress (file to be provided by AREVA)
14	Jointly with the licensee, ASN asks you to conduct a technical assessment of scenarios for extracting the RPV body from the reactor building cavity and for replacing the RPV bottom head dome. This study shall analyse the advantages and drawbacks in terms of the quality of the work done and the safety of the facility.	In progress (file to be provided by AREVA)
15	Without in any way anticipating the results of the forthcoming mechanical tests campaign, ASN asks you to study the manufacture of a new RPV head taking account of experience feedback form the design and manufacture of the existing one.	In progress (file to be provided by AREVA)

APPENDIX 2: Breakdown of tests by laboratory

Dome	Temperature	FA3 lower	FA3 upper	UK upper			UA lower				UA upper				Total per type of test
Tests		Acceptance zone	Acceptance zone	Acceptance zone	Segregated zone ¼ th.	Segregated zone ½ th.	Acceptance zone	Segregated zone ¼ th.	Segregated zone ½ th.	Segregated zone ¾ th.	Acceptance zone	Segregated zone ¼ th.	Segregated zone ½ th.	Segregated zone ¾ th.	
Charpy (transition curve)	variable (incl. 0°C)	18	18	18	**72**	**44**	18	36	36	36	18	36	36	36	422
Charpy (for RTndt)	function of Tndt	/	/	/	2X12	2X12	/	12	12	12	/	2X12	2X12	12	144
Toughness (ductile CT 25)	330°C	1	1	1	1	1	1	1	1	1	1	1	1	1	
Toughness (ductile CT 25)	50°C	3	3	3	3	3	3	3	3	3	3	3	3	3	**86**
Toughness (ductile CT 25)	50 or 330°C	2	2	2	8	4	2	2	2	2	2	2	2	2	
Toughness (brittle CT 12.5)	Variable	**40**	**40**	48	**144**	**84**	**40**	72	72	48	**20**	72	72	48	800
Tensile	330°C	1	1	1	1	1	1	1	1	1	1	1	1	1	
Tensile	50°C	1	1	1	1	1	1	1	1	1	1	1	1	1	
Tensile	Ambient	/	/	/	3	3	/	3	3	3	/	3	3	/	**129**
Tensile at transition T°	Variable	6	6	6	10	6	6	6	6	6	6	6	6	6	
Drop-weight	Variable	/	/	/	2X8	2X8	/	8	8	8	/	2X8	2X8	8	96
Chemical analysis		**18**	**18**	**80**	**283**	**187**	**18**	145	145	121	**18**	165	165	118	1481
Total per zone (excl. chemical analyses)		72	72	80	283	187	72	145	145	121	52	165	165	118	1677

AREVA technical centre in Erlangen (Germany)

SCK.CEN in Mol (Belgium)

3rd laboratory (outside AREVA)

AREVA in Saint Marcel

FILAB in Dijon

XX Adaptation of number of tests

APPENDIX 3: Summary of maps of carbon content per thickness level (ICP-MS measurements)

UK upper dome

1/4 thickness

1ATG2	1	2	3	4	5	6	7	8	9	10	11	12	1ATD2
A	0,23	0,24	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,24	
B	0,23	0,24	0,25	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,25	0,25	
C	0,23	0,24	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,27	0,26	
D	0,23	0,24	0,25	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,26	0,26	
E	0,23	0,23	0,24	0,25	0,26	0,26	0,27	0,26	0,25	0,26	0,26	0,26	
F	0,23	0,23	0,23	0,25	0,27	0,26	0,26	0,26	0,26	0,25	0,26	0,26	
G	0,23	0,22	0,23	0,25	0,27	0,26	0,26	0,26	0,25	0,25	0,25	0,26	
H	0,23	0,23	0,24	0,26	0,27	0,26	0,27	0,26	0,25	0,25	0,25	0,26	
I	0,25	0,25	0,25	0,26	0,26	0,26	0,27	0,26	0,25	0,25	0,26	0,26	
J	0,25	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,25	0,26	0,27	0,27	
K	0,25	0,25	0,25	0,26	0,26	0,26	0,27	0,26	0,26	0,27	0,26	0,25	
L	0,25	0,24	0,24	0,25	0,26	0,26	0,27	0,26	0,26	0,26	0,25	0,24	
2ATD2													2ATG2

Legend

Most macrosegregated zone %C > 0.25

0,27
0,26
0,25
0,24
0,23
0,22
0,21

1/2 thickness

1ATG5	1	2	3	4	5	6	7	8	9	10	11	12	1ATD5
A	0,21	0,21	0,20	0,20	0,20	0,21	0,21	0,21	0,22	0,22	0,22	0,23	
B	0,22	0,21	0,20	0,20	0,20	0,21	0,21	0,21	0,21	0,21	0,22	0,22	
C	0,22	0,22	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,21	
D	0,23	0,23	0,22	0,22	0,22	0,22	0,22	0,22	0,21	0,21	0,20	0,21	
E	0,24	0,23	0,23	0,23	0,23	0,23	0,24	0,22	0,22	0,21	0,21	0,21	
F	0,23	0,24	0,25	0,24	0,24	0,24	0,24	0,23	0,23	0,22	0,21	0,21	
G	0,24	0,23	0,24	0,24	0,24	0,24	0,25	0,24	0,22	0,21	0,21	0,21	
H	0,23	0,23	0,23	0,24	0,24	0,25	0,25	0,24	0,23	0,21	0,20	0,21	
I	0,22	0,22	0,22	0,23	0,24	0,24	0,25	0,24	0,23	0,21	0,20	0,21	
J	0,21	0,22	0,22	0,22	0,23	0,23	0,24	0,24	0,23	0,22	0,21	0,21	
K	0,21	0,21	0,21	0,22	0,22	0,23	0,24	0,23	0,23	0,22	0,22	0,22	
L	0,21	0,21	0,20	0,21	0,21	0,22	0,23	0,23	0,23	0,23	0,23	0,23	
2ATD5													2ATG5

Legend

Most macrosegregated zone

0,26
0,25
0,24
0,23
0,22
0,21
0,20

UA upper dome

Mapping in progress.

UA lower dome

1/4 thickness

1ATG2	1	2	3	4	5	6	7	8	9	10	11	12	1ATD2*
A	0,22	0,23	0,24	0,23	0,24	0,24	0,23	0,23	0,23	0,24	0,23	0,23	A
B	0,23	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	B
C	0,23	0,24	0,25	0,25	0,26	0,26	0,25	0,24	0,24	0,25	0,24	0,24	C
D	0,24	0,25	0,26	0,27	0,27	0,26	0,26	0,26	0,26	0,25	0,25	0,24	D
E	0,24	0,25	0,27	0,27	0,27	0,27	0,26	0,26	0,26	0,26	0,26	0,25	E
F	0,24	0,25	0,26	0,27	0,27	0,27	0,27	0,26	0,26	0,26	0,26	0,25	F
G	0,24	0,25	0,26	0,28	0,27	0,27	0,27	0,27	0,27	0,27	0,26	0,25	G
H	0,24	0,25	0,26	0,27	0,28	0,27	0,27	0,27	0,26	0,26	0,26	0,25	H
I	0,24	0,24	0,25	0,25	0,26	0,27	0,27	0,26	0,26	0,26	0,26	0,25	I
J	0,24	0,24	0,24	0,25	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,25	J
K	0,23	0,23	0,24	0,24	0,24	0,25	0,25	0,26	0,26	0,26	0,26	0,24	K
L	0,23	0,23	0,24	0,24	0,24	0,24	0,24	0,25	0,25	0,25	0,25	0,24	L
2ATD2													2ATG2

* Contents of 1ATD2 to xx mm away from the skin

Legend

Most macrosegregated zone %C > 0.25

Legend
0,28
0,27
0,26
0,25
0,24
0,23
0,22
0,21

1/2 thickness

1ATG3	1	2	3	4	5	6	7	8	9	10	11	12	1ATD3
A	0,22	0,23	0,23	0,22	0,22	0,22	0,22	0,22	0,22	0,23	0,23	0,22	A
B	0,23	0,23	0,22	0,22	0,23	0,22	0,23	0,23	0,22	0,23	0,23	0,23	B
C	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	C
D	0,23	0,24	0,23	0,24	0,25	0,24	0,25	0,24	0,24	0,23	0,24	0,24	D
E	0,24	0,24	0,25	0,26	0,26	0,26	0,26	0,26	0,25	0,24	0,23	0,24	E
F	0,24	0,25	0,26	0,27	0,26	0,26	0,26	0,26	0,25	0,25	0,24	0,24	F
G	0,25	0,25	0,27	0,27	0,27	0,26	0,26	0,25	0,25	0,24	0,24	0,24	G
H	0,24	0,25	0,26	0,26	0,26	0,26	0,26	0,25	0,24	0,23	0,23	0,23	H
I	0,24	0,25	0,25	0,26	0,26	0,26	0,26	0,24	0,23	0,22	0,22	0,23	I
J	0,24	0,25	0,25	0,26	0,26	0,25	0,25	0,24	0,22	0,22	0,22	0,23	J
K	0,24	0,25	0,25	0,25	0,25	0,25	0,25	0,24	0,22	0,22	0,22	0,23	K
L	0,24	0,25	0,25	0,25	0,25	0,24	0,25	0,24	0,23	0,22	0,23	0,24	L
2ATD3													2ATG3

Legend

Most macrosegregated zone

Legend
0,28
0,27
0,26
0,25
0,24
0,23
0,22
0,21

1ATG4	1	2	3	4	5	6	7	8	9	10	11	12	1ATD4
A	0,21	0,21	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	A
B	0,21	0,21	0,20	0,20	0,20	0,21	0,20	0,20	0,20	0,20	0,20	0,20	B
C	0,21	0,20	0,21	0,20	0,21	0,21	0,21	0,21	0,20	0,20	0,20	0,20	C
D	0,21	0,21	0,22	0,22	0,22	0,22	0,21	0,21	0,20	0,20	0,20	0,20	D
E	0,22	0,22	0,23	0,23	0,23	0,23	0,23	0,22	0,21	0,21	0,20	0,21	E
F	0,22	0,23	0,24	**0,25**	0,24	0,24	0,24	0,22	0,21	0,21	0,21	0,21	F
G	0,23	0,24	**0,25**	**0,25**	**0,25**	0,24	0,23	0,22	0,21	0,20	0,20	0,20	G
H	0,23	0,24	**0,25**	**0,25**	**0,25**	0,24	0,22	0,21	0,20	0,20	0,19	0,20	H
I	0,23	0,24	0,24	0,24	0,24	0,23	0,22	0,20	0,19	0,19	0,19	0,19	I
J	0,22	0,23	0,23	0,23	0,23	0,22	0,21	0,20	0,19	0,19	0,19	0,19	J
K	0,22	0,22	0,23	0,23	0,22	0,22	0,21	0,20	0,19	0,19	0,19	0,19	K
L	0,22	0,22	0,22	0,22	0,22	0,22	0,21	0,20	0,19	0,19	0,19	0,20	L
2ATD4													2ATG4

3/4 thickness

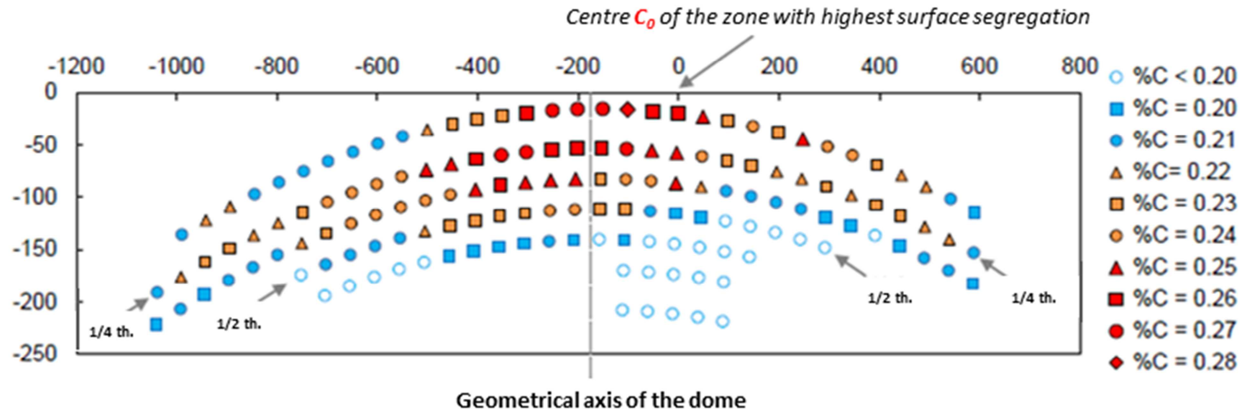
Legend

Most macrosegregated zone

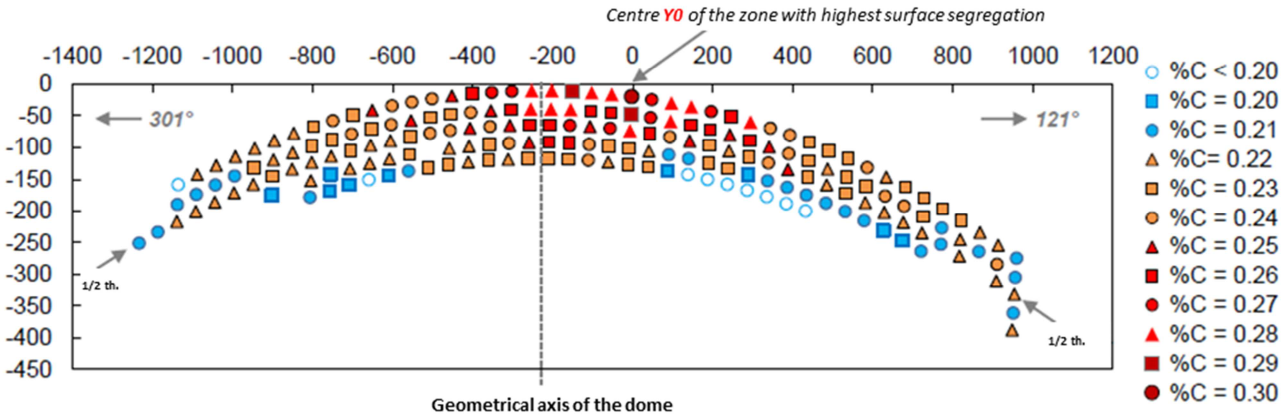
0,26
0,25
0,24
0,23
0,22
0,21
0,20
0,19

APPENDIX 4: Summary of maps of carbon content in the thickness (portable OES)

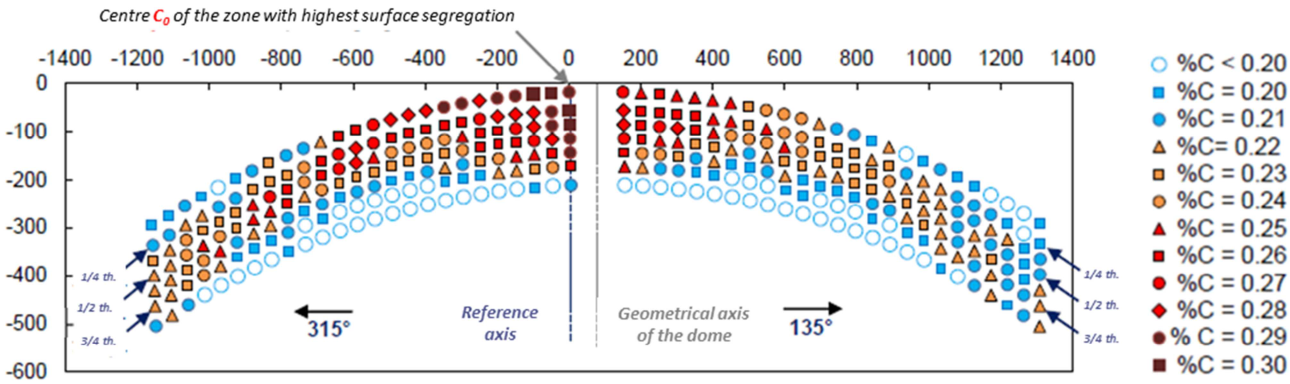
UK upper dome
(map stopping below mid-thickness)



UA lower dome
(total thickness represented)



UA upper dome
(total thickness represented)



APPENDIX 5: Documentary architecture of AREVA's final demonstration file

(the topics underlined in yellow do not systematically lead to issue of a specific document)

Level 1		Level 2		Level 3		Level 4	
No.	Topic or subject of document	No.	Topic or subject of document	No.	Topic or subject of document	No.	Topic or subject of document
1	Summary document on compliance with mechanical criteria	1-1	Determination of mechanical characteristics necessary to demonstrate the suitability of the domes for service	1-1-1	Identification of transients and mechanical analysis concerning hot shocks		
				1-1-2	Identification of transients and mechanical analysis concerning cold shocks for flaws at ¼ thickness Internal		
		1-2	Summary data on transposition of results obtained on scale-one replica domes to the parts of the FA3 vessel domes	1-2-1	Associated measurement and performance techniques	1-2-1-1	Portable OES analyses protocol and performance
						1-2-1-2	ICP-MS analyses protocol and performance
						1-2-1-3	Influence of ghost lines on the measured carbon contents
				1-2-2	Definition of a family of domes	1-2-2-1	Summary of results obtained under the MOPPEC programme Segregation in the Arcelor-Mittal 2550 ingots
						1-2-2-2	Stability of manufacturing with regard to segregations and quench effects Manufacturing stability: Summary note on positioning of domes, uncertainty and variability of segregations Solidification and forging simulations Reproducibility of manufacturing of EPR RPV domes: study of manufacturing parameters of upper and lower domes of FA3/UK/UA
						1-2-2-3	Combination of quench and carbon effects Simulation of quench gradients Combined influence of quench effects and carbon contents on toughness
				1-2-3	FA3 domes membership of the family - Summary Coherence of the FA3 RPV domes forging process with those of the scale-one replica domes	1-2-3-1	Summary of carbon measurements taken on the outer surface of the FA3 domes Characterisation of segregation in the blocks: macros, OES and ICP-MS
		1-3	Definition of toughness characteristics of the segregated zones at different depths in the thickness of the domes.	1-3-1	Choice of laboratories	1-3-1-1	Carbon content measurements
						1-3-1-2	Mechanical tests
				1-3-2	Interpretation of results by comparison with the ASN requirements of the upper UK dome	1-3-2-1	Sampling Plans Portable OES maps of outer surface ICP-MS measurements mapping of internal surface Characterisation of segregation on 1/2 dome: macrography and OES.
						1-3-2-2	Test report
				1-3-3	Interpretation of results by comparison with the ASN requirements of the lower UA domes	1-3-3-1	Sampling Plans Portable OES maps of outer surface ICP-MS measurements mapping of internal surface Characterisation of segregation on 1/2 dome: macrography and OES.
						1-3-3-2	Test report
				1-3-4	Interpretation of results by comparison with the ASN requirements of the upper UA dome	1-3-4-1	Sampling Plans Portable OES maps of outer surface ICP-MS measurements mapping of internal surface Characterisation of segregation on 1/2 dome: macrography and OES.
						1-3-4-2	Test report
		1-4	Characterisation of ageing effects on mechanical properties				

Level 1		Level 2		Level 3		Level 4	
No.	Topic or subject of document	No.	Topic or subject of document	No.	Topic or subject of document	No.	Topic or subject of document
2	Summary of elements guaranteeing the absence of defects	2-1	Summary of elements guaranteeing the absence of defects at the end of manufacturing	2-1-1	Summary of non-destructive manufacturing inspection results		
				2-1-2	Technical demonstration file and results of surface measurement on vessel bottom head		
		2-2	Reinforced commissioning oversight, operation and in-service monitoring measures.				
3	Replacement of domes	3-1	Technical study on scenarios for extraction of vessel body and replacement of dome on vessel bottom head				
		3-2	Study for manufacture of a new vessel head.				

APPENDIX 6: ASN position statement letter of 14th December 2015

Please refer to this link on ASN website :

http://www.french-nuclear-safety.fr/Information/News-releases/Flamanville-3-EPR-ASN-has-no-objection-to-the-initiation-of-a-new-test-programme