Office for Nuclear Regulation

An agency of HSE

Generic Design Assessment – New Civil Reactor Build

GDA Close-out for the EDF and AREVA UK EPR™ Reactor

– GDA Issue GI-UKEPR-SI-02 Revision 1

– Structural Integrity – RPV Surveillance Scheme

Assessment Report: ONR-GDA-AR-12-014
Revision 0
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EXECUTIVE SUMMARY

This report presents the close-out of part of the Office for Nuclear Regulation's (an agency of HSE) Generic Design Assessment (GDA) within the area of Structural Integrity. The report specifically addresses the GDA Issue **GI-UKEPR-SI-02 Revision 1** generated as a result of the GDA Step 4 Structural Integrity Assessment of the UK EPR™. The assessment has focussed on the deliverables identified within the EDF and AREVA Resolution Plan published in response to the GDA Issue and on an additional deliverable submitted later in response to ONR feedback.

The EPR™ reactor pressure vessel (RPV) is subjected to neutron irradiation in service which has the potential to degrade the toughness of the material in the most highly irradiated regions. This degradation of the material is monitored using samples of material which are placed inside the reactor vessel in a region of enhanced irradiation and withdrawn and measured at intervals during the operating life.

The EPR™ design includes a heavy steel neutron reflector which surrounds the core and reduces the neutron dose on the RPV wall. Another effect of the heavy reflector is to change the neutron energy spectrum so that, at the location of the surveillance samples, the proportion of lower energy neutrons is substantially increased compared with that of a standard pressurised water reactor (PWR).

GDA Issue **GI-UKEPR-SI-02** requires a demonstration that the principles of the surveillance scheme adequately take account of the differences in neutron spectra caused by the heavy reflector in the EPR™ design.

For standard PWRs the surveillance schemes normally rely on measuring the fluence (i.e. the total number) of high energy neutrons (E> 1MeV) at the locations of the surveillance specimens and the RPV wall. However, the most widely accepted approach for assessing irradiation damage in situations where the neutron spectra are varying involves a prediction of the number of displacements per atom (dpa).

The analyses provided by EDF and AREVA towards the end of GDA Step 4 show that the dpa rates in the surveillance samples are dominated by damage from lower energy neutrons whereas the dpa rates in the RPV wall are dominated by the damage from high energy neutrons.

I was not convinced by the arguments initially provided by EDF and AREVA in attempting to address this GDA Issue, primarily because of their reliance on an experimental programme involving only a very small number of measurements.

However EDF and AREVA have now undertaken new analysis and proposed a revised approach which comprises:

- Derivation of a tentative dose-damage correlation based on dpa as the dose parameter to take account of the differences in neutron spectrum between the EPR™ surveillance specimen location and the RPV wall.
- Analyses of the advantages and disadvantages of fluence and dpa indexations.
- An example of a flexible withdrawal scheme using dpa as the dose parameter.

Having assessed this revised approach, I judge that EDF and AREVA have now developed an adequate definition of the surveillance programme and withdrawal scheme for this stage of the safety case development and the GDA Issue may be closed. The detailed implementation of the scheme and the analysis of results may now be left to the licensing phase.

Any Licensee will need to develop a detailed RPV surveillance programme which takes account of the differences in neutron energy spectra between the RPV wall and the location of the surveillance capsules and I have created an Assessment Finding to this effect (**AF-UKEPR-SI-42**).

LIST OF ABBREVIATIONS

AREVA	AREVA NP SAS
CEA	(French) Atomic Energy Commission
CMF	Change Modification Form
DAC	Design Acceptance Confirmation
DBTT	Ductile to Brittle Transition Temperature
dpa	Displacements per Atom
EDF	Electricité de France SA
GDA	Generic Design Assessment
HSE	The Health and Safety Executive
IAEA	International Atomic Energy Agency
IDAC	Interim Design Acceptance Confirmation
NNL	National Nuclear Laboratory
ONR	Office for Nuclear Regulation (an agency of HSE)
ONR HOW2	(ONR) Business Management System
PCSR	Pre-construction Safety Report
PWR	Pressurised Water Reactor
RO	Regulatory Observation
RP	Requesting Party
RPV	Reactor Pressure Vessel
RSEM	Règles de Surveillance en Exploitation des Matériels Mécaniques des Ilots Nucléaires
SAP	Safety Assessment Principle(s) (HSE)
TAG	Technical Assessment Guide(s) (ONR)
TQ	Technical Query
TSC	Technical Support Contractor
WENRA	Western European Nuclear Regulators’ Association

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1 INTRODUCTION

1.1 Background

1 This report presents the close-out of the Office for Nuclear Regulation's (an agency of HSE) Generic Design Assessment (GDA) within the area of Structural Integrity. The report specifically addresses the GDA Issue **GI-UKEPR-SI-02 Revision 1** and associated GDA Issue Action (Ref. 5) generated as a result of the GDA Step 4 Structural Integrity Assessment of the UK EPR™ (Ref. 4). The assessment has focussed on the deliverables identified within the EDF and AREVA Resolution Plan (Ref. 6) published in response to the GDA Issue and on an additional deliverable (Ref. 22) provided in response to feedback from ONR.

2 GDA followed a step-wise-approach in a claims-argument-evidence hierarchy. In Step 2 the claims made by the EDF and AREVA were examined and in Step 3 the arguments that underpin those claims were examined. The Step 4 assessment reviewed the safety aspects of the UK EPR™ reactor in greater detail, by examining the evidence, supporting the claims and arguments made in the safety documentation.

3 The Step 4 Structural Integrity Assessment identified a number of GDA Issues and Assessment Findings as part of the assessment of the evidence associated with the UK EPR™ reactor design. GDA Issues are unresolved issues considered by regulators to be significant, but resolvable, and which require resolution before nuclear island safety related construction of such a reactor could be considered. Assessment Findings are findings that are identified during the regulators' GDA assessment that are important to safety, but not considered critical to the decision to start nuclear island safety related construction of such a reactor.

4 The Step 4 Assessment concluded that the UK EPR™ reactor was suitable for construction in the UK subject to resolution of 31 GDA Issues. The purpose of this report is to provide the assessment which underpins the judgement made in closing GDA Issue **GI-UKEPR-SI-02**.

1.2 Scope

5 This report presents only the assessment undertaken as part of the resolution of the GDA Issue **GI-UKEPR-SI-02** and it is recommended that this report be read in conjunction with the Step 4 Structural Integrity Assessment (Ref. 4) in order to appreciate the totality of the assessment of the evidence undertaken as part of the GDA process.

6 This assessment report is not intended to revisit aspects of assessment already undertaken and confirmed as being adequate during previous stages of the GDA. However, should evidence from the assessment of EDF and AREVA's responses to GDA Issues highlight shortfalls not previously identified during Step 4, there would be a need for these aspects of the assessment to be highlighted and addressed as part of the close-out phase or be identified as Assessment Findings to be taken forward to site licensing.

7 Further Assessment Findings may be generated as a result of this assessment given that resolution of the GDA Issue may leave open some aspects requiring further detailed evidence which will only become available at a later stage.

1.3 Methodology

8 The methodology applied to this assessment follows the approach taken during GDA Step 4 which was based on the ONR HOW2 document 'Permissioning - Purpose and Scope of Permissioning', PI/FWD Issue 3 (Ref. 1).

9 This assessment has been focussed primarily on the submissions relating to resolution of the GDA Issues as well as any further requests for information or justification derived from assessment of those specific deliverables.

10 The assessment allows ONR to judge whether the submissions provided in response to the GDA Issue are sufficient to allow it be closed. Where requirements for more detailed evidence have been identified that are appropriate to be provided at the design, construction or commissioning phases of the project these can be carried forward as Assessment Findings.

1.4 Structure

11 This Assessment Report structure differs slightly from the structure adopted for the previous reports produced within GDA, most notably the Step 4 Structural Integrity Assessment. The report has been structured to reflect the assessment of the individual GDA Issue rather than a report detailing close-out of all GDA Issues associated with this technical area.

12 The reasoning behind adopting this report structure is to allow closure of GDA Issues as the work is completed rather than having to wait for the completion of all the GDA work in this technical area.

2 ONR'S ASSESSMENT STRATEGY FOR STRUCTURAL INTEGRITY

13 The intended assessment strategy for GDA Close-out for the Structural Integrity topic area was set out in an assessment plan that identified the intended scope of the assessment and the standards and criteria that would be applied (Ref. 7).

14 The overall bases for the assessment of the GDA Issues are the Structural Integrity elements of:

- Submissions made to ONR in accordance with the resolution plans.
- Update to the Submission / Pre-construction Safety Report (PCSR) / Supporting Documentation (Refs 10 and 11).
- The Design Reference that relates to the Submission / PCSR as set out in UK EPR™ GDA Project Instruction UKEPR-I-002 Revision 11 (Ref. 8) which will be updated throughout GDA Issue resolution and includes Change Management Forms (CMF).
- Design Change Submissions – which are proposed by EDF and AREVA and submitted in accordance with UK EPR™ GDA Project Instruction UKEPR-I-003 (Ref. 9).

15 The objective of the assessment has been to review submissions made by EDF and AREVA in response to the GDA Issues and the design changes requested and, if the proposals are judged acceptable, to close the GDA Issues.

2.1 The Approach to Assessment for GDA Close-out

16 The methodology applied to this assessment is identical to the approach taken during Step 4 which followed the ONR HOW2 document 'Permissioning - Purpose and Scope of Permissioning', PI/FWD Issue 3 (Ref. 1), in relation to mechanics of assessment within ONR.

17 The approach involves:

- Assessment of submissions provided by EDF and AREVA in response to GDA Issues identified through the GDA process.
- In the event of requiring further supporting evidence for the assessment, Technical Queries (TQ) have been generated (Ref. 14).
- When requests for further information through production of TQs did not adequately resolve the GDA Issue, formal notification in the form of a letter detailing the shortfall(s) in ONR expectations was sent to EDF and AREVA.

2.2 Standards and Criteria

18 The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAP) (Ref. 2), internal ONR Technical Assessment Guides (TAG), relevant national and international standards and relevant good practice informed from existing practices adopted on UK nuclear licensed sites. National and international standards and guidance have been referenced where appropriate within the assessment report. Relevant good practice, where applicable, has also been cited within the body of the assessment.

2.3 Safety Assessment Principles

19 The key SAPs applied during this assessment of the UK EPR™ are included within Table 1 of this report.

2.3.1 Technical Assessment Guides

20 The following Technical Assessment Guide has been used as part of this assessment:

- T/AST/016 Issue 3. Integrity of Metal Components and Structures (Ref. 3).

21 The Structural Integrity related SAPs, and relevant IAEA (International Atomic Energy Agency) standards and WENRA (Western European Nuclear Regulators' Association) reference levels are embodied and enlarged on in Ref. 3 and in practice this guide is the principal reference for assessing the Structural Integrity aspects.

2.4 Use of Technical Support Contractors

22 I engaged NNL as a Technical Support Contractor (TSC) to provide a specialist consultancy in support of my own assessment. The TSC attended two meetings with EDF and AREVA to support the regulatory position which I presented.

2.5 Out-of-scope Items

23 No out-of-scope items were identified through the GDA Close-out assessment for GDA Issue **GI-UKEPR-SI-02** and this Issue has been addressed in its entirety.

3 ASSESSMENT OF GDA ISSUE GI-UKEPR-SI-02

3.1 Background to the GDA Issue

24 The EPR™ reactor pressure vessel (RPV) is subjected to neutron irradiation in service which has the potential to degrade the toughness of the material in the most highly irradiated regions. One of the effects is a shift to higher temperatures of the ductile to brittle fracture transition temperature (DBTT).

25 The SAPs (Ref. 2) address the importance of operating with the material fully ductile (rather than in the transition region) in EMC.23 and Para 268 which state that:

- Clear safety benefits derive from operating on the upper shelf of the toughness transition curve;
- RPVs must, for normal steady-state operation, operate on the upper shelf.

26 The shift in transition temperature of the material is monitored using samples of material which are placed inside the reactor vessel in a region of enhanced irradiation and withdrawn and measured at intervals during the operating life.

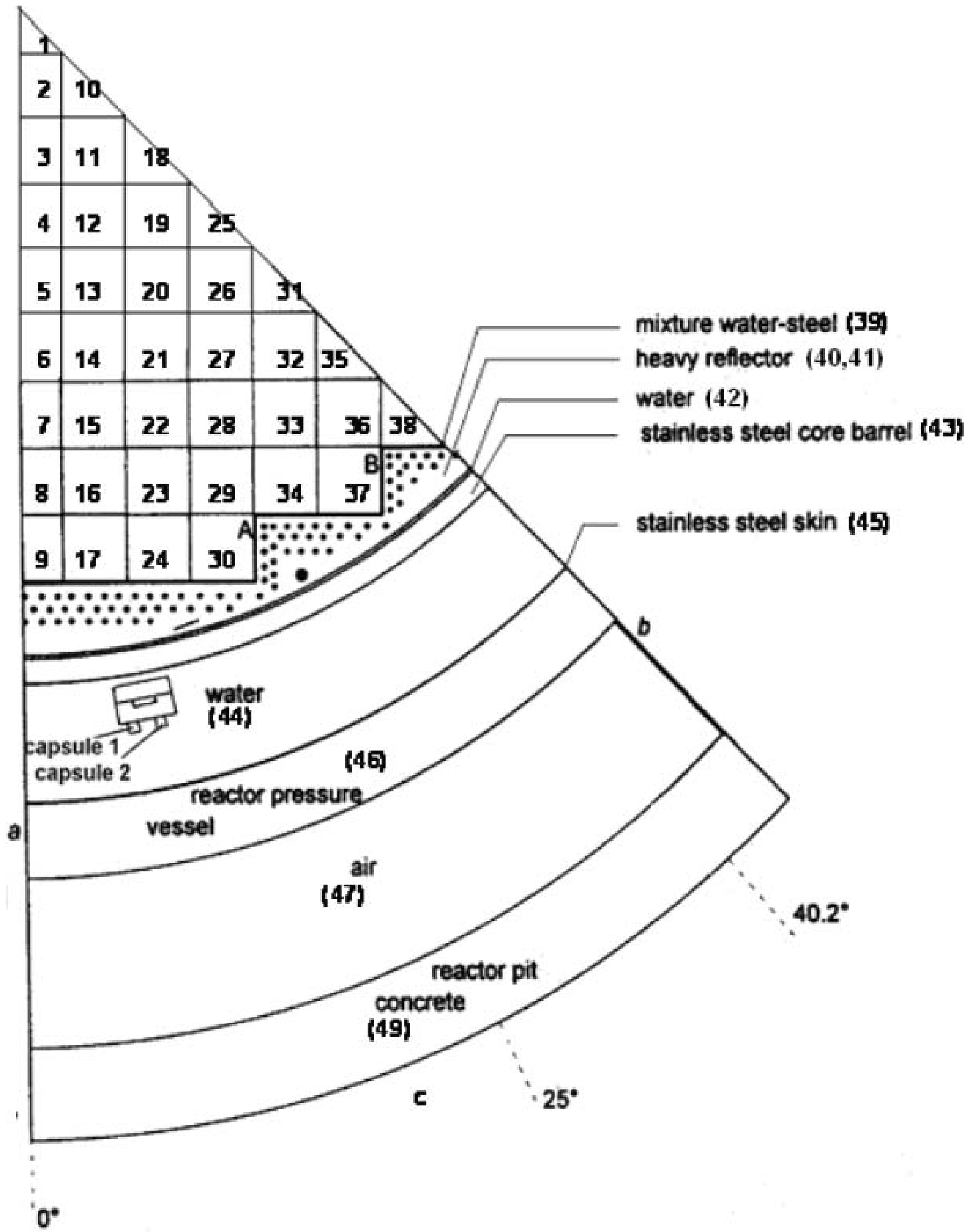
27 When samples are withdrawn, the parameter normally measured is the shift to higher temperature of the transition temperature (DBTT). An empirical correlation is then used to estimate the corresponding change in material properties for the RPV wall and to check that any change is consistent with predictions.

28 The EPR™ design includes a heavy steel neutron reflector which surrounds the core but sits within the core barrel and which reduces the neutron dose on the RPV wall. Another effect of the heavy reflector is to change the neutron energy spectrum so that, at the location of the surveillance samples, the proportion of lower energy neutrons is substantially increased compared with that of a standard pressurised water reactor (PWR).

29 The surveillance specimens used to monitor progress of embrittlement in the EPR™ are placed close to the heavy reflector, whereas there is a significant water gap between the reflector and the RPV wall which reduces the proportion of lower energy neutrons at the RPV wall. As a result the EPR™ neutron spectrum is quite different from a standard PWR at the location of the surveillance capsules, but the effect is much less pronounced at the RPV wall where the spectrum is similar to a standard PWR. Consequently the empirical correlation used to relate damage in the surveillance specimens to damage in the RPV wall, which has been derived using data from standard PWRs, is not directly applicable to the EPR™.

30 The figure below which is taken from Ref. 15 illustrates the arrangement of the heavy reflector, core barrel and RPV wall as well as the surveillance capsules and water gaps.

Schematic section through the heavy reflector, core barrel and RPV wall



31 For standard PWRs the surveillance schemes are normally based on the fluence (i.e. the total number) of high energy neutrons (E> 1MeV) at the locations of the surveillance specimens and at the RPV wall. This fluence approach, which ignores the lower energy neutrons, is a valid approximation for standard PWRs since the proportion of high to low energy neutrons is similar for the specimens and the RPV wall. However, in the case of the EPR™ this approximation is not necessarily valid and an approach which allows for the variation in spectrum of neutron energies should be more accurate.

32 The most widely accepted approach for assessing irradiation damage in such situations involves a prediction of the number of displacements per atom (dpa). This parameter (dpa) is a measure of neutron dose based on a prediction of the number of defects generated in the material at the atomic level, and it is such defects which lead to changes in a material's resistance to deformation and fracture. Although the dpa approach does take account of differences in neutron energy spectrum, it is still only an approximation. International research on irradiation damage continues with the objective of improving understanding of the damage mechanisms and might lead to development of a more refined indexation parameter than dpa.

33 The effect of the heavy reflector was raised as a Regulatory Observation (Ref. 12) in Step 3 of GDA (**RO-UKEPR-25**) and progressed during GDA Step 4.

34 Towards the end of GDA Step 4 EDF and AREVA provided a report (Ref. 15) on the maximum lifetime irradiation of the RPV wall and the surveillance capsules but evaluated on the basis of displacements per atom (dpa) for comparison with the use of fluence of high energy neutrons (E>1MeV). The report also compares the effect of a heavy reflector with that of a water reflector using EPR capsule baskets in both cases. A more recent report submitted during the GDA close-out (Ref. 18) provides similar analyses but includes the configuration with a conventional capsule basket and water reflector as used in standard PWRs, and the data in the table below has been derived from this report.

35 The table below provides a comparison of the proportions of damage calculated using dpa for capsule 1 and RPV wall locations; firstly, for a heavy reflector with EPR capsule basket and secondly, for a water reflector with conventional basket. With a heavy reflector, 26.7% of the damage is caused by high energy neutrons (E>1MeV), whereas at the RPV wall this rises to 69.5%. These predictions show that with a heavy reflector (as in the EPR™) the dpa rates in the surveillance samples are dominated by damage from lower energy neutrons (E<1MeV) whereas the RPV dpa values are dominated by the damage from high energy neutrons (E>1MeV).

Comparison of the proportions of damage evaluated by dpa for a surveillance capsule and the RPV wall with a heavy reflector or standard (water) reflector for high energy and lower energy neutrons

	Neutron energy	Capsule 1	RPV wall
Heavy reflector + EPR basket	E> 1MeV	26.7%	69.5%
	E< 1MeV	73.3%	30.5%
Water reflector + conventional basket	E> 1MeV	51.3%	72.1%
	E< 1MeV	48.6%	27.8%

Data derived from Ref. 18.

36 It is usual to design surveillance schemes so that the damage occurring at the specimen locations leads that occurring in the RPV wall. The ratio of the two neutron doses is normally referred to as the Anticipation Factor. The values of Anticipation Factor predicted using either dpa or fluence for the capsules and the RPV wall are very similar for a water reflector; however the heavy reflector virtually doubles the Anticipation Factor for the capsules when using dpa, as shown in the table below for Capsule 1.

Comparison of Anticipation Factors using dpa or flux (fluence) for a surveillance capsule and the RPV wall with a heavy reflector or standard (water) reflector.

	Dpa Anticipation Factor Capsule 1/RPV wall	Flux (fluence) Anticipation Factor Capsule 1/RPV wall
Heavy Reflector	4.00	2.01
Water Reflector	2.33	1.98

Data derived from Refs 15 and 18

37 Because of the effect of the heavy reflector on both the dpa rate and the Anticipation Factors at the surveillance specimens compared with the RPV wall, I concluded that dpa analysis should be taken into account when designing the surveillance scheme and interpreting the results. I note that even the highest Anticipation Factor predicted using dpa is within the range (<5) allowed by the ASTM Standard E185 (Ref. 28), so that the dose-damage relationship should still be within its limits of validity.

38 Notwithstanding the differences in neutron spectrum between the surveillance specimens and the RPV wall, Ref 15 suggested that high energy fluence rather than dpa was still intended to be used as the dose parameter. Consequently I arranged a TSC review by NNL, to provide an independent specialist opinion on the approach proposed by EDF and AREVA.

39 Since the NNL assessment (Ref 16) supported my view, I informed EDF and AREVA that I was not convinced by the arguments and evidence provided. I was not convinced it would be valid to relate damage measured in the surveillance capsules to damage predicted in the RPV wall using an approach based solely on high energy neutrons (E>1MeV).

40 On 4 April 2011 EDF and AREVA presented a new argument that the shift in DBTT is not reliably predicted using a dpa approach and also claimed that damage to the RPV wall and to the surveillance specimens is dominated by high energy neutrons (Ref. 17).

41 Since there was little time to progress this matter further during GDA Step 4, I made the judgement that I was able to support an IDAC because I had sufficient confidence that an adequate surveillance scheme could be designed and implemented. However I raised GDA Issue **GI-UKEPR-SI-02** (Ref. 5) to enable the matter to be investigated more thoroughly during the close-out of GDA and the activities defined in **GI-UKEPR-SI-02** would need to be satisfactorily completed before I could support a full DAC.

3.2 Assessment of GI-UKEPR-SI-02 undertaken during GDA Close-out

3.2.1 Scope

42 I based my assessment on those items specified in GDA Issue **GI-UKEPR-SI-02** Action 1:

- Revision of the principles of the surveillance scheme to take account of the implications of the difference in neutron energy spectra between the location of the specimens and the RPV wall;
- Justification of the revised principles and explanation of any implications for the typical withdrawal schemes.

43 I performed this assessment in accordance with the ONR HOW2 document 'Permissioning - Purpose and Scope of Permissioning', PI/FWD Issue 3 (Ref. 1) and because of the specialist nature of the evidence I again arranged for NNL to provide specialist consultancy to support my own assessment.

44 My initial assessment focussed on the four Deliverables which EDF and AREVA originally committed to supply in response to this GDA Issue, as detailed within their Resolution Plan (Ref. 6). These are listed below: the first is a report by AREVA, two are published conference papers, and one is a report by CEA, the French Atomic Energy Commission. After ONR assessment of these deliverables, further discussions and written feedback from ONR, EDF and AREVA agreed to provide a further deliverable (No. 5) in the table below.

3.2.2 Deliverables for Action 1

Deliverable No.	Original plan (O) or revised proposal (R)	Deliverable	Ref.
1	O	HSE Feedback about the potential implications of DORT and MCNP calculations – RP position concerning ISP anticipation factor and dpa issue. AREVA NP. Report PEEM-F 11.0642A. 3 May 2011.	18
2	O	Neutron Spectrum Effect and damage analysis on pressure vessel steel irradiation behaviour. C Pichon et al. Effects of Radiation on Materials 19th ASTM Symposium 1998.	19
3	O	Simulation of irradiation effects in light water reactor vessel steels. S Jumel & JC Van Dyusen. Journal of Nuclear Materials 366 (2007) 256 – 265.	20
4	O	Influence of neutron spectra on the embrittlement of RPV steels - ESTEREL Programme Final Report. CEA report DRE-SRO-SIEN 95-123. 25 April 1996.	21
5	R	RPV Irradiation Surveillance Programme (ISP)- Design Principles for UK EPR™. EDF SA Report Ref. H-T27-2012-00181-EN, 17 February 2012.	22

3.2.2.1 Deliverable 1

45 This report describes the principles of the surveillance scheme and the impact of the heavy reflector on the differences of neutron spectrum between the surveillance capsules and the RPV. Based on the results of the ESTEREL Programme, the report examines the effect of lower energy neutrons (E<1MeV) and their impact and concludes that fluence

rather than dpa is the more appropriate parameter for monitoring the EPR™ Irradiation Surveillance Programme. The report also discusses the different designs of the baskets holding the surveillance capsules in the EPR™ and conventional PWRs.

3.2.2.2 Deliverable 2

46 This conference paper provides an overview of the French experimental programme, ESTEREL, to investigate the potential neutron spectrum effect between surveillance specimens and the RPV wall of standard PWRs. It concludes that fluence (E>1MeV) is the most appropriate exposure parameter.

3.2.2.3 Deliverable 3

47 This published paper explains the theoretical models developed to simulate irradiation effects on materials and the comparison of these predictions with the results of the French experimental programme. These analyses are used to quantify the neutron effect between surveillance specimens and reactor vessel materials and the paper concludes that fluence is a more appropriate parameter than dpa for assessing the surveillance scheme results (for the standard PWRs in France).

3.2.2.4 Deliverable 4

48 This report presents the experimental work which was carried out in the SILOE and ORISIS experimental reactors to determine the best irradiation damage correlation with fluence E>1MeV, fluence E>0.1MeV or dpa using specimens from two welded mock-ups made from RPV steel with two different residual element contents. The report also includes the interpretation of experimental test results and analysis to derive the relative contributions of different neutron energies and to establish a dose-damage correlation. The report concludes that fluence best accounts for the data set generated by the ESTEREL programme and that dpa overestimates the role of lower energy (epithermal) neutrons on irradiation embrittlement.

3.2.2.5 Deliverable 5

49 This additional deliverable was prepared in response to ONR feedback on earlier deliverables and describes a revised approach to predicting embrittlement of the RPV wall which includes dpa as an alternative to fluence as the dose parameter. This report describes how EDF and AREVA propose to:

1. establish a dose-damage correlation using dpa as dose parameter;
2. provide a comparison of fluence and dpa indexations on surveillance scheme predictions including their impact on the withdrawal scheme;
3. provide an example of a flexible withdrawal scheme using dpa as the dose parameter.

50 This report contains a conclusion which contrasts with the four earlier deliverables. It concludes that there is “strong theoretical and practical evidence supporting the superiority of dpa over fluence as an ageing index in situations of marked spectrum variations.”

3.3 ONR Assessment of GI-UKEPR-SI-02 – Original Deliverables

51 EDF and AREVA supplied report PEEM-F 11.0642 (Ref. 18) with two supporting references on 6 May 2011. This was provided to address the concerns of ONR and to

justify the proposal to base the surveillance scheme on fluence of high energy neutrons (E>1MeV) rather than dpa.

52 Although there was insufficient time for formal assessment of the new information including a specialist review, I undertook a high level review and provided informal feedback to EDF and AREVA on 12 May 2011 to aid the production of their Resolution Plan for GDA Issue **GI-UKEPR-SI-02**.

53 My high level review of Ref. 18 identified three key arguments.

1. The neutron energy spectrum generated at the EPR™ RPV inner wall with a heavy reflector in place is similar to that of the operating RPV fleet with a standard reflector. Hence the use of the RCC-M dose-damage correlation remains valid for the EPR™ RPV wall.

2. Experimental data are quoted as evidence that the shift in ductile to brittle transition temperature (DBTT) is dominated by high energy neutrons and the contribution of lower energy (epithermal) neutrons is small. Hence the EPR™ surveillance scheme should only introduce a small (6^0C), conservative error.

3. Experimental data are quoted as evidence that there is little correlation between DBTT shifts and dpa rate calculations. Consequently use of a surveillance scheme based on high energy neutrons (E>1MeV) is argued to be the most appropriate.

54 My opinion was that Argument 1 was not new and had already been accepted by ONR. However I considered that Arguments 2 and 3 were new and would require a full assessment, supported by a specialist review of the evidence.

55 As part of my assessment for GDA Issue SI-02, I arranged for a specialist review by NNL (Ref. 23) to review the basis for the EDF/AREVA approach. This review considered whether the data from the ESTEREL programme support:

1. The sole use of neutron flux or fluence as an indexing parameter in the UK EPR™ surveillance programme.

2. The deduction that damage from lower energy (epithermal) neutrons (0.1<E<1MeV) does not contribute significantly to the total embrittlement, i.e. the observed embrittlement is dominated by the damage created by neutrons with energy > 1MeV.

56 NNL concluded, on the basis of the reports supplied by EDF and AREVA, that the data from the ESTEREL program are not sufficient to rule out dpa as an exposure unit. On the basis of international understanding of irradiation embrittlement, NNL believe that dpa is preferred to units such as neutron fluence (E> 1MeV) when data have to be correlated from locations with different neutron spectra.

57 In addition, NNL did not agree with the deduction that the observed embrittlement is dominated by damage created by neutrons with energy > 1MeV. They considered that such a deduction is not warranted because of the limited dataset (four data points), the uncertainties associated with these data (which have not been taken into account), and the fact that mechanistically such a deduction is not consistent with international understanding of irradiation embrittlement.

58 Finally, NNL considered that fluence Anticipation Factors should be treated with caution whether they are based directly on high energy fluence (E>1MeV) or enhanced on the basis of an analysis of the ESTEREL data to make an allowance for the embrittlement from lower energy (epithermal) neutrons in EPR™ capsules.

59 I agreed with NNL's conclusions and raised TQ-UKEPR-1489 (Ref. 14) in which I listed the two key arguments which rely on experimental data derived during the ESTEREL programme:

1. Experimental data are quoted as evidence that the shift in ductile to brittle transition temperature (DBTT) for the EPR™ surveillance specimens will be dominated by high energy neutrons and the contribution of epithermal neutrons will be small. Hence the EPR™ surveillance scheme should only introduce a small (6^0C), conservative error.

2. Experimental data are quoted as evidence that there is little correlation between DBTT shifts and dpa rate calculations. Consequently use of a surveillance scheme based only on high energy neutrons (E>1MeV) is argued to be the most appropriate.

60 I explained that my concerns about these arguments were based on:

1. the small number of measurements of embrittlement on which the arguments are based;

2. the lack of consideration of the significant uncertainties associated with the experimental measurements and the assumptions implicit in the analysis of the results;

3. the apparent inconsistency between the arguments and the generally accepted international understanding of irradiation embrittlement.

61 A meeting was held on 13 October 2011 to discuss the different understandings of the reliability of dpa and fluence as dose parameters for the EPR™ surveillance scheme. NNL supported ONR at the meeting which resulted in EDF and AREVA agreeing to produce a revised proposal.

62 After the meeting ONR wrote to EDF and AREVA to confirm the common ground which had been established amongst the participants and to clarify what had been agreed (Ref. 24). ONR understood that EDF and AREVA had accepted that their original claims based on the results of the ESTEREL programme needed to be revised. ONR also believed that EDF and AREVA had accepted the international consensus that embrittlement of RPV steels is caused by neutrons of all energies (above a low threshold) and that dpa is an appropriate parameter to analyse situations where the neutron spectra are varying.

63 EDF and AREVA responded to TQ-UKEPR-1489 on 19 December 2011 (Ref. 14), and conceded that the ESTEREL data were not sufficient to demonstrate conclusively whether fluence (E> 1MeV) or dpa were more appropriate to interpret the experimental results. The response also conceded that their interpretation of the ESTEREL experimental results might be challenged and that there were reasons why dpa might be a better indexation parameter.

64 A further technical meeting was held on 6 January 2012 at which EDF and AREVA presented a revised approach to the surveillance scheme which included an analysis based on dpa. This is discussed in the next section.

3.4 ONR Assessment of GI-UKEPR-SI-02 – New Deliverable 5

65 EDF and AREVA have now developed a revised approach to the surveillance scheme, which was confirmed by letter on 2 February 2012 (Ref. 25), and was subsequently documented in a report, Deliverable 5 (Ref. 22). The approach comprises:

- Derivation of a tentative dose-damage correlation based on dpa as the dose parameter to take account of the differences in neutron spectrum between the EPR™ surveillance specimen location and the RPV wall.
- Analyses of the advantages and disadvantages of fluence and dpa indexations, in terms of both analysis of surveillance results and the withdrawal scheme, given the low end-of-life fluence for EPR™.
- An example of a flexible withdrawal scheme including dpa as the dose parameter.

66 The latest approach adopted towards the indexation parameter no longer relies on data from the ESTEREL programme which removes one of my key concerns about the earlier proposals.

67 From my perspective, one of the most significant conclusions in the report (Ref. 22) is:

- There is strong theoretical and practical evidence supporting the superiority of dpa over fluence as an ageing index in situations of marked spectrum variations.

This demonstrates that EDF and AREVA have now accepted the international consensus of the relative merits of dpa and fluence for such situations.

68 The report makes clear that in western countries the vessel surveillance programmes of standard PWRs normally use neutron fluence (E>1MeV). However it notes that fast neutron fluence is restricted to vessel ageing assessment of light water reactors and that dpa is a more generally applicable dose parameter.

69 According to Ref. 22, the widespread use of fluence for standard light water reactor surveillance programmes is based on:

1. The large number of displacements caused by high energy neutrons;
2. The similarity of spectra from one reactor to another;
3. The similarity of spectra at the locations of capsules and the RPV wall;
4. Fast fluence can be quantified more easily and accurately than dpa.

70 Ref. 22 also notes that fluence indexation induces a slight conservatism for application to standard PWR RPV walls, if embrittlement is 100% controlled by dpa, because of the higher mean dpa rate predicted at the capsules location compared to the vessel inner surface.

71 EDF and AREVA now propose to modify their latest embrittlement correlation given in the RSE-M in-service inspection code (Ref. 27) using three steps:

1. Selection of data relevant to the EPR™;
2. Definition of a mean dpa cross-section;
3. Transformation of the embrittlement correlation equation.

72 The current RSE-M embrittlement correlation based on neutron fluence (E>1MeV) is supported by a database of 495 surveillance data points for 900MW(e) reactors as well as 65 data points from materials test reactors with broadly comparable conditions.

73 Since full recalibration of the embrittlement correlation has not yet been considered, the analyses presented are based on either:

- Method 1: A single average value of dpa/fluence
- Method 2: Partial recalibration of the correlation by adjusting the numerical constant in the equation so as to achieve the best fit with the data.

74 Preliminary estimates for shift in DBTT after 60 years operation are 29^{0}C using fluence for indexation (as stipulated for the RSE-M correlation) and 19^{0}C using the tentative dpa correlation. These estimates are consistent with the anticipation factor (dose ratio) for the EPR™ surveillance specimens based on dpa being approximately twice the value derived using neutron fluence, as discussed in Section 3.1 above.

75 EDF and AREVA argue that the use of fluence indexation is more conservative than using dpa and that end-of-life doses are sufficiently low that fluence predictions could still be used to interpret the damage measured in the surveillance samples. For example, they predict that if fluence is used for indexation but the actual damage is consistent with dpa predictions, the probability of measuring a shift exceeding the mean + two standard deviations (mean + 2σ) only reaches 0.07 at 60 years. However I have pointed out that this conclusion reflects the large value of σ (approx 13^{0}C) and that a closer analysis of the DBTT shift measured compared with the predicted trend would be expected from a licensee.

76 EDF and AREVA conclude that fluence indexation could be acceptable given the low doses and embrittlement levels expected in the EPR™ RPV, but further consideration of the spectrum effect has led them to integrate dpa in the design and interpretation of the irradiation surveillance programme. I consider this use of dpa to be appropriate, although I recognise that a more refined indexation parameter might be developed in future.

77 The proposed capsule withdrawal scheme is based on four capsules being inserted at the start of reactor operation and withdrawn after 4.5, 7.5, 12 and 15 years operation. Using dpa indexation, 15 years in the reactor represents 66 years of vessel operation whereas with fluence indexation, 15 years in the reactor represents 34.5 years of vessel operation.

78 New capsules are proposed to be inserted in locations 2 and 1 after 7.5 and 15 years respectively and will be withdrawn after 30 and 49.5 years operation respectively. These additional capsules would extend the duration of the surveillance up to a level of irradiation equivalent to 60 years RPV irradiation using fluence (E>1MeV) or equivalent to 120 years of RPV irradiation using dpa indexation.

79 I believe this outline withdrawal scheme is appropriate because it provides for capsules to be withdrawn from the reactor progressively over most of the planned operating life, and it is possible to interpret the results on the basis of dpa analysis as well as using neutron fluence.

80 I arranged a specialist review by NNL to cover the revised proposals in Ref. 22. NNL supported the revised approach to the indexation parameter to be employed in the UK EPR™ surveillance scheme (Ref. 26) because EDF and AREVA acknowledge the value of dpa in situations where data have to be correlated between locations with differing neutron energy spectra.

81 NNL also supported the outline design of the surveillance withdrawal scheme which meets the requirements for use of dpa as an indexation parameter and also ensures that the reactor has a surveillance capsule in-situ throughout the majority of the 60 year design life.

82 On the basis of my assessment and the clear support from NNL, I consider that EDF and AREVA have defined an acceptable set of principles for the surveillance scheme including the analysis of the results and that the GDA Issue may be closed. I am content that detailed implementation of the surveillance scheme may be left to the licensing phase.

83 Any Licensee will need to develop a detailed RPV surveillance programme which takes account of the differences in neutron energy spectra between the RPV wall and the

location of the surveillance capsules and I have created an Assessment Finding to this effect.

> ***AF-UKEPR-SI-42:*** *The licensee shall develop an in-service surveillance scheme which takes account of the differences in neutron energy spectra between the RPV wall and the location of the surveillance capsules.*
>
> ***Required timescale****: Install RPV.*

4 REVIEW OF THE UPDATE TO THE PCSR

84 The 2012 update of the PCSR contains important changes and additions in Sub-Chapter 5.3 Section 7.4 entitled ‘Material Irradiation Monitoring’. The latest version now recognises that due to the presence of the heavy reflector, the neutron energy spectrum is “not strictly equivalent” between the locations of the surveillance specimens and the RPV wall. It also specifies that the differences in neutron spectrum (as well as flux) between the two locations will be taken into account in the analysis of the surveillance specimen data. Furthermore, the schedule for removal of surveillance capsules will account for differences in spectrum by considering dpa as well as (high energy) neutron fluence as the dose parameter.

85 In the light of these changes, I believe that the updated PCSR now provides an acceptable definition of the principles of the RPV surveillance programme for this stage in the development of the safety case.

5 ASSESSMENT FINDING

86 I conclude that the following Assessment Finding, also listed in Annex 1, should be programmed during the forward programme of this reactor as normal regulatory business, in addition to those identified in the Step 4 Structural Integrity Assessment Report (Ref. 4).

> ***AF-UKEPR-SI-42:*** *The licensee shall develop an in-service surveillance scheme which takes account of the differences in neutron energy spectra between the RPV wall and the location of the surveillance capsules.*
>
> ***Required timescale****: Install RPV.*

87 There are no impacted Step 4 Assessment Findings.

6 CONCLUSIONS

88 I was not convinced by the arguments initially provided by EDF and AREVA in attempting to address this Issue, primarily because of the reliance on an experimental programme involving only a very small number of measurements.

89 Subsequently EDF and AREVA proposed a revised approach which comprises:

- Derivation of a tentative dose-damage correlation based on dpa as the dose parameter to take account of the differences in neutron spectrum between the EPR™ surveillance specimen location and the RPV wall.
- Analyses of the advantages and disadvantages of fluence and dpa indexations.
- An example of a flexible withdrawal scheme using dpa as the dose parameter

90 Having assessed this revised approach, I judge that EDF and AREVA have now developed an adequate definition of the surveillance programme and withdrawal scheme for this stage of the safety case development and the GDA Issue may now be closed. The detailed implementation of the scheme and the analysis of results may now be left to the licensing phase.

91 Any Licensee will need to develop a detailed RPV surveillance programme which takes account of the differences in neutron energy spectra between the RPV wall and the location of the surveillance capsules and I have created an Assessment Finding to this effect (**AF-UKEPR-SI-42**).

7 REFERENCES

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Table 1

Relevant Safety Assessment Principles Considered for Close-out of GI-UKEPR-SI-02 Rev 1

SAP No.	SAP Title	Description
EMC.1	Integrity of metal components and structures: highest reliability components and structures. Safety case and assessment	The safety case should be especially robust and the corresponding assessment suitably demanding, in order that an engineering judgement can be made for two key requirements: the metal component or structure should be as defect-free as possible; The metal component or structure should be tolerant of defects.
EMC.2	Integrity of metal components and structures: highest reliability components and structures. Use of scientific and technical issues	The safety case and its assessment should include a comprehensive examination of relevant scientific and technical issues, taking account of precedent when available.
EMC.3	Integrity of metal components and structures: highest reliability components and structures: Evidence	Evidence should be provided to demonstrate that the necessary level of integrity has been achieved for the most demanding situations.
EMC.4	Integrity of metal components and structures: general. Procedural control	Design, manufacture and installation activities should be subject to procedural control.
EAD.1	Ageing and degradation. Safe working life	The safe working life of structures, systems and components that are important to safety should be evaluated and defined at the design stage.
EAD.2	Ageing and degradation. Lifetime margins	Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components that are important to safety.
EAD.3	Ageing and degradation. Periodic measurement of material properties	Where material properties could change with time and affect safety, provision should be made for periodic measurement of the properties.
EAD.4	Ageing and degradation. Periodic measurement of parameters	Where parameters relevant to the design of plant could change with time and affect safety, provision should be made for their periodic measurement.
EMC.11	Integrity of metal components and structures: design. Failure modes	Failure modes should be gradual and predictable.

Table 1

Relevant Safety Assessment Principles Considered for Close-out of GI-UKEPR-SI-02 Rev 1

SAP No.	SAP Title	Description
EMC.12	Integrity of metal components and structures: design. Brittle behaviour	Designs in which components of a metal pressure boundary could exhibit brittle behaviour should be avoided.
EMC.13	Integrity of metal components and structures: manufacture and installation. Materials	Materials employed in manufacture and installation should be shown to be suitable for the purpose of enabling an adequate design to be manufactured, operated, examined and maintained throughout the life of the facility.
EMC.17	Integrity of metal components and structures: manufacture and installation. Examination during manufacture	Provision should be made for examination during manufacture and installation to demonstrate the required standard of workmanship has been achieved.
EMC.21	Integrity of metal components and structures: operation. Safe operating envelope	Throughout their operating life, safety-related components and structures should be operated and controlled within defined limits consistent with the safe operating envelope defined in the safety case.
EMC.23	Integrity of metal components and structures: operation. Ductile behaviour	For metal pressure vessels and circuits, particularly ferritic steel items, the operating regime should ensure that they display ductile behaviour when significantly stressed.
EMC.24	Integrity of metal components and structures: monitoring. Operation	Facility operations should be monitored and recorded to demonstrate compliance with the operating limits and to allow review against the safe operating envelope defined in the safety case.

Annex 1

Technical Queries Raised During GDA Close-Out of GI-UKEPR-SI-02 Rev 1

TQ Reference	GDA Issue Action	Related Submission	Description
TQ-UKEPR-1489	GI-UKEPR-SI-02	PEEM-F 11.0642A	RPV Surveillance Scheme – effect of neutron spectrum. 23 September 2011

Annex 2

GDA Assessment Findings Arising from GDA Close-out of GI-UKEPR-SI-02 Rev 1

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-SI-42	The licensee shall develop an in-service surveillance scheme which takes account of the differences in neutron energy spectra between the RPV wall and the location of the surveillance capsules.	Install RPV

Note: It is the responsibility of the Licensees / Operators to have adequate arrangements to address the Assessment Findings. Future Licensees / Operators can adopt alternative means to those indicated in the findings which give an equivalent level of safety.
For Assessment Findings relevant to the operational phase of the reactor, the Licensees / Operators must adequately address the findings during the operational phase. For other Assessment Findings, it is the regulators' expectation that the findings are adequately addressed no later than the milestones indicated above.

Annex 3

GDA Issue, **GI-UKEPR-SI-02 Rev 1** – *Structural integrity* – UK EPR™

Technical Area	STRUCTURAL INTEGRITY		
Related Technical Areas	None		
GDA Issue Reference	**GI-UKEPR-SI-02**	**GDA Issue Action Reference**	**GI-UKEPR-SI-02**.A1
GDA Issue	RPV Surveillance Scheme – Implications of Change in Neutron Energy Spectrum Caused by the Heavy Reflector. Demonstration that the principles of the surveillance scheme adequately take account of the implications of the difference in neutron energy spectra between the location of the specimens and the RPV wall.		
GDA Issue Action	Demonstration that the principles of the surveillance scheme adequately take account of the implications of the differences in neutron energy spectra between the location of the specimens and the RPV wall. This is expected to include the following activities: • Provision of evidence showing that the principles of the surveillance scheme adequately take account of the implications of the differences in neutron energy spectra between the location of the specimens and the RPV wall; • Justification of the concepts inherent in the analysis and interpretation of the surveillance scheme results including the treatment of uncertainties and consideration of any implications for the withdrawal scheme; • Adequate responses to questions arising from ONR assessment of documents submitted as a result of this Action. With agreement from the Regulator this action may be completed by alternative means.		