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-FS-01 Revision 0 – Heterogeneous Boron Dilution Safety Case

Assessment Report: ONR-GDA-AR-12-010
Revision 0
March 2013

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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 Fault Studies design basis analyses. This report specifically addresses the GDA Issue **GI-UKEPR-FS-01** Revision 0 generated as a result of the GDA Step 4 Fault Studies Assessment of the UK EPR™. The assessment has focused on the deliverables identified within the EDF and AREVA Resolution Plan published in response to the GDA Issue.

During the GDA assessment it became apparent that EDF and AREVA had not provided a comprehensive safety case for heterogeneous boron dilution faults within the Pre-Construction Safety Report (PCSR). No design basis analysis was presented for external dilution within the PCSR and no safety case was presented for inherent dilution faults. For this reason, **GI-UKEPR-FS-01** was raised requiring EDF and AREVA to provide such cases.

In response to GDA Issue **GI-UKEPR-FS-01**, EDF and AREVA produced a revised safety case for external heterogeneous boron dilution faults including significant changes to the design of the UK EPR™ protection system as well as changes in the plant operating procedures. For inherent heterogeneous boron dilution faults, EDF and AREVA have presented a new safety case.

My assessment has focused on:

- The design basis safety case for both external and inherent heterogeneous boron dilution faults for the UK EPR™. In the case of external dilution faults, I have focused on the grouping of the initiating events, the robustness of the proposed new interlock protection systems and the quality of the As Low As Reasonably Practicable (ALARP) review. In the case of inherent boron dilution fault, I have focused on the balance of the technical arguments used to underpin the safety case.
- The design of the thermal hydraulic test rigs used to support the validation of the Computational Fluid Dynamics (CFD) model applied in both the external and inherent boron dilution safety cases. In addition to assessing the validation evidence provided by EDF and AREVA, independent confirmatory analysis has been commissioned from a technical support contractor using alternative computer codes and analysts. This work, which is valuable for reaching judgements on the adequacy of the codes and analysis of EDF and AREVA, is summarised in this report.

In some areas there has been a lack of detailed information which has limited the extent of my assessment. As a result, the Office for Nuclear Regulation (ONR) will need additional information to underpin my judgements and conclusions and these are identified in eleven Assessment Findings to be carried forward into the site specific detailed design phase. These are listed in Annex 2.

From my assessment, I have concluded that:

EDF and AREVA have undertaken a large amount of analysis work within the Fault Studies assessment area during the close-out phase of GDA and made significant progress against the GDA Issue **GI-UKEPR-FS-01** on heterogeneous boron dilution faults identified in my GDA Step 4 assessment report.

In my opinion, EDF and AREVA have considerably strengthened the design basis safety against heterogeneous boron dilution faults for the UK EPR™ through the additional safety case information and new analysis performed in response to GDA Issue **GI-UKEPR-FS-01**. This has included a rationalisation of the postulated initiating events leading to an external heterogeneous

boron dilution fault which has helped to focus the comprehensive review of potential ALARP improvements. In addition, they have developed a completely new safety case for the inherent heterogeneous boron dilution fault.

The analytical work performed by EDF and AREVA has been aided by a number of important design changes to the Control and Instrumentation (C&I) systems on the UK EPR™ and also by some important changes in operating procedures that in my opinion will significantly improve safety of the design. These changes have been proactively identified by EDF and AREVA. The changes identified are:

- A Class 1 interlock is to be implemented to prevent the operator from restarting Reactor Coolant Pump (RCP) n°1 if the Chemical and Volume Control System (CVCS) letdown has not run sufficiently to purge loop 1.
- A Class 1 interlock is to be implemented to prevent the operator from restarting the other RCP pumps until RCP n°1 has first been restarted.
- A modification will be implemented to automatically isolate the heat exchangers used to cool the mechanical seals on the Residual Heat Removal System (RHRS) pump when the pump is not in operation.
- Procedures will be revised such that, when the reactor is depressurised, the operator is required to close the containment isolation valves on the Component Cooling Water System (CCWS) lines that cool the High Pressure (HP) cooler on the CVCS letdown line.
- Procedures will be revised such that, when the reactor is depressurised and the RCPs are not in operation, the operator is required to close the containment isolation valves on the CCWS lines that cool the RCP thermal barriers.

Although there are a number of Assessment Findings, these are mostly associated with the C&I interlock systems or providing additional evidence to validate claims made in the safety case. In my judgement, it is unlikely that these will result in design changes that affect plant layout, mechanical equipment design or operational procedures.

Overall, based on my assessment undertaken in accordance with ONR procedures, I am satisfied that the safety case for heterogeneous boron dilution faults presented in the supporting documentation submitted in response to GDA Issue **GI-UKEPR-FS-01** is adequate subject to satisfactory progression and resolution of the Assessment Findings identified in Annex 2. These are to be addressed during the site specific detailed design phase. For this reason, I am satisfied that GDA issue **GI-UKEPR-FS-01** can now be closed.

LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
C&I	Control and Instrumentation
CCWS	Component Cooling Water System
CFD	Computational Fluid Dynamics
CMF	Change Modification Form
CVCS	Chemical Volume and Control System
DNB	Departure from Nucleate Boiling
EBS	Emergency Boration System
EDF and AREVA	Electricité de France SA and AREVA NP SAS
GDA	Generic Design Assessment
GRS	Gesellschaft für Anlagen und Reaktorsicherhiet mbH
HHSI	High Head Safety Injection
HP	High Pressure
HSE	Health and Safety Executive
IRWST	In-containment Refuelling Water Storage Tank
LHSI	Low Head Safety Injection
LP	Low Pressure
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
MHSI	Medium Head Safety Injection
MOX	Mixed Oxide Fuel
NSS	Nuclear Sampling Systems
ONR	Office for Nuclear Regulation (an agency of HSE)
PCC	Plant Condition Category
PCSR	Pre-Construction Safety Report
PIRT	Phenomenon Identification and Ranking Technique
PKL	Primaer KreisLauf
PS	Protection System
PSA	Probabilistic Safety Analysis
PWR	Pressurised Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System

LIST OF ABBREVIATIONS

SAP	Safety Assessment Principle(s) (HSE)
SAS	Safety Automation System
SBLOCA	Small Break Loss of Coolant Accident
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SIS	Safety Injection System
TAG	Technical Assessment Guide(s) (ONR)
TQ	Technical Query
TSC	Technical Support Contractor

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1 INTRODUCTION

1.1 Background

1 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 Fault Studies design basis analyses. This report specifically addresses the GDA Issue **GI-UKEPR-FS-01** Revision 0 and its associated Action (Ref. 1) generated as a result of the GDA Step 4 Fault Studies Assessment of the UK EPR™ (Ref. 2). The assessment has focused on the deliverables identified within the EDF and AREVA Resolution Plan (Ref. 3) published in response to the GDA Issue.

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 Fault Studies Assessment identified five GDA Issues and a number of Assessment Findings as part of the assessment of the evidence associated with the UK EPR™ reactor design. A GDA Issue is an observation of particular significance that requires resolution before the Office for Nuclear Regulation (ONR), an agency of HSE, would agree to the commencement of nuclear safety related construction of the UK EPR™ within the UK. An Assessment Finding results from a lack of detailed information which has limited the extent of assessment and as a result the information is required to underpin the assessment. However, they are to be carried forward as part of normal regulatory business.

4 During the GDA Step 4 assessment it became apparent that EDF and AREVA had not provided a comprehensive safety case for heterogeneous boron dilution faults within the PCSR. No design basis analysis was presented for external dilution within the PCSR and no safety case was presented for inherent dilution faults. For this reason, **GI-UKEPR-FS-01** was raised requiring EDF and AREVA to provide such cases.

5 The aim of this assessment is to provide a comprehensive assessment of the submissions provided in response to GDA Issue **GI-UKEPR-FS-01** to enable ONR to gain confidence that the concerns raised have been resolved sufficiently so that the issue can either be closed or lesser safety significant aspects be carried forward as Assessment Findings.

1.2 Scope of Assessment

6 The scope of this assessment differs from that adopted for the previous reports produced within GDA, most notably the Step 4 Fault Studies Assessment. This report specifically presents the assessment of an individual GDA Issue rather than a report detailing close-out of all five GDA Issues associated with the technical area of Fault Studies.

7 The reasoning behind adopting this approach 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.

8 Further to the assessment work undertaken during Step 4 (Ref. 2), and the resulting GDA Issue **GI-UKEPR-FS-01** (Ref. 1), this assessment focuses on the design basis safety case for both external and inherent heterogeneous boron dilution faults for the UK EPR™. In the case of external dilution faults, I have focused on the grouping of the initiating events, the robustness of the proposed interlock protection systems and the quality of the

ALARP review. In the case of inherent boron dilution fault, I have focused on the balance of the technical arguments used to underpin the safety case.

9 The assessment has also focused upon the design of the thermal hydraulic test rigs used to support the validation of the CFD model that has been applied in both the external and inherent boron dilution safety cases. In addition to assessing the validation evidence provided by EDF and AREVA, ONR commissioned independent confirmatory analysis from a technical support contractor (TSC) using alternative computer codes and analysts. This work, which is valuable for reaching judgements on the adequacy of the codes and analysis of EDF and AREVA, is summarised in this report (Ref. 4).

10 The purpose of this assessment is to consider whether the deliverables provided in response to the GDA Issue, **GI-UKEPR-FS-01**, and the associated GDA Issue Action, provide an adequate response sufficient to justify closure of the issue. The GDA Issue and its action are detailed within Annex 3 of this report. As such, this report presents only the assessment undertaken as part of the resolution of this GDA Issue and it is recommended that this report be read in conjunction with the Step 4 Fault Studies Assessment of the EDF and AREVA UK EPR™ in order to appreciate the totality of the assessment of evidence undertaken as part of the GDA process.

11 Specifically, 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 will 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.

12 The possibility of further Assessment Findings being generated as a result of this assessment is not precluded given that resolution of the GDA Issues may identify areas where further detailed evidence will be required when the information becomes available at a later stage of the design process.

1.3 Assessment Methodology

13 The methodology applied to this assessment is identical to the approach taken during Step 4 and follows ONR guidance and procedures (Ref. 5).

14 This assessment has focused 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.

1.4 Structure of Report

15 The structure of the report is as follows. In Section 2, the strategy adopted for this Fault Studies assessment is set out. In Section 3, the deliverables provided by EDF and AREVA in response to the GDA Issue as detailed within their resolution Plan (Ref. 3) are briefly summarised. My assessment of EDF and AREVA safety case for heterogeneous boron dilution faults is presented in Section 4. The conclusions of this Fault Studies assessment are presented in Section 5. Section 6 lists the Assessment Findings.

2 ONR'S ASSESSMENT STRATEGY FOR THE HETEROGENEOUS BORON DILUTION FAULT SAFETY CASE

2.1 Assessment Plan

16 The intended assessment strategy for GDA Close-out of the Fault Studies topic area was set out in an assessment plan (Ref. 6). The assessment plan, which is based upon the GDA issues from the GDA Step 4 Assessment Report (Ref. 2), identifies the intended scope of the assessment and the standards and criteria that would be applied. The assessment strategy is summarised in the following sub-sections:

2.2 Standards and Criteria

17 Judgements have been made against the 2006 HSE Safety Assessment Principles (SAP) for Nuclear Facilities (Ref. 7). In particular, the fault analysis and design basis accident SAPs (FA.1 to FA.9), the severe accident SAPs (FA.15 to FA.16), the assurance of validity SAPs (FA.17 to FA.22), the numerical target SAPs (NT.1, Target 4, Target 7 to Target 9) and the engineering principles SAPs (EKP.2, EKP.3, EKP.5, EDR.1 to EDR.4, ESS.1, ESS.2, ESS.7 to ESS.9, ESS.11, ERC.1 to ERC.3) have been considered. In addition, the following Technical Assessment Guides (TAG) have been used as part of this assessment (Ref. 8):

- T/AST/034 – Transient analysis for Design Basis Accidents in Nuclear Reactors.
- T/AST/042 – Validation of Computer Codes and Calculational Methods.

18 EDF and AREVA have assessed the safety case against their own design requirements.

2.3 The Approach to Assessment for GDA Close-out

19 The overall basis for the assessment of the GDA Issue **GI-UKEPR-FS-01** are the Fault Studies elements of the following documents:

- Submissions made to ONR in accordance with the resolution plans.
- The specific updates made to the Submission / Pre-construction Safety Report (PCSR) / Supporting Documentation associated with the Heterogeneous Boron Dilution Safety Case.
- The Design Reference that relates to the Submission / PCSR as set out in UK EPR™ GDA Project Instruction UKEPR-I-002 (Ref. 9) which has been updated throughout GDA Issue resolution to include Change Management Forms (CMF).
- In addition to, and as result of, the assessment of the submissions made in accordance with the resolution plan, a number of Technical Queries (TQ) were issued. The responses made by EDF and AREVA to the TQs (Ref. 10) have been subjected to detailed assessment against the same standards and criteria.

20 The objective of the fault studies assessment has been to assess submissions made by EDF and AREVA in response to the GDA Issue identified through the GDA process and the design changes proposed by EDF and AREVA and, if judged acceptable, clear the GDA Issue.

2.3.1 Use of Technical Support Contractors

21 ONR has continued to utilise TSCs during the close-out phase of GDA to support the ONR assessment of the UK EPR™. In the fault study area, Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH has been used to undertake independent confirmatory analysis of transient analysis studies performed by EDF and AREVA. Ultimately, it is for

EDF and AREVA to demonstrate the adequacy of their safety case. However, analyses undertaken by independent analysts using a different computer code can provide additional confidence in a safety case if the results obtained are comparable with those of EDF and AREVA.

22 Specifically, GRS has completed a technical assessment of heterogeneous boron dilution faults (Ref. 4) using a Computational Fluid Dynamics (CFD) model of the UK EPR™ reactor vessel. GRS utilised a commercially available code for the CFD analysis that is independent of the code used by EDF and AREVA for their equivalent assessment. The analysis undertaken with the model is discussed further in Sections 4.1.2 and 4.2.2.

2.3.2 Cross-cutting Topics

23 Fault analysis, by its very nature, tends to interface with many of the technical areas associated with a safety case. During Step 4, a number of areas have been identified as “cross-cutting topics”. One of these areas was heterogeneous boron dilution faults. This practice has continued during the close-out of this issue and the assessment work has been co-ordinated with the Probabilistic Safety Analysis (PSA) and Reactor Chemistry topic leads and particularly the Human Factors topic leads (Refs. 11 and 12) who have assessed the pre-accident operator errors that could cause heterogeneous boron dilution faults under GDA Issue **GI-UKEPR-HF-01**.

2.3.3 Out of Scope Items

24 During Step 4 (Ref. 2), a number of items were identified as being outside the scope of GDA. Of these, those that are relevant to the heterogeneous boron dilution fault safety case are the development of suitable Operational Technical Specifications, operation with mixed oxide fuel (MOX) in the reactor and maintenance activities at “¾ loop” during shutdown operations with the fuel still loaded.

3 EDF AND AREVA DELIVERABLES IN RESPONSE TO THE GDA ISSUE

25 The information provided by EDF and AREVA in response to this GDA Issue, as detailed within their Resolution Plan (Ref. 3), was broken down under Action 1 of the GDA Issue into the following specific deliverables for detailed assessment:

GDA Issue Action	Technical Area	Deliverable	Ref.
GI-UKEPR-FS-01.A1	External Boron Dilution Faults	Heterogeneous Boron Dilution Fault Schedule	13
GI-UKEPR-FS-01.A1	External Boron Dilution Faults	Counter Measures against Heterogeneous Dilution Initiators	14
GI-UKEPR-FS-01.A1	Validation Evidence	CFD stimulation of the Juliette Tests - Star CD Physical Validation for external and inherent dilution	15
GI-UKEPR-FS-01.A1	External Boron Dilution Faults	Heterogeneous Boron Dilution resulting from improper Reactor Coolant Pump start-up	16
GI-UKEPR-FS-01.A1	ALARP review for External Boron Dilution Faults	Design Improvements for Heterogeneous Boron Dilution Faults	17
GI-UKEPR-FS-01.A1	Inherent Boron Dilution Faults	Safety Case for Inherent Boron Dilution following LOCA	18
GI-UKEPR-FS-01.A1	PCSR – Chapter 14 PCSR – Chapter 15 PCSR – Chapter 16	Design Basis Analysis Probabilistic Safety Analysis Risk Reduction and SA Analysis	19

26 A brief overview of each of the deliverables is provided within this section. It is important to note that this information is supplementary to the information provided within the November 2009 PCSR (Ref. 20) which has already been subject to detailed assessment during earlier stages of GDA. The deliverables are intended to provide a complete safety case for heterogeneous boron dilution faults on the UK EPR™.

Heterogeneous Boron Dilution Fault Schedule

27 This report (Ref. 13) summarises the dilution scenarios and countermeasures implemented against external heterogeneous boron dilution faults in the format of a fault schedule.

Counter Measures against Heterogeneous Dilution Initiators

28 The purpose of this report (Ref. 14) is to present the scenarios and protections of potential external heterogeneous boron dilution accidents on the EPR™ in situations where all the reactor coolant pumps (RCP) are stopped such that the flow in the reactor coolant circuit is not sufficient to avoid the formation of unborated water slugs in one of the loops should an injection of water occur from a source external to the primary circuit.

CFD simulation of the Juliette Tests – Star CD – Physical Validation for External and Internal Dilution

29 This report (Ref. 15) deals with the physical validation of the STAR-CD CFD code and its associated numerical models which have been used by EDF and AREVA to stimulate boron dilution transients, both for external and inherent dilution phenomena. The validation is based upon the Juliette mock-up test rig which EDF and AREVA claim is representative of the EPR™ reactor vessel geometry at 1/5 scale.

Heterogeneous Boron Dilution resulting from improper Reactor Coolant Pump Start-up

30 This report (Ref. 16) presents the transient analysis studies performed by EDF and AREVA to assess external heterogeneous boron dilution faults.

Design Improvements for Heterogeneous Boron Dilution Faults

31 The aim of this report (Ref. 17) is to study potential design options for improving protection against heterogeneous dilution from an ALARP perspective. A number of important design changes are identified including a new Class 1 interlock which aims to prevent start-up of the RCPs until unborated water slugs have been removed from the Reactor Coolant System (RCS) loops.

Safety Case for the Inherent Boron Dilution following LOCA

32 This report (Ref. 18) presents a complete description of the transient analysis studies performed by EDF and AREVA to assess an inherent boron dilution fault following a loss of coolant accident (LOCA). The calculational procedure is based on the CATHARE 2 thermal-hydraulic systems code supported by experimental results from a number of Primaer KreisLauf (PKL) tests and on the STAR-CD CFD code.

PCSR Updates

33 In addition to the technical reports, EDF and AREVA have also provided updates (Ref. 19) to the March 2011 PCSR (Ref. 21) for Chapter 14 on design basis faults, Chapter 15 on PSA and Chapter 16 on risk reduction and severe accident analysis.

4 ONR ASSESSMENT

34 My assessment against the SAPs of the UK EPR™ heterogeneous boron dilution fault safety case is presented below.

35 The assessment commences in Section 4.1 with an assessment of the safety case for heterogeneous boron dilution faults for the situation where the unborated slug of water is inadvertently introduced into one or more loops of the primary circuit from a reactor auxiliary system that is connected to the primary system; an external heterogeneous boron dilution fault.

36 Section 4.2 presents my assessment of the safety case for heterogeneous boron dilution fault for the situation where the unborated slug of water is created within the primary circuit during the reflux condensation phase of a small break loss of coolant accident (SBLOCA); an inherent heterogeneous boron dilution fault.

37 The assessment concludes in Section 4.3 with a brief review of the updates to those areas of the PCSR concerning heterogeneous boron dilution faults.

38 In some areas there has been a lack of detailed information which has limited the extent of my assessment. As a result, ONR will need additional information to underpin my judgements and conclusions and these are identified as assessment findings to be carried forward as normal regulatory business. These are listed in Annex 2.

4.1 External Heterogeneous Boron Dilution Fault Safety Case

4.1.1 Summary of EDF and AREVA's Safety Case

39 Faults in this category result in the introduction of an unborated slug of water in a loop of the primary circuit of a pressurised water reactor (PWR) while the RCPs are stopped. The concern is that in the case of the RCPs starting-up the unborated slug can be transported into the reactor core resulting in a sudden increase in the reactivity of the core. If the slug is sufficiently large the core can return to criticality with potentially very serious consequences.

40 The basis of the EDF and AREVA safety case (Ref. 19) is that they have reviewed a number of postulated events that they consider to be within the design basis of the plant and that could result in an external heterogeneous boron dilution fault. For each initiating event they claim to have identified a number of countermeasures which either prevent formation of an unborated slug in the first place or ensure that the slug is purged harmlessly out of the loop prior to RCP start-up. Depending upon the particular initiating event, these measures include operational procedures, manual or automatic isolation of potential leak sites, automatic isolation actuated by signals from a boron meter and interlocks which prevent the improper start-up of the RCPs.

41 These arguments are supplemented by experimental rig work and transient analysis studies using CFD methods that aim to demonstrate that the safety margins associated with the determination of critical slug size are adequate.

42 On the basis of arguments presented EDF and AREVA claim that adequate protection is provided for the complete range of faults considered.

4.1.2 Assessment

Fault Sequence Analysis

43 In response to this GDA issue, EDF and AREVA have extensively revised their safety case for external heterogeneous boron dilution faults (Refs 13 to 17) from the one presented in earlier submissions (Ref, 20). The first deliverables (Refs 13 & 14) aiming to identify the various dilution scenarios are similar in scope to the earlier reviews (Ref. 20) although no attempt is made to perform a probabilistic assessment as was performed previously. EDF and AREVA acknowledge in their resolution plan that an update to the PSA will be required during site licensing. Given that SAP FA.1 requires that fault analysis should be carried out comprising design basis analysis, probabilistic safety analysis and severe accident analysis and recognising that extensive revisions have been made to the overall safety case (including design changes) there is a need for EDF and AREVA to update the previous PSA (Ref. 20) to confirm that the risk targets in SAPs T.8 and T.9 are met. For this reason, I am raising Assessment Finding **AF-UKEPR-FS-30** for a future licensee to provide a revised PSA for external heterogeneous boron dilution faults. Nevertheless, the approach to fault identification presented (Ref. 14) is systematic, reviewing each potential failure mode on the auxiliary systems connected to the RCS to see if it has the potential to generate a large unborated water slug that can enter the RCS and identifying the countermeasures available to protect against such an event. The RCS interfaces considered are the chemical and volume control system (CVCS) and connected systems, the component cooling water system (CCWS), the nuclear sampling systems (NSS), the vent and drain system, the safety injection system (SIS) including the low head safety injection system (LHSI), the medium head safety injection system (MHSI) and accumulators, the emergency borating system (EBS), and the steam generators (SG). SAP FA.2 requires that the process for identifying initiating faults should be systematic, auditable and comprehensive. In my judgment, the fault identification process applied by EDF and AREVA (Ref. 14) meets this requirement.

44 Although the approach is detailed and comprehensive and provides a suitable input into a PSA study, it results in a list of initiating events that contains over 120 events which is unwieldy for inclusion in a fault schedule. For this reason, TQ-EPR-1540 (Ref. 10) was raised requesting EDF and AREVA to perform a grouping exercise in which initiating events that call upon the same protection systems are grouped together as a single bounding initiating event that can be included in the fault schedule. In their response, EDF and AREVA have performed such a grouping exercise (Ref. 19). This rationalisation process represents a traditional approach to design basis analysis and has the advantage that clear insights into potential weaknesses in the design of the protection systems become readily apparent.

45 From the rationalisation process, EDF and AREVA have identified (Ref. 19) the following five faults within this category that they consider to be limiting design basis events that need to be presented in the PCSR including the fault schedule under the pre-existing Assessment Finding **AF-UKEPR-FS-29**:

- CVCS malfunction resulting in the injection of unborated water into reactor loops with the RCPs stopped.
- Tube failures in the heat exchanger on the CVCS letdown line resulting in the injection of unborated water into reactor loops with the RCPs stopped.
- Inadvertent injection of unborated water from reactor auxiliary systems other than the CVCS with the RCPs stopped.

- Leakage of secondary coolant into primary coolant following Steam Generator Tube Rupture (SGTR) repair or SG hydrotest with the RCPs stopped.
- Inadvertent introduction of unborated water into reactor loops during RCS refilling following reactor outage.

46 The first of these events differs from all the rest in that the fault is protected against by the provision of two online boron meters that provide Class 1 protection on the CVCS discharge line downstream of the charging pumps. Each device consists of a neutron source and two radiation detectors which determine boron concentration (specifically ^{10}B concentration) by measuring neutron absorption. On detection of low boron concentration the suction of the charging pumps is automatically realigned to the In-containment Refuelling Water Storage Tank (IRWST) and the normal suction line and the letdown line are automatically isolated by a Class 1 protection system. EDF and AREVA claim that the isolation is sufficiently fast that the injected volume remains below an acceptable volume of 2 m^3.

47 EDF and AREVA (Ref. 19) provide what they claim are illustrative bounding frequencies for these events. This first event has a frequency of 7.5×10^{-2} failures per year which would make it a candidate PCC-2 event. EDF and AREVA emphasise (Ref. 19) that the derivation of these frequencies is not intended to replace or be a substitute for the existing PSA studies but are an artefact aimed at giving what they consider to be a simple and conservative quantitative assessment of the fault frequency in order to assess the potential need for design improvements. Nevertheless, I judge that it would be difficult to demonstrate that this first fault is not a frequent fault (i.e. a fault with a frequency greater than 1×10^{-3} per year) given that the contribution to the initiating event frequency is dominated by two scenarios in which single human errors occur while the operator is maintaining the CVCS system leading to the fault condition.

48 In a well argued ALARP report (Ref. 17), EDF and AREVA have proposed a diverse means of protection for the first fault which they also claim provides protection for the four remaining faults. The proposed modification is to create a new Class 1 interlock which will prevent the operator from starting RCP pump n°1 if the CVCS letdown has not run sufficiently to clear unborated water slugs from loop 1. A further interlock is proposed to prevent restart of RCPs 2, 3 and 4 until RCP pump n°1 has run for a sufficient time to mix efficiently any unborated water slugs from the other three loops.

49 The frequencies claimed for the other events (Ref. 19) would make them either PCC-3 or PCC-4 events but not frequent events (greater than 1×10^{-3} per year). All these events have the potential to inject unborated water slugs into the loops of the RCS. As with the previous initiating event, the safety case claims that the new Class 1 interlocks that are proposed will protect against these faults as well.

50 EDF and AREVA have treated all of these faults as design basis faults meeting the requirements of FA.4 and FA.5 although they have not formally allocated them as Plant Condition Category (PCC) events. For this reason, Assessment Finding **AF-UKEPR-FS-31** has been raised for a future licensee to formally demonstrate that the case meets the PCC analysis rules defined in the PCSR. Nevertheless, given that there are multiple redundancies within the protection system I accept that the single failure criterion requirements of SAPs FS.6, EDR.2 and EDR.4 are automatically met providing the boron meters and the RCP start-up interlocks are functionally capable of preventing an unborated water slug from entering the core with the potential to cause the reactor to become critical.

51 With regard to other potential ALARP improvements, EDF and AREVA summarise the position in their ALARP report (Ref. 17). This argues that the bounding scenarios discussed above can be gathered into three groups according to the design enhancements that are feasible:

- As noted above, for all scenarios the slug has to be transported in the RCS before being sent to the core, and so the proposed RCP interlock is claimed to provide protection.
- Scenarios whose initiating event is a CCWS leak where there are potential design options to either isolate the leak upon its detection or perform a precautionary isolation of parts of the system when the reactor is shutdown and depressurised.
- Scenarios which occur due to operator faults during maintenance operations on the Safety Injection System (SIS) (consisting of the medium head safety injection (MHSI), Low Head Safety Injection (LHSI) and the Accumulators), the Emergency Boration System (EBS), and the SGs for which no feasible ALARP improvements are identified.

52 Each of these groups of scenarios is discussed in the following paragraphs.

53 The proposed RCP restart interlock has been raised by EDF and AREVA as Change Modification Form CMF#54 (Ref. 9) and is a potentially effective solution to protect against heterogeneous boron dilution faults. It essentially reinforces the operator actions that have to be performed, so enhancing their reliability. The interlock will be implemented on the reactor Protection System (PS) as a part of that Class 1 system. However, given the importance of this claim within the revised safety case (Ref. 1) it is highly desirable that a test is performed either during reactor commissioning or on a full scale test rig of the cool leg loop to demonstrate the functional capability of the CVCS letdown flow to fully purge any unborated slug in the loop. For this reason, Assessment Finding **AF-UKEPR-FS-32** has been raised for a future licensee to provide such a demonstration.

54 There are a number of potential faults that can result in the injection of unborated slugs from sources other than the CVCS charging system. These are generally associated with leaks from the CCWS into auxiliary systems connected to the RCS (CVCS letdown line, RHR heat exchanger, LHSI/RHR pump seals, sampling lines heat exchangers, and the RCP pump thermal barrier). These faults cannot be detected by the boron meters and so greater reliance is placed upon the RCP restart interlock. The ALARP option study identifies three additional modifications under CMF#55 (Ref. 9) that will enhance the protection against such faults.

- The first proposal is to automatically isolate the CCWS cooling of the LHSI/RHRS pump heat exchanger when the pumps are not in service as a precaution against a leak that could result in a boron dilution fault. The automation eliminates the need for an operator action and will be backed up with an alarm. The proposal will be implemented as Class 2 system.
- The second proposal is a change to the operating procedures so as to require the operator in the main control room to manually isolate the containment isolation valves on the CCWS lines that feed the HP cooler on the CVCS once all the RCPs are shutdown and the CVCS has switched from HP letdown to Low Pressure (LP) letdown. Additional alarms will be provided to reinforce the actions.
- The third proposal is also a change to the operating procedures so as to require the operator in the main control room to manually isolate the containment isolation

valves on the CCWS lines that cool the thermal barrier on the RCP pumps once the RCP pumps have been shutdown as a diverse back-up to the automatic isolation already provided.

55 While I welcome these proposed changes my judgement is that there is a further ALARP design change that needs to be considered. The ALARP report (Ref. 17) identifies two fault sequences, S18 and S19, involving leaks from the CCWS through either LHSI/RHR heat exchanger or the LHSI/RHR mechanical seals into the RHR system. The report identifies the following procedure to protect against these potential dilution sources. During cold shutdown, before connecting the RHR train to the RCS, the pump is manually started on its mini-flow line allowing its contents to be mixed with the large quantity of borated water in the IRWST. However, the report never considers the potential to provide an interlock to reinforce this operator action, in a manner analogous to that proposed for the CVCS such that the RHR train could not be placed into operation until the pump has operated on its mini-flow line for a sufficiently long period of time to ensure good mixing. Such a modification could be further enhanced by an additional interlock requiring that the RHR train on loop 1 is placed into operation prior to the start-up of RCP pump no.1 to ensure the evacuation of the hot and cold leg sections of the loop that are remote from the CVCS letdown flow claimed in the current RCP interlock. The advantage of introducing such interlocks from an ALARP perspective is that they are simply reinforcing current operating practice and so any changes are limited to the C&I interlock system without the need for changes to plant layout, equipment design or operational procedures. For this reason, Assessment Finding **AF-UKEPR-FS-33** has been raised requesting a future licensee to explore the feasibility of implementing these potential interlocks.

56 Nevertheless, there remains a number of faults for which the only engineered means of protection is the RCP start-up interlock and so the claims on administrative control remain an important aspect of the safety case. For this reason, the human factors aspects of the safety case have been reviewed by ONR’s Human Factor specialists (Refs 11 and 12). They have assessed the human factors analysis performed by EDF and AREVA (Ref. 22). This latter report concludes that there are multiple protective features in place including administrative controls within both the maintenance and operational domains to protect against these faults, although it also identifies a number of potential improvements that could be made to the arrangements to protect against boron dilution faults. ONR’s Human Factor specialists (Ref. 12) have reviewed this analysis and conclude that EDF and AREVA have provided adequate human factor substantiation of the safety claims. In particular, the main defences that are reliant on operator actions appear reasonable and appropriate and that the associated human error probabilities are reasonable and achievable provided that the specific design and procedure features identified in the recommendations of the human factors analysis (Ref. 22) are implemented. It is noted that the conclusions of the EDF and AREVA safety case (Ref. 19) also recognises the need for a further review of ALARP options during the site specific detailed design phase. For this reason, I have raised Assessment Finding **AF-UKEPR-FS-34** for a future licensee to implement the human factors issue register recommendations for design and procedure features from the human factors analyses to support the heterogeneous boron dilution safety case, or provide a justification as to why these are not required to meet ALARP requirements.

57 As noted above, EDF and AREVA are effectively acknowledging that the design basis events associated with operator failures while maintaining the CVCS system are frequent faults. As such, there is a need to review whether additional protection needs to be provided on a diverse C&I platform such as the Safety Automation System (SAS), for these faults. However, it should be recognised that failure of an interlock should not

directly lead to a fault since the operator would still be expected to follow the correct operating procedures irrespective of whether or not the interlock is functioning correctly. Assessment Finding **AF-UKEPR-FS-35** has been raised for a future licensee to consider whether there is a need for additional diversity on one of the C&I interlocks to provide diverse protection against these frequent faults.

Methods and Assumptions

58 SAP FA.7 requires that the design basis analysis demonstrate, so far as is reasonably practicable, that none of the physical barriers to prevent the escape of a significant quantity of radioactivity is breached or, if any are, then at least one barrier remains intact and without a threat to its integrity. In practice, for the faults considered here, the aim of EDF and AREVA is to demonstrate that this is achieved by ensuring that the reactor remains shutdown and does not become critical. I agree with this objective. In addition, SAP FA.7 also requires that the analysis of design basis fault sequences should be performed on a conservative basis. To confirm that these objectives have been achieved, the design basis analysis of EDF and AREVA and the technical arguments that underpin it have been assessed. In particular, I have assessed the validation of the EDF and AREVA methods against the requirements of SAPs FA.18 to FA.19 and the relevant TAG on the validation of computer codes and calculational methods (Ref. 8).

59 As explained above, the basis of the external heterogeneous boron dilution safety case is that given the operational procedures put in place to avoid the creation of diluted slugs in the first place together with the interlocks provided to prevent such slugs from entering the core, sequences involving the transportation of large unborated slugs of water into the core are effectively removed from the design basis. Nevertheless, EDF and AREVA concede that the engineered safeguards such as the boron meters and RCP start-up interlocks may not be entirely effective at preventing smaller residual slugs from entering the core. A key claim is that providing the slug size is below 2 m^3 the reactor will not undergo a return to criticality. To support this claim in response to TQ-EPR-1560 (Ref. 10), EDF and AREVA have provided a report (Ref. 23) on a series of test measurements performed on the Juliette test rig to explore the behaviour of an unborated slug as it flows through the downcomer and into the lower plenum following RCP start-up. These experimental studies have been complimented by some computational fluid dynamics (CFD) calculations (Refs 15 and 16) which predict the boron concentration of the slug as it enters the core inlet. The results of the calculations are assessed against the results of a reactor physics calculation that determines the average minimum boron concentration needed to ensure the reactor does not return to criticality.

60 The Juliette test rig (Ref. 23) is a 0.192 scale model of the EPR™ representing the cold legs, lower plenum and core inlet of the design including the entire height of the annulus and all intruding structures (inlet and outlet nozzles, safety injection nozzles, irradiation specimen baskets, radial support keys and flow distribution device). The aim of the tests is to determine the path and mixing through the reactor pressure vessel to the core inlet of an unborated slug of water that is initially present in one of the cold legs and injected after restart of a single pump. The water slug injected into the cold leg is thermally traced. The slug propagation in the cold leg, downcomer and at the core inlet is measured using arrays of thermocouples. All thermocouples measurements are simultaneously monitored during the entire transient. Flow rates in the cold legs are also measured.

61 An impressive number of test measurements are presented. Four test scenarios (I to IV) were performed, each being repeated three times. Tests I and II studied 2 m^3 slugs but with slightly different rates of increase in the flow. Test III studied a 4 m^3 slug while

Test IV repeated Test I but with a slight counter flow in the three loops not associated with the pump start-up. The test results illustrate how the slug mixes in the downcomer region as it flows down but also rotates around the downcomer. Comparison of the test results giving the maximum relative core inlet temperature presented in Figs 48, 56, 64, and 72 of the test report (Ref. 23) demonstrates that tests result are repeatable. The maximum relative inlet temperature is about 0.16 for tests I, II and IV and 0.3 for test III where the temperature scale corresponds to 1.0 for completely unmixed flow and 0.0 for totally mixed flow. It can be seen that the results suggest that good mixing occurs. These results can be directly converted into predictions of minimum boron concentration given the initial boron concentrations of the slug and the primary circuit. If it is assumed that the initial concentration of the unborated slug is zero and the primary circuit has an initial concentration of 2293 ppm then the results predict a minimum boron concentration of 2293 x (1.0 – 0.16) = 1926 ppm in the case of a 2 m^3 slug, which is comfortably above the critical boron concentration of 1300 ppm identified in the safety case, strongly suggesting that the requirements of SAP FA.7 have been met at least for the 2 m^3 slug.

62 However, only minimal justification is given that the Juliette test rig provides an accurate representation of the important thermal hydraulic phenomenon relevant to the full scale EPR™ reactor. EDF and AREVA argue that buoyancy effects are unimportant since the flow is driven by inertia from the pumps and the size of the Reynolds number ensures that the flows on both the test and reactor scale will be turbulent. However, the maximum flow rate selected for the test rig is about twice the value required to ensure good time similitude with the reactor scale. No justification is given for this choice. SAP FA.18 requires that validation should be performed against appropriate experiments that replicate as closely as possible the expected plant condition. While the experimental work performed by EDF and AREVA is impressive, in my opinion there is a need to provide further evidence of the appropriate scaling of the test rig. For this reason, Assessment Finding **AF-UKEPR-FS-36** has been raised for a future licensee to present a rigorous Phenomenon Identification and Ranking Technique (PIRT) analysis and scaling analysis of the Juliette test rig to confirm that the rig has been appropriately scaled to minimise distortion in the thermal hydraulic phenomenon being studied when compared with the full reactor scale to confirm safety margins.

63 The experimental work performed on the Juliette test rig (Ref. 23) has been supplemented by CFD analysis (Refs 15 & 23) aimed at validating the CFD model for application in transient analysis calculations representing the reactor at full scale (Ref. 16). Very good agreement is achieved between the experimental results and the code predictions of the slug's kinetics and mixing although the model tends to slightly underestimate the amount of mixing. EDF and AREVA state that this is due to the turbulence model used which they claim is known to underestimate the amount of mixing. However, good practice expects model parameters to be tuned to one set of data and tested against a separate set of data and the qualification documentation does not make clear whether this practice has been followed. There is also no treatment of uncertainties. Hence, in my opinion it would be unwise to place much confidence on this CFD work as additional validation evidence.

Transient Analysis

64 As noted above, the results of the Juliette measurements (Ref. 23) suggest that there is significant margin to the critical boron concentration for slug sizes less than 2 m^3. In addition to these measurements, EDF and AREVA have also performed some additional CFD transient analysis (Ref. 16) at the reactor scale. A series of calculations with

sensitivity studies performed for different slug sizes, different pump start-up rates and different initial locations of the slug within the loop. The calculations predict the boron concentration of 1591 ppm (Ref. 16) for slug sizes up to 4 m^3 which is above the critical boron concentration of 1300 ppm. EDF and AREVA have supplemented this analysis with additional analysis presented in an appendix of the main safety case in Section 7 of Chapter 16.4 (Ref. 19). This performs additional sensitivity studies to slug size but also performs coupled reactor physics calculations to remove some of the inherent conservatism associated with performing the original decoupled approach. This is because the decoupled approach aims to ensure that the local minimum boron concentration everywhere in the core remains above the core uniform critical concentration. As the safety case notes, this criterion is conservative as, even if the critical boron concentration is reached locally, this does not necessarily imply re-criticality of the core or risk of core damage. Using the original decoupled approach, the studies demonstrate that for slug volumes greater than 6 m^3 a return to criticality could not be ruled out. In the revised analysis, the boron distribution at the core inlet at the worst point in the transient is applied uniformly to all axial elevations of the 3D reactor physics core model conservatively assuming no further mixing takes place. This gives some insights into the inherent margin provided by the decoupled approach. The reactor physics calculations performed predict that there will be no return to criticality for slug sizes up to 9 m^3 corresponding to a critical boron concentration of 689 ppm.

65 In my opinion, this reactor physics calculation coupled with experimental test work on slug mixing provides strong evidence that a 2 m^3 slug would not result in a return to criticality following pump start-up and is entirely supportive of the EDF and AREVA design basis safety case.

Confirmatory Analysis

66 Recognising that complex CFD calculations are providing one of the supporting arguments to the safety case, I commissioned GRS to perform some confirmatory analysis (Ref. 4) for the 4 m^3 case. The analysis builds on earlier work that GRS had performed during GDA Step 4 (Ref. 24) for the same case and incorporates comments made by EDF and AREVA about the earlier work. In particular, enhancements have been made to the modelling of the cold leg inlet nozzle, the lower plenum and core inlet. The changes include modelling of the irradiation baskets and eight radial position keys in the downcomer and the development of three geometry models and associated numerical grids, representing different possible treatments of the flow distribution device located in the lower plenum beneath the core.

67 The main conclusions of the GRS analysis (Ref. 4) are that adding the irradiation baskets and eight radial position keys in the downcomer has a notable effect on the calculated boron concentration transient giving much improved agreement with the EDF and AREVA results as illustrated in Figure 28 of the GRS report. The predicted minimum boron concentration is seen to increase from 850 ppm (Ref. 24) to 1500 ppm (Ref. 4) which compares well with the EDF and AREVA prediction of 1507 ppm (Ref. 4). However, replacing the porous medium model of the flow distribution device with a geometrically resolved model causes the agreement to deteriorate with the predicted minimum boron concentration reducing to 1187 ppm. GRS concludes that the differences are still unexplained. I agree with this conclusion. For this reason, I have raised Assessment Finding **AF-UKEPR-FS-37** for a future licensee to provide further justification for the flow resistance data assumed in the CFD modelling of the flow distribution device.

4.1.3 Findings

68 Following my assessment of the external heterogeneous boron dilution faults, I am content with the fundamental design of the UK EPR™ to protect against this class of fault. In particular, the provision of an RCP start-up interlock which has been proactively identified by EDF and AREVA is regarded as a very significant safety improvement to the protection system for these faults and is welcomed. The provision of this interlock together with the experimental results from the Juliette test rig and the revised reactor physics calculations has considerably strengthened the design basis safety case for these faults. The safety case now has a much better balance with less reliance placed upon administrative control, CFD and PSA analysis.

69 Eight assessment findings have been raised (**AF-UKEPR-FS-30** to **AF-UKEPR-FS-37**). In general, these are items requiring either further analysis or support from commissioning tests rather than a fundamental issue with the design and, in my judgement, they can be closed out as part of the site licensing process. However, Assessment Findings **AF-UKEPR-FS-33** and **AF-UKEPR-FS-35** may require changes to the design of the C&I interlocks used to protect against these faults. While these may be important changes in terms of safety, in my judgement they are relatively straight forward and are unlikely to result in any changes to the plant layout.

4.2 Inherent Heterogeneous Boron Dilution Fault Safety Case

4.2.1 Summary of EDF and AREVA's Safety Case

70 The single fault that is assessed in this category results from the creation of an unborated slug of water in the loops of the primary circuit of a pressurised water reactor (PWR) during a SBLOCA as a result of reflux condensation occurring in the steam generators.

71 The basis of the EDF and AREVA safety case (Ref. 18) is that such a slug will be adequately mixed within the downcomer of the primary circuit prior to entering the reactor core such that the reactor does not return to criticality. This argument is supported by a series of experimental results and analytical studies that EDF and AREVA believe provide sufficient justification to underpin their claims of adequate mixing.

72 On the basis of the arguments presented EDF and AREVA claim that adequate protection is provided for this fault.

4.2.2 Assessment

73 EDF and AREVA have identified two initiating events that can result in a fault in this category:

- Small Break Loss of Coolant Accident (SBLOCA);
- Loss of cooling during "¾ loop" operation.

74 Assessment of "¾ loop" shutdown operations with the fuel still loaded is outside the scope of GDA. The main assessment of the design basis safety case for SBLOCA faults is provided in Section 4.2.8.4 of the GDA Step 4 fault studies report (Ref. 2) and is not revisited here other than to note that SBLOCA faults are classified in the PCSR as PCC-3 faults for which the expectation is that a design basis safety case would be provided. This assessment focuses only on the heterogeneous boron dilution aspects of the safety case.

75 I have chosen to focus on this safety case because the assessment methodology that EDF and AREVA have applied to this fault is both novel and complex.

Fault Sequence Analysis .

76 EDF and AREVA have treated this fault as being within the design basis meeting the requirements of SAPs FA.4 and FA.5. For the purposes of penalising the boron dilution transient they have assumed (Ref. 18) that preventive maintenance is being performed on one of the trains of the safety injection system minimising the amount of borated water injected into the reactor circuit. They have also assumed (Ref. 18) a single failure of the EBS pump associated with the same loop in which the safety injection train is assumed to be unavailable. Since, the EBS system injects borated water into the RCS this assumption ensures that there is at least one loop into which no borated water is injected. EDF and AREVA are therefore modelling what they judge to be the most onerous single failure meeting the expectations of SAPs FA.6, EDR.2 and EDR.4. However, another possibility would be to assume the single failure of another train of the safety injection system. No explicit justification is presented within the safety case for not considering this as the additional single failure. It may be that EDF and AREVA are discounting this sequence on the grounds that they judge the likelihood of natural circulation flow starting simultaneously in two loops to be very low. This aspect is discussed further below during the assessment of the experimental test work but nevertheless, in my opinion, further justification is required for making this assumption. For this reason, I am raising Assessment Finding **AF-UKEPR-FS-38** for a future licensee to provide further justification for not selecting failure of an additional train of the safety injection system as the most onerous single failure.

Method and Assumptions

77 SAP FA.7 requires that the analysis demonstrate, so far as is reasonably practicable, that none of the physical barriers to prevent the escape of a significant quantity of radioactivity is breached or, if any are, then at least one barrier remains intact and without a threat to its integrity. EDF and AREVA's safety criterion for a PCC-3 event is that less than 10% of the fuel rods undergo a departure from nucleate boiling (DNB). In practice, for the fault considered here, the aim of EDF and AREVA is to demonstrate that this is achieved by ensuring that once the reactor is tripped it remains shutdown and does not experience a re-criticality. I agree with this objective. SAP FA.7 also requires that the analysis of design basis fault sequences should be performed on a conservative basis. To confirm that these objectives have been achieved, the results of the design basis analysis of EDF and AREVA need to be assessed.

78 To understand the EDF and AREVA safety case it is necessary to understand the phenomenology of the SBLOCA fault. The key events following a break occurring (more details are given in the EDF and AREVA safety case (Ref. 18)) are the following:

- The reactor is tripped on low pressuriser pressure.
- The pressure and water inventory in the primary circuit decrease until the primary coolant reaches its saturation condition and coolant starts to vaporise in the hot parts of the circuit initiating a period of two-phase circulation.
- The safety injection system, consisting of the MHSI and LHSI systems, is actuated on low pressuriser pressure. On the secondary side an initial phase of automatic cooling is established by opening the main steam relief trains (MSRT) to perform a

controlled depressurisation of the steam generators. The reactor is cooled at a rate of 250°C/hour. Assuming a consequential loss of off-site power (LOOP) results in the RCPs being tripped and the loss of main feedwater. In such circumstances, the emergency feedwater system (EFWS) is automatically started up. Note that the RCPs will in any case be tripped once the pressure drop across them is less than 80% of the nominal value.

- Following the shutdown of the RCPs a period of two-phase natural circulation is established. There will be a range of break sizes for which the water inventory will continue to drain as the break flow will be too great for the safety injection system to compensate for in the short-term such that steam collects in the hot legs although boron concentration remains homogeneous.
- For smaller break sizes, the reactor coolant pressure stabilises above the secondary side pressure and a considerable portion of the residual power is evacuated via the steam generators.
- For larger break sizes, the reactor coolant may fall below the secondary side pressure. In such circumstances, heat removal by the steam generators is only re-established after the operator manually re-opens the MSRTs to depressurise the secondary side so as to commence a further cooldown of the primary side. The operator will also start EBS injection.
- For break sizes of sufficient size, the reduction in reactor inventory leads to the end of natural circulation. When the water level falls beneath the level of the SG tube bundle (highest part of the circuit) the SGs switch to reflux-condensation mode of cooling where hot steam from the primary system is condensed and returned to the primary system liquid mass inventory.
- On the ascending (or hot-leg) side of the SG inlet plenum, experiments at the PKL test rigs (Ref. 25) have shown that the condensate mixes with the water in the hot-leg due to counter-current flow. However, on the descending (or cross-leg) side of the SG outlet plenum the condensate has the potential to produce unborated slugs of water due to a siphoning process in the shorter tubes. The size of the slug is limited to the size of the cross-over leg and the SG outlet plenum (about 11 m^3). If the safety injection system associated with a given loop is successfully actuated then the borated water it injects will mix with the unborated water. However, failure of a train of the safety injection system on a loop means that there is at least potential for an unborated slug to build up.
- For break sizes of a very specific size it is possible for the safety injection system to eventually start to refill the RCS and for natural circulation to restart. There is then the potential for any unborated slug to be transported into the core.
- In summary, an inherent boron dilution accident may occur following a small or intermediate break together with the shutdown of the RCPs when the residual power is being evacuated via the SGs acting in reflux condensation mode.

79 It is important to realise that unlike “classic” LOCA transients where the safety concern is associated with the possibility of short-term core uncovering resulting in fuel damage, the transients associated with an inherent heterogeneous boron dilution fault are associated with much longer time frames, typically lasting more than one hour depending on the size of the break, as potential unborated slugs are first generated in the loops and then transported in to the core following the re-establishment of natural circulation cooling.

80 To analyse inherent heterogeneous boron dilution faults EDF and AREVA have developed a complex and multi-legged safety case that draws upon the results of two extensive experimental thermal hydraulic research programmes as well as being supported by thermal hydraulic system code analysis, CFD analysis and reactor physics analysis. The basic strategy of EDF and AREVA is to divide the safety case argument into two main parts. The first part concerns the likelihood of a slug of unborated water forming in one or more loops of the UK EPR™ during a SBLOCA as a result of the reflux condensation process. The second part of the argument makes the decoupling assumption that the slug of unborated water is nevertheless formed and then looks at the potential for the slug to mix as it moves towards the core following the restart of natural circulation with the aim of demonstrating that a return to criticality will not occur. In the following sub-sections, my assessment of each of these arguments is presented in turn. In each case I considered the validation evidence for the methods, the results of the transient analysis and the outcome of some reviews and confirmatory analysis that I have commissioned from GRS.

Validation (Part 1 – slug creation)

81 In their safety case (Ref. 18), EDF and AREVA make extensive reference to the experimental work performed on the PKL III test rig (Ref. 25). The PKL III test rig replicates a 1300 MW PWR of the KONVOI design with all elevations scaled 1:1. The scaling factor for diameters is 1:12 and for volumes and power is 1:145. It has a 4-loops and a core stimulator consisting of a bundle of 314 electrical heater rods. The four steam generator units each consist of 28 U-tubes (full scale). Extensive instrumentation is provided with about 1500 measuring locations. In particular, for the measurement of boron concentration at specific locations in the RCS piping four boron meters are provided. Additional sampling points are also provided for taking grab samples at several locations in the primary system. Within the PKL III experimental test series, test E and F included several integral tests aimed at addressing the inherent heterogeneous boron dilution issue following SBLOCA. The relevant PKL III tests that EDF and AREVA report in support of their safety case are as follows:

- Test E2.2: break (32 cm^2/145) in cold leg with high pressure safety injection into 2 cold legs and cooldown at 100°C/hr.
- Test F1.1: break (21 cm^2/145) in cold leg with high pressure safety injection into 4 cold legs and cooldown at 56°C/hr.
- Test F1.2: parametric study with drain and replenishment of coolant at 12 bar.
- Test F4.1: parametric study with drain and replenishment of coolant (performed as two tests at 30 and 40 bar).

82 The first test represents a German KONVOI PWR reactor. Although the geometry is similar to UK EPR™, the capabilities of the safety injection system is not totally prototypic since the KONVOI reactor has a High Head Safety Injection (HHSI) system whereas the UK EPR™ has a MHSI system and the injection capacity of the LHSI on the KONVOI is greater than that on the UK EPR™. In addition, the emergency operating procedures for post fault manual cooldown also differ. Nevertheless, of the four tests, this test is most representative of the design basis fault being analysed for the UK EPR™. In particular, two safety injection trains are assumed to fail.

83 The second test is more prototypic of a French N4 PWR reactor. In particular, only a HHSI is represented as there is no LHSI. This makes for a slower transient with greater

steam production from the core. All four safety injection trains are assumed to operate successfully.

84 The next two tests are separate effect tests aimed at performing parametric studies on the effect on primary inventory and pressure on the occurrence of boron dilution processes during phases of steady state operation.

85 The safety case (Ref. 18) states that the key claims that are supported by these tests are as follows:

- The level of the water in the SG outlet plenum must be located beneath the tube bundle to enable an unborated slug of clear water to accumulate.
- Counter-current exchanges between the SG inlet plenum, the hot leg and the upper plenum of the reactor pressure vessel prevent unborated slugs from forming on the hot leg side of the SG inlet plenum. Hence the size of the unborated slug is limited to the volume of the cross over leg and part of the SG outlet plenum (11 m^3 on the UK EPR™). The boron concentration of this slug is approximately 50 ppm.
- Natural circulation does not restart simultaneously in different loops even in the case of loops with purely symmetrical configurations.
- Natural circulation restarts in those loops without safety injection.
- During the filling phase that precedes the sustained restart of natural circulation, intermittent flows of borated water from the hot leg and the SG inlet plenum are responsible for pre-mixing the unborated slug before it sets off towards the core.
- Slugs of slightly borated water have been observed at the reactor vessel inlet to the downcomer (approximately 350 ppm) but only on loops with no safety injection.

86 In addition, I note that the PKL tests are also claimed for the following purpose:

- To determine the natural circulation flowrate assumed as input into the Juliette tests and the CFD transient analysis studies which are presented below.

87 In the following paragraphs, I review the evidence from the PKL tests supporting each of these claims.

88 The evidence from Tests F1.2 and F4.1 is quite compelling that unborated slugs can only start to form once the primary inventory has fallen below the level of the SG tube sheet. Prior to the level falling below the tube sheet complex flow patterns are possible due to the 2-phase conditions that are present. This allows for an intermittent circulation phenomenon known as “fill and dump” due to the differing lengths of the U-tubes. Once the outlet vents of the SG U-tubes are exposed enabling a pressure balance to be established the flow of borated water through shorter U-tubes is prevented and the reflux condensation process can start to generate unborated slugs. This is seen very clearly in Fig. 63 of the test report for Test 4.1 (Ref. 25).

89 Using estimates of the amount of condensate produced together with the measured boron concentration, EDF and AREVA have concluded that the interchange of fluid and mixing process between SG inlet plenum, the hot leg, upper plenum and core region is sufficient to ensure that that accumulation of unborated slugs in the hot leg is not possible. This is supported by the measurements of the boron concentration in the SG inlet plenum quoted (Ref. 25) which never falls below 400 ± 50 ppm and rises to 1200 ppm prior to the restart of natural circulation as the swell levels increase intensifying the mixing processes. Thus the maximum slug size is limited to the volumes of the outlet chamber and the associated

pump seal. On the UK EPR™ this corresponds to a volume of 11 m^3. In my opinion, the evidence from the detailed test data is convincing.

90 It should be emphasised that the boron concentration in the SG outlet plenum reduces to less than 50 ppm as is seen for example in Fig. 25 for loop 3 in Test E2.2 and Fig. 47 for loop 4 in Test F1.1. This clearly illustrates how effective the reflux condensation process is at creating unborated slugs during the period in which there is no natural circulation. In my opinion, the evidence is again totally convincing.

91 As the safety injection system gradually refills the loops there will be a return to natural circulation. This is clearly shown for Test E2.2 in Fig 17a of the test report (Ref. 25) which presents the measured flow rate in the four loops as a function of time. It is seen that the restart of natural circulation occurs first on loop 4. The slug from loop 3 arrives in the core 270 seconds after the slug from loop 4. This delay is greater than the time needed for the first slug to complete its transit of the core. EDF and AREVA consider that this is a general phenomenon arguing that asymmetries within the U-tubes due to complex two phase flow oscillations (see below) and slight differences in pressure differentials on individual loops result in asymmetric conditions in the different loops. The transition to intermittent circulation in one SG causes coolant to transit through the loop seal into the core. This coolant entering the core causes a temporary reduction in steam production, decreases the inlet swell decreasing the drive for natural circulation. Hence the loops interact with each other creating phases with stagnating flow and asymmetric fluctuations during the restart phase of natural circulation flow. Constant refilling eventually forces natural circulation to restart but it is not an abrupt start but a slow change. Depending on the refill rate, there may be a distinct flow peak in the loop that first establishes natural circulation as seen in Fig 17a for Test E2.2. However, once continuous natural circulation is established in one loop, the cold water entering the core reduces steam production resulting in reduced swell levels on the inlet sides of all the other SGs without established natural circulation. EDF and AREVA judge that this effect will prevent the simultaneous restart of natural circulation in more than one loop and probably explains why EDF and AREVA discount failure of a second safety injection train as the most onerous single failure.

92 My own view is that only a very limited number of tests have been performed and it is not clear how prototypic they are for the UK EPR™. As already noted, the PKL test rig is designed to represent the German KONVOI reactor. Only limited detailed information is provided to justify the applicability of the PKL test rig results to the UK EPR™. The test report (Ref. 25) claims that the geometry of the UK EPR™ is very similar to the KONVOI reactor such that the results from the PKL test rig remain applicable. However, no scaling analysis is provided covering such phenomenon as the LHSI injection rate and the rate of steam production in the PKL tests compared with the UK EPR™. Hence, while I accept that the test results suggest it is unlikely that natural circulation will restart simultaneously in two loops, I do not consider this has been conclusively proven for the UK EPR™. I consider that further work is still required to justify discounting the single failure of an additional safety injection train as required by Assessment Finding **AF-UKEPR-FS-38** which was raised above. These concerns also reinforce the need for PIRT and scaling analysis to be performed as discussed further below.

93 Test E2.2 is the only test that represents asymmetric conditions with two loops with safety injection and two without safety injection. Fig. 18a of the test report (Ref. 25) shows that natural circulation flow restarts first in the two loops without safety injection before it restarts in the two loops with safety injection by a period of about ten minutes. EDF and AREVA argue that this is because the safety injection flow causes the slugs in the two

loops with safety injection to be displaced towards the SG. This retardation in the flow delays the refill of these loops when compared with the loops without safety injection and so the restart of natural circulation occurs sooner on the loops without safety injection. The report notes that the safety injection flow which causes the displacement of the slugs towards the SGs will also cause enhanced flow oscillations in these loops which enhances the mixing processes such that only a marginal decrease in boron concentration occurs at the pressure vessel inlet following the onset of natural circulation for these loops. This is clearly illustrated for Test E2.2 in Fig 18c for loops 1 and 2 which are the loops associated with safety injection. However, the test report (Ref. 25) notes that on the UK EPR™ the cold water volumes may be smaller due to the difference in capacity of the LHSI system and so the impact of the safety injection on the flow retardation may be smaller than that observed in Test E2.2 confirming my comments made above.

94 One of the major findings of the PKL experimental programme is that prior to the restart of sustained natural circulation, there is a period of intermittent flow oscillations that contributes to the mixing of slugs within the loop seal. This mixing process occurs prior to the onset of any coolant transportation from the SGs. It is noticeable that these oscillations are more marked in the Test F1.1 than in the Test E2.2. Fig. 46a illustrates these oscillations in flow for Test F1.1 while Fig 26.1b shows these oscillations for Test E2.2. EDF and AREVA argue that this is due to the greater steam production in Test F1.1 compared to Test E2.2 where greater core cooling is provided by the LHSI system in comparison with Test F1.1 for which on N4 plant only the HHSI system is available. The greater steam production results in greater oscillations in the flow. Similar observations are made in the GRS confirmatory analysis (Ref. 24) reported below. Given that the UK EPR™ is provided with a LHSI system but that this has a lower flow capacity than that of the KONVOI reactor it might be expected that the results for the UK EPR™ will lie somewhere between the two tests. However, care must be taken since the scaling analysis reported in section 7 of the PKL test report (Ref. 25) acknowledges that steam production is greater on the PKL test rig compared with reactor scale because of the lower pressure.

95 Fig 17b also illustrates the minimum boron concentration at the reactor pressure vessel inlet for Test E2.2. The boron concentration measurements show that the minimum reduces to about 350 ± 100 ppm in agreement with the claim made in the safety case. As the boron concentration in the cold leg prior to restart of intermittent natural circulation was considerably lower EDF and AREVA interpret this as evidence of mixing effect due to intermittent flows. This is the reason why EDF and AREVA argue that the safety case assumption of modelling pure unborated slug in the slug transport analysis is very conservative.

96 Taking the test results in there entirety, I accept that there is strong evidence of intermittent circulation and mixing causing an increase in the boron concentration in the SG outlet plenum and loop seal prior to the restart of natural circulation. However, this is tempered by the concern about how prototypic these results are for the UK EPR™.

97 The natural circulation start-up transient shown in Fig. 17a for loop 4 from Test E2.2 is used to determine the transient boundary conditions for the Juliette test programme and the CFD transport calculations discussed below. Section 7 of the test report (Ref. 25) presents a scaling analysis of the peak valve of the natural circulation flow and concludes that little distortion in introduced and that this can be corrected with appropriately conservative scaling factors. Given that the PKL test rig is a full height test facility with appropriately scaled geometry, in my judgement these are sound arguments. What is

less clear is whether the transient variation in the flow taken from Test E2.2 is bounding since the dynamics of the rate of change are clearly dependent upon the rate of refill from the LHSI system. This is an important parameter since it will determine the period of time over which the whole of the unborated slug enters the reactor pressure vessel. This again emphasises the need for a full PIRT and scaling analysis.

98 In summary, while I am impressed with the experimental work performed on the PKL test rig, given the importance of the results, I still believe there is a need for a formal PIRT and scaling analysis to be performed to demonstrate that the results and conclusions of the PKL experiments are fully applicable to the UK EPR™. For this reason, I have raised Assessment Finding **AF-UKEPR-FS-39** requesting a future licensee to provide a PIRT and scaling analysis of the PKL test rig. Depending on the results of this analysis there may be a need for further experimental tests to be performed to more accurately represent the UK EPR™.

Transient Analysis (Part 1 – slug creation)

99 To support their safety case (Ref. 18), EDF and AREVA have used the thermal-hydraulic systems code CATHARE to perform a series of parametric transient analysis sensitivity studies to identify what they consider to be the most onerous break size to be analysed. This is then used to provide the boundary conditions for the subsequent CFD analysis although in practice these are supplemented by additional insights gained from the PKL tests. The validation of the CATHARE computer code is reviewed in detail in the GDA Step 4 Fault Studies report (Ref. 2) in which it was concluded that CATHARE is a modern thermal-hydraulic code that is well documented and validated meeting the requirements of SAPs FA.17 to FA.24. The modelling assumptions include the normal conservative assumptions made with regard to the modelling of safety injection system with regard to flow rates and boron concentrations. However, the analysis is based upon a 4300 MWth EPR™ design that differs from the UK EPR™ design. In addition, the design of the main coolant loop of the UK EPR™ has subsequently been altered slightly under CMF#31 (Ref. 9). I agree with the view of EDF and AREVA that these differences are unlikely to cast any doubt on the calculational procedure or on the conclusions of the safety case given the decoupled approach that has been adopted to the analysis. Nevertheless there is a need under Assessment Finding **AF-UKEPR-FS-08** raised during Step 4 (Ref. 2) for analysis to be updated to reflect the UK EPR™ design. Probably the most significant assumptions are related to the choice of single failure and the modelling of operator actions, specifically, the timing at which the manual cooldown is assumed to start. The operator is assumed to start the manual cooldown at 30 minutes at a rate of 50°C/hr after commencing EBS operation. As noted above, the single failure and preventive maintenance assumptions are applied to the EBS and safety injection (MHSI + LHSI) systems on the same loop which is not the loop associated with the break. This ensures that there is a loop in which no borated water is injected. However, as the flow from the EBS is relatively modest at 1.4 kg/s compared to the flow of 40 kg/s from a train of the safety injection system, in my opinion, the failure of an additional train of safety injection will need to be considered by a future licensee as the potentially bounding single failure during the site specific detailed design phase as already requested under Assessment Finding **AF-UKEPR-FS-38**.

100 The main finding from the studies is that there is only a very limited range of break sizes for which inherent heterogeneous boron dilution faults can occur. The break needs to be on the cold leg and needs to be sufficiently large to ensure that the decrease in mass inventory is sufficient to cause the interruption of natural circulation flow. However, it

must not be too large such that the pressure of the primary side falls below the SG pressure since cooling by reflux condensation is then not possible. Indeed, the size is even more restricted than this because the break size needs to be sufficiently small so as to minimise steam production in the cross-over leg so as to ensure efficient reflux condensation cooling by the SGs in which all the steam that is produced is condensed. Otherwise, the flow of steam is too great causing oscillations in the flow that repeatedly flush the cross-over legs resulting in the mixing and disruption of the unborated slug.

101 The analysis notes that limitations in the CATHARE modelling ensure that the calculated slug sizes are conservatively overestimated since the model cannot represent the intermediate over-spilling phase seen on PKL tests just prior to the re-establishment of natural circulation that will dilute any slugs that are present. The analysis concludes that the most penalising break size is 14 cm^2. This case is used to inform the selection of the boundary conditions assumed for the CFD analysis discussed below in part 2.

Confirmatory Analysis (Part 1 – slug creation)

102 Recognising the extremely complex arguments and calculations that are being used to justify the safety case for inherent heterogeneous boron dilution faults, I commissioned GRS to review the system code analysis (Ref. 4) for the SBLOCA case. The review builds on earlier work that GRS had performed during GDA Step 4 (Ref. 24) for the SBLOCA case. In this latter work, GRS used the ATHLET thermal hydraulic system computer code to try and identify the most onerous conditions in terms of break size for an inherent heterogeneous boron dilution fault on the UK EPR™ following a SBLOCA. The GRS analysis identifies a break size of 20-25 cm^2 as being the most onerous compared with the analysis of EDF and AREVA which identifies 14 cm^2 as being the most onerous size. Different assumptions are made in the two analyses. The EDF and AREVA analysis is based upon the 4300 MWth reactor power and assumes the failure of one train of the safety injection system and one EBS train while the GRS analysis is for the UK EPR™ specific design of 4500 MWth and assumes the failure of two trains of the safety injection system. The assumed manual cooldown rates are also different. EDF and AREVA assume 50°C/hr while GRS assume 25°C/hr since at the time the calculation was performed the EDF and AREVA analysis was not available and so the GRS analysis was performed blind without the cooldown rate information given in the proposed EPR emergency operating procedures.

103 The GRS review of both sets of analysis (Ref. 4) notes that when comparing the results of transient analysis studies with comparable break size the EDF and AREVA analysis predicts that virtually all the safety injection flow from the extra train modelled in the EDF and AREVA case is lost through the break which is located in the same loop. The cooling provided by the extra train ensures the flow remains sub-cooled at break location and so the extra flow can be accommodated without perturbing the conclusions of the study. GRS also notes that the higher core power will also lead to larger break size for the same geometry. GRS therefore conclude that the extra train of safety injection has little influence on the identification of the most onerous break size and that the differences are primarily associated with the choice of cooldown rate. For this reason, TQ-EPR-1608 (Ref. 10) was raised requesting EDF and AREVA to provide additional sensitivity studies to the assumed cooldown rate.

104 In their response, EDF and AREVA requested not to do this stating that the 50°C/hr is optimised from a safety perspective to ensure that the maximum water inventory is retained in the primary circuit following a SBLOCA. They note that the calculations

performed by GRS leads to small condensation rates, steam from the core not being condensed in the SG tubes and so being released at the break, and strong oscillating mass flows in the loops which prevents the build up of large deborated slugs. They also state that in their opinion the assumed cooldown rate is not a key parameter of the study and that the break size assumed by GRS of 25 cm^2 is too favourable, adding that their own studies reported in the safety case (Ref. 18) confirm that smaller break sizes in the range 10 cm^2 to 20 cm^2 could lead to the accumulation of a diluted slug, claiming that this would be regardless of the applied cooldown rate.

105 Clearly there is disagreement here that will need to be resolved through additional sensitivity studies during the site specific detailed design phase when EDF and AREVA will need to update their analysis for the UK EPR™ design in line with Assessment Finding **AF-UKEPR-FS-08** as discussed above. In my judgement, it is clear that the thermal hydraulic system codes have difficulty accurately predicting the size of unborated slugs that can be produced and so I place more weight on the experimental evidence from the PKL test programme discussed above. I also note that in the Julliette experiments and CFD analysis discussed below, EDF and AREVA make the assumption by not including the effects of a break in one of the loops and so, in my judgement, the precise size of the most onerous break is not too central to their safety case argument.

Validation (Part 2 – slug transport)

106 The Juliette test rig discussed above in the context of external heterogeneous boron dilution faults has also been used to study inherent heterogeneous boron dilution faults (Refs 15 & 23). It will be recalled that the Juliette test rig (Ref. 23) is a 0.192 scale model of the EPR™ representing the cold legs, lower plenum and core inlet of the design including the entire height of the annulus and all intruding structures. The aim of the inherent dilution tests is to determine the path and mixing through the reactor pressure vessel to the core inlet of an unborated slug of water initially located in the SG outlet plenum and cross-over leg that is transported into the core when natural circulation restarts in at least one of the loops. For the inherent boron dilution tests, the test loop is modified in order to allow the representation of flow from the safety injection system and the release of a large slug. A hot water tank is needed in order to create the hot slug which is representative of the unborated slug. A smooth diffuser is added in order to obtain a flat velocity profile in the upstream pipe whether it is hot fluid or cold fluid which is injected. Again, the water slug is injected into the cold leg and is thermally traced. The safety injection flow is represented by a highly concentrated flow of brine made in a circuit consisting of a tank of stirred up brine, a pump and two injection circuits equipped with flow meters and control valves. A control valve is also used to control the flow that injects the slug so as to represent the start-up of natural circulation flow. A three-way pneumatic valve allows quick switching from the cold circuit to the hot brine circuit. EDF and AREVA claim that the characteristics of the valve opening and the flowrate for the whole circuit have been calibrated beforehand to appropriately scale the flow from reactor conditions. When the slug volume is reached, the valve allows switching to the cold circuit again with conservation of flowrate.

107 As with the external dilution case discussed above only a preliminary justification is given that the Juliette test rig provides an accurate representation of the important thermal hydraulic phenomenon as relevant to the full scale EPR™ reactor. EDF and AREVA argue that for the inherent dilution case buoyancy effects are important and so they have attempted to conserve the Froude number. The ratio of the velocities and the mass flows of the slug flow and the safety injection flow are also conserved. However, time similitude

is again not conserved and the test rig is limited to atmospheric pressure. Assessment Finding **AF-UKEPR-FS-36** which has been raised for the external dilution case is judged to be equally relevant for the inherent dilution case. Hence, there is a need for a future licensee to present a PIRT and scaling analysis of the Juliette test rig to confirm that the rig has been appropriately scaled to minimise distortion for the important thermal hydraulic phenomenon being studied for inherent boron dilution case when compared with the conditions at full reactor scale to confirm safety margins. It should also be noted that Assessment Finding **AF-UKEPR-FS-38** requiring consideration of the failure of an additional safety injection train may result in the need for further experimental tests to represent the simultaneous restart of natural circulation in two loops.

108 As with the external dilution case, an impressive number of test measurements are presented. This time three test scenarios (1 to 3) were performed. In Test 1, EDF and AREVA claim that the equivalent of a 32 m^3 slug at full reactor scale is injected into cold leg 1 and thermally traced. It is noted that in the reactor the initial temperature of the core is higher than the safety injection flow. On the test facility the temperature of these two fluids is the same (50°C) to enable the hot slug to be thermally traced and so the relative density of the Safety Injection (SI) flow has instead to be increased by using brine solution. Test 2 is identical to Test 1 except that the safety injection is into loops 2 and 3 rather than loops 1 and 3. Hence there is no safety injection into loop 1 which is the loop associated with the unborated test slug. Test 3 is also identical to Test 1 except that the volume of the slug is reduced in size to be the equivalent of an 11 m^3 slug at the full reactor scale. EDF and AREVA considered that Test 3 is the most representative of the three tests and therefore they chose to repeat the test three times to assess the repeatability of the experiments.

109 The test results are summarised in Figs 31, 36, 41 of the report (Ref. 23) for Tests 3, 1, and 2 respectively. These show the maximum relative core inlet temperature where again the temperature scale corresponds to 1.0 for complete unmixed flow and 0.0 for totally mixed flow. Comparison of the Test 3 results in Fig. 31 suggests that the results are again very repeatable. The maximum relative inlet temperature is about 0.23 for Test 3, 0.38 for Test 1, and 0.32 for Test 2. Since Test 3 corresponds to a smaller slug size it is not surprising that it has a maximum that is less than Test 1. More surprising is the fact that Test 2 has a lower peak than Test 1 given that for Test 2 the loop associated with the slug does not have any safety injection flow unlike Test 1. My expectation is that Test 2 would have been more onerous. The report does not appear to comment on this apparent anomaly although the CFD validation report (Ref. 15) implies it is due to the slug mixing in the downcomer with safety injection flow from cold leg 3. Nevertheless, the overall results are encouraging suggesting that due to stratification in the upper part of the downcomer significant mixing occurs before the slug enters the core inlet irrespective of whether it is associated with a loop in which the safety injection is assumed to have failed. If it is assumed that the initial concentration of the unborated slug is zero and the primary circuit has an initial concentration of 2133 ppm then the results predict a minimum boron concentration of 2133 x (1.0 – 0.23) = 1642 ppm in the case of a 11 m^3 slug which can be compared with the critical boron concentration of 1258 ppm.

Transient Analysis (Part 2 – slug transport)

110 In addition to the Juliette measurements (Ref. 23), EDF and AREVA have again supplemented their safety case by performing some CFD analysis (Ref. 18) at the reactor scale. The boundary conditions for these studies are determined using expert judgement based on information from the transient analysis studies performed using the CATHARE

thermal hydraulics system code (Ref. 18) and the findings from the PKL experiments (Ref. 25) on unborated slug creation discussed above in Part 1 of this assessment. EDF and AREVA recognise that while the CATHARE code is good at representing the overall thermal hydraulic response, particularly the filling and draining phases, its capability is limited for modelling boron transfer and to represent counter-current flow in the hot legs during the reflux-condensation phase. Hence the boundary conditions defining slug size and boron concentration are deduced from the findings of the PKL experiments. EDF and AREVA argue that this is a very conservative approach since it ignores the fact that over spilling plays a significant part in fragmenting and mixing a slug formed during the reflux-condensation prior to the restart of sustained natural circulation. I agree that the evidence from the PKL experiments demonstrates that this is a very conservative assumption. The reactor coolant pressure which determines the saturation conditions in the primary circuit, and the safety injection flow and its associated temperature and boron concentration are determined from the CATHARE code calculations while the maximum size of the slug volume of 11 m^3, its boron concentration of 50 ppm, and natural circulation flow transient are determined from the PKL experiment. Specifically, the natural circulation flow start-up transient is taken from PKL test E2.2.

111 The safety case (Ref. 18) outlines how mesh geometry, mesh sizes, turbulence models, numerical schemes and boundary conditions are selected. Safety injection flow is modelled in loops 1 and 3 while the break is assumed to occur in loop 4 and to exactly match the safety injection flow. The accumulators are not modelled. The slug is modelled in loop 2. The safety injection is assumed to be at 40 kg/s at 50°C with a boron concentration of 2113 ppm. The flow from the EBS is assumed to be 1.4 kg/s at 50°C with a boron concentration of 13292 ppm and is injected into loop 3.

112 The calculations predict significant stratification due to the low velocities associated with natural circulation flow coupled with the significant temperature differences between the fluid initially within the pressure vessel (120°C), the safety injection flow (50°C), and the hot unborated slug (235°C). This results in the slug initially remaining in the upper part of the downcomer. The slug only starts to be displaced when as a result of the continuing natural circulation flow in loop 2 hot and highly borated water starts to enter the downcomer. This flushes the unborated water which has started to mix and cool causing it to descend into the downcomer. The results are summarised in Figure 21 of the report (Ref. 18) which illustrates the minimum concentration at the core inlet as a function of time. The concentration is seen to fall from its initial valve of 2133 ppm to a minimum of 1351 ppm which is slightly above the critical boron concentration of 1258 ppm. EDF and AREVA therefore conclude that a return to criticality is avoided.

Confirmatory Analysis (Part 2 – slug transport)

113 Given that extremely complex CFD analysis is being used to support the safety case, I commissioned GRS to perform some confirmatory CFD analysis (Ref. 4) for the SBLOCA case. The work builds on earlier work that GRS had performed during GDA Step 4 (Ref. 24) for the SBLOCA case but incorporates refinements in the modelling to take into account comments made by EDF and AREVA and to also better reflect the new analysis performed by EDF and AREVA. Significantly, GRS have tried to match as close as possible the boundary conditions assumed in the EDF and AREVA analysis (Ref. 18) that were not available at the time of the earlier studies. The most important of these is that the EDF and AREVA test work and analysis do not actually consider the effects of the break flow on the flow distribution in the reactor loops. This is important because of the stratification of flow that is predicted to occur in the downcomer. The implication of this is

that the unborated slug remains in the downcomer for a significant period of time and so discounting the break flow is potentially a conservatism in the EDF and AREVA analysis since the likelihood is that a portion of the slug would immediately exit the primary circuit through the break without first passing through the core.

114 In the original CFD analysis performed by GRS (Ref. 24) this break flow was modelled based upon boundary conditions taken from the ATHLET analysis discussed above. The break is modelled in cold leg 1 and safety injection is assumed to be successful in cold legs 1 and 4. The unborated slug is modelled in cold leg 2. It has a size of 11 m^3 and a minimum boron concentration of 50 ppm and is assumed to be at saturation temperature of 269°C. At the core inlet, the minimum local boron concentration is predicted to be 1042 ppm, down from an initial value of 1200 ppm. The latter value is unrealistically low and in the later GRS work has been revised to 2133 ppm and so it is more important to focus on the change in concentration of about 158 ppm. This is a very small change compared with the EDF and AREVA analysis which predicts a change from 2133 ppm to 1351 ppm, a swing of 782 ppm. Further insight is gained by studying the stream-lines in Figure 3-21 of the report (Ref. 24) which show that most of the unborated slug stays at the top of the downcomer or is entrained out through the break. The remainder mixes with the colder safety injection water and looses its high concentration before it reaches the core inlet. In summary, the original GRS analysis predicts that much of the slug would by-pass the core and the remainder would be well mixed.

115 In the revised CFD analysis performed by GRS (Ref. 4) the break is not modelled. Safety injection is assumed to be successful in cold legs 1 and 3 with the unborated slug modelled in cold leg 2. It has a size of 11 m^3 and a minimum boron concentration of 50 ppm and a saturation temperature of 232°C. The flow in the other cold legs is set to zero. Instead of modelling a break in loop 4, the outflow through the break is assumed to be set equal to the inflow injected from the safety injection train on that loop. The safety injection flow in cold leg 1 is set equal 40 kg/s at 50°C with a boron concentration of 2113 ppm. The mass flow in loop 3 is set equal to 41.4 kg/s at 50°C with a boron concentration of 2491 ppm to account for the additional EBS flow. The initial pressure vessel temperature is set to 120°C with a boron concentration of 2130 ppm. The hot leg pressure boundary condition on all loops is set to 35 bar.

116 The results are summarised in Figure 41 of the report (Ref. 4). This shows that the minimum concentration reduces from 2130 ppm to 1700 ppm, a change of 430 ppm. This is considerably greater change than in the original studies but still significantly less than that predicted by EDF and AREVA which reduces from 2130 ppm to 1350 ppm, a change of 780 ppm. Comparing the transients it is clear that the two results are very similar for the first 85 seconds. Only after this time do the results diverge with the EDF and AREVA prediction for minimum concentration continuing to fall. To try and better understand the differences GRS have compared the predicted boron concentrations in the downcomer region at different time steps in Figure 43 of their report (Ref. 4). Initially at 20 seconds and 40 seconds the results are incredibly similar with the slug staying at the top of the downcomer and spreading around the full circumference of the downcomer. The cold and strongly borated water from cold leg 3 is seen to fall down the downcomer to the lower plenum. After 60 seconds the first differences appear. Lower borated water in the EDF and AREVA simulation is seen to reach the lower areas of the downcomer than in the GRS simulations and this trend continues in the later time steps. GRS makes the observation that in their simulation much of the hot and low borated water from the slug is temporarily stored in the other cold legs were it displaces the colder water that is initially present in these cold legs. This cold water is not displaced in the EDF and AREVA simulations. In view of these differences, I have decided to raise an Assessment Finding

AF-UKEPR-FS-40 for a future licensee to provide further justification for the modelling of the boundary conditions on the cold legs for the inherent boron dilution case.

117 GRS also note that neither of the simulations model the effect of core decay heat and that both simulations predict reverse flow in the central core channels due to recirculation flow. As they note, it is unlikely that such a phenomenon would really occur with realistic modelling of decay heat. This phenomenon will need to be explored further with a future licensee when they respond to Assessment Finding **AF-UKEPR-FS-40**.

118 Although there are differences between the results of the EDF and AREVA analysis and the GRS analysis it is important to note that they both predict significant stratification of the hot unborated slug at the top of the downcomer and that this is predicted to result in good mixing of the slug before it enters the core inlet. Other generic parametric studies of this phenomenon (Ref. 26) have also demonstrated significant stratification is possible although the effect is strongly dependent upon Froude Number. As with the slug creation phase, for the slug transport phase, I tend to place more weight on the experimental evidence from the Juliette test programme discussed above. This also demonstrates strong evidence for flow stratification and mixing.

4.2.3 Findings

119 The inherent heterogeneous boron dilution safety case that EDF and AREVA have presented for the UK EPR™ in response to GDA Issue **GI-UKEPR-FS-01** is an extremely complex multi-legged safety case. I am particularly impressed with the considerable amount of experimental test work that has been performed at the PKL and Juliette test facilities.

120 In my judgement there are a number of conservative assumptions made within the safety case:

- Although the fault is conceded as a PCC-3 event it must be recognised that a very specific break size and location is required for the necessary conditions to occur that would lead to reflux condensation generating slugs of unborated coolant and this has to be in coincidence with a single failure or plant maintenance condition on at least one of the safety injection trains.
- The fault is also assumed to occur early in cycle when the minimum critical boron concentration is at its highest. The comparison against minimum boron concentration is also conservative in that it is assuming the localised reduction in boron concentration should be uniformly applied across the whole core.
- Even though the restart of natural circulation occurs typically an hour or so after reactor trip, the effect of the xenon transient on the minimum shutdown margin is completely ignored. Instead an assumption of zero xenon poisoning is made. The equilibrium level of xenon at power alone is worth about 3000 pcm, which is equivalent to an additional boron concentration of about 600 ppm, even before taking account of any transient increase.
- In a decoupling assumption, the Juliette test rig and the CFD analysis covering the transportation of the unborated slug assume the size of the slug is 11 m^3 with a boron concentration of about 50 ppm. Work from the PKL test rig has demonstrated that this is the theoretical maximum size of the slug and that in reality intermittent flows prior to the restart of natural circulation will result in an increase in the boron concentration.

- There is strong evidence from the Juliette test rig for stratification of the natural circulation flow in the downcomer resulting in the mixing of the slug prior to it being transported to the core inlet. In addition, the Juliette test rig and in the CFD analysis used to analysis the transportation of the slug ignore the effects of the break on the flow distribution in the downcomer. Given the stratification of the natural circulation flow this is likely to lead to a portion of the slug exiting the vessel through the break without first passing through the core.

121 In my opinion, these conservatisms when taken together provide sufficient evidence when judged against the requirements of SAP FA.7 and SAPs FA.17 to FA.24 to conclude that an adequate safety case has been presented for the purposes of GDA subject to the satisfactory close out of the four assessment findings that have been raised (**AF-UKEPR-FS-36, AF-UKEPR-FS-38, AF-UKEPR-FS-39** and **AF-UKEPR-FS-40)**. In general, these are items requiring further analysis or possibly additional experimental tests rather than a fundamental issue with the design. In my judgement, they can be closed out as part of the site specific detailed design phase. EDF and AREVA have therefore made sufficient progress with the safety case for inherent heterogeneous boron dilution faults to justify the closure of **GI-UKEPR-FS-01**.

4.3 Review of the Updates to the PCSR

122 Sub-chapters 14.7, 15.1, 16.3 and 16.4 of the updated PCSR (Ref. 19) consider heterogeneous boron dilution faults. These sub-chapters were reviewed to ensure that the outcome of the GDA assessment had been appropriately captured within the PCSR. I am satisfied that the revised sub-chapters accurately reflect the analysis work and design modifications developed to justify the closure of **GI-UKEPR-FS-01**.

5 ASSESSMENT CONCLUSIONS

123 EDF and AREVA have undertaken a large amount of analysis work within the Fault Studies assessment area during the close-out phase of GDA and made significant progress against the GDA Issue **GI-UKEPR-FS-01** on heterogeneous boron dilution faults identified in my GDA Step 4 assessment report.

124 In my opinion, EDF and AREVA have considerably strengthened the design basis safety against heterogeneous boron dilution faults for the UK EPR™ through the additional safety case information and new analysis performed in response to GDA Issue **GI-UKEPR-FS-01**. This has included a rationalisation of the postulated initiating events leading to external heterogeneous boron dilution faults which has helped focus the comprehensive review of potential ALARP improvements. In addition, they have developed a completely new safety case for the inherent heterogeneous boron dilution fault.

125 The analytical work performed by EDF and AREVA has been aided by a number of important design changes to the C&I systems on the UK EPR™ and also by some important changes in operating procedures that in my opinion will significantly improve safety of the design. These changes have been proactively identified by EDF and AREVA. The changes identified are:

- A Class 1 interlock is to be implemented to prevent the operator from restarting RCP pump n°1 if the CVCS letdown has not run sufficiently to purge loop 1.
- A Class 1 interlock is to be implemented to prevent the operator from restarting the other RCP pumps until RCP n°1 has first been restarted.
- A modification will be implemented to automatically isolate the heat exchangers used to cool the mechanical seals on the RHRS pump when the pump is not in operation.
- Procedures will be revised such that, when the reactor is depressurised, the operator is required to close the containment isolation valves on the CCWS lines that cool the HP cooler on the CVCS letdown line.
- Procedures will be revised such that, when the reactor is depressurised and the RCPs are not in operation, the operator is required to close the containment isolation valves on the CCWS lines that cool the RCP thermal barriers.

126 Although there are a number of Assessment Findings, these are mostly associated with the C&I interlock systems or providing additional evidence to validate claims made in the safety case. In my judgement, it is unlikely that these will result in design changes that affect plant layout, mechanical equipment design or operational procedures.

5.1 Overall Conclusions

127 Overall, based on my assessment undertaken in accordance with ONR procedures, I am satisfied that the safety case for heterogeneous boron dilution faults presented in the supporting documentation submitted in response to GDA Issue **GI-UKEPR-FS-01** is adequate subject to satisfactory progression and resolution of the Assessment Findings identified in Annex 2. These are to be addressed during the site specific detailed design phase. For this reason, I am satisfied that GDA issue **GI-UKEPR-FS-01** can now be closed.

6 ASSESSMENT FINDINGS

6.1 Additional Assessment Findings

128 The following Assessment Findings have been raised that are required to be resolved during the site specific detailed design phase:

> ***AF-UKEPR-FS-30:*** *The future licensee shall provide a revised PSA for external heterogeneous boron dilution faults.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-31:*** *The future licensee shall explicitly demonstrate that the design basis safety case for external heterogeneous boron dilution faults meets the requirements of the PCC analysis rules presented in the PCSR.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-32:*** *The future licensee shall demonstrate the functional capability of the CVCS letdown line to purge an unborated slug from a loop on the primary circuit. Ideally, the demonstration should take the form of a test performed upon either a full scale test rig or an EPR™ reactor plant during commissioning.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-33:*** *The future licensee shall review the feasibility of providing additional interlocks on the RHR system to ensure the system is purged with borated water from the IRWST prior to injection into the RCS and to ensure that the RHR is used to purge the hot and cold legs of loop 1 prior to RCP restart.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-34:*** *The future licensee shall implement the human factors issue register recommendations for design and procedure features from the human factors analyses to support the heterogeneous boron dilution safety case, or provide a justification as to why these are not required to meet ALARP requirements.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-35:*** *The future licensee shall review the design of the C&I interlock systems to ensure that adequate diversity is provided for frequent heterogeneous boron dilution faults.*
>
> ***Required timescale:*** *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*
>
> ***AF-UKEPR-FS-36:*** *The future licensee shall perform PIRT and scaling analyses for the Juliette test rig to confirm its applicability for providing validation evidence of the important thermal hydraulic phenomena associated with heterogeneous boron dilution faults and to confirm safety margins.*

Required timescale: *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*

AF-UKEPR-FS-37: *The future licensee shall provide further justification for the flow resistance data assumed in the CFD modelling of the flow distribution device.*

Required timescale: *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*

AF-UKEPR-FS-38: *The future licensee shall provide further justification for not selecting failure of an additional train of the safety injection system as the most onerous single failure for the inherent heterogeneous boron dilution safety case.*

Required timescale: *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*

AF-UKEPR-FS-39: *The future licensee shall perform PIRT and scaling analyses for the PKL test rig to confirm its applicability for providing validation evidence of the important thermal hydraulic phenomena associated with heterogeneous boron dilution faults.*

Required timescale: *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*

AF-UKEPR-FS-40: *The future licensee shall provide further justification for the CFD modelling of the boundary conditions assumed in the cold leg loops for the inherent boron dilution transient analysis studies.*

Required timescale: *Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site*

129 These Assessment Findings are listed in Annex 2.

6.1.1 Impacted Step 4 Assessment Findings

130 As noted in the main text of the report, a couple of Assessment Findings have been impacted as a result of this assessment. In the fault studies area **AF-UKEPR-FS-08** requires the fault analysis be updated to reflect the UK EPR™ design. Some of the transient analysis reported in the heterogeneous boron dilution safety case is not specific to the UK design and so will need to be updated. Similarly, **AF-UKEPR-FS-29** requires that the fault schedule in the PCSR is regularly updated to reflect revisions in the safety case.

7 REFERENCES

1 *GDA Issue GI-UKEPR-FS-01 Heterogeneous Boron Dilution safety Case Revision 0.* ONR. July 2011. TRIM Ref. 2011/385301

2 *Step 4 Fault Studies – Design Basis Faults Assessment of the EDF and AREVA UK EPR™ Reactor*. ONR Assessment Report ONR-GDA-AR-11-020a Revision 0. TRIM Ref. 2010/581404.

3 *Resolution Plan for GDA Issue GI-UKEPR-FS-01 Revision 0.* EDF and AREVA. June 2011. TRIM Ref. 2011/347614

4 *Unborated Slug of Water Assessment* GRS-HSE/ONR-WP04. GRS. October 2012. TRIM Ref. 2012/448580

5 *ONR HOW2 Permissioning – Purpose and Scope of Permissioning.* PI/FWD Issue 3. HSE. August 2011.

6 *Assessment Plan for Fault Studies, Closure of GDA for the EPR™.* ONR-GDA-AP-11-007 Revision 0, October 2011. TRIM Ref. 2011/479495

7 *Safety Assessment Principles for Nuclear Facilities.* 2006 Edition Revision 1. HSE. January 2008. www.hse.gov.uk/nuclear/SAP/SAP2006.pdf.

8 *Technical Assessment Guide. Transient Analysis for Design Basis Accidents in Nuclear Reactors*. T/AST/034 Issue 1. HSE. Nov 1999.
Technical Assessment Guide. Validation of Computer Codes and Calculational Methods T/AST/042 Issue 1. HSE.
www.hse.gov.uk/nuclear/operational/tech_asst_guides/index.htm.

9 *Reference Design Configuration*. UKEPR-I-002 Revision 15. UK EPR™. December 2012. TRIM Ref. 2012/478281.

10 *EDF and AREVA UK EPR™ - Schedule of Technical Queries Raised during GDA Close-out.* Office for Nuclear Regulation. TRIM Ref. 2011/389411.

11 *Human Factors Assessment Report for GI-UKEPR-HF-01* ONR Assessment Report ONR-GDA-AR-12-009 Revision 0. TRIM Ref. 2012/9.

12 *GDA Issue GI-UKEPR-HF-01 Close Out Submission Assessment Note* EDF/AREVA GDA Human Factors: Heterogeneous Boron Dilution, October 2012, TRIM Ref. 2012/363738

13 *Heterogeneous Boron Dilution Fault Schedule – July 2011,* PEPR-F 67 Revision A, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR00923N. 29 July 2011. TRIM Ref. 2011/403790

14 *Countermeasures against Heterogeneous Dilution Initiators – July 2011,* PEPR-F DC 70 Revision A, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR00913N. 28 July 2011. TRIM Ref. 2011/402502

15 *CFD Simulation of the Juliette Tests – STAR-CD – Physical Validation for External and Inherent Dilution – November 2011.* PEPD-F DC 13 Revision B, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR01021N. 1 December 2011. TRIM Ref. 2011/615556.

16 *Heterogeneous Boron Dilution resulting from an improper Reactor Coolant Pump start-up – November 2011.* PEPR-G DC 100032 Revision A, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR01006N. 7 November 2011. TRIM Ref. 2011/571520

17 *Design Improvements for Heterogeneous Boron Dilution Faults – June 2012,* PEPR-F DC 97 Revision A, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR01191N. 7 June 2012. TRIM Ref. 2012/240887

18 *UK EPR^{TM} –Safety Case for the Inherent Boron Dilution following LOCA – July 2011.* PEPR-F DC 24 Revision A, EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR00913N. 28 July 2011. TRIM Ref. 2011/402499

19 *PCSR Sub-Chapter 14.4 Update – Analyses of the PCC-3 events* UKEPR-0002-144 Issue 08, November 2012, TRIM Ref. 2012/462138
PCSR Sub-Chapter 15.1 Update – Level 1 PSA UKEPR-0002-151 Issue 05, November 2012, TRIM Ref. 2012/439082
PCSR Sub-Chapter 16.3 Update – Practically Eliminated Situations UKEPR-0002-163 Issue 04, November 2012, TRIM Ref. 2012/460008
PCSR Sub-Chapter 16.4 Update – Specific Studies UKEPR-0002-166 Issue 04, November 2012, TRIM Ref. 2012/467463

20 *UK EPR™ Pre-construction Safety Report – November 2009 Submission.* Submitted under cover of letter UN REG EPR00226N. 30 November 2009. TRIM Ref. 2009/481363 and as detailed in UK EPR Master Submission List. November 2009.
TRIM Ref. 2011/46364.

21 *UK EPR™ GDA Step 4 Consolidated Pre-construction Safety Report – March 2011.* EDF and AREVA. Detailed in EDF and AREVA letter UN REG EPR00997N.
18 November 2011. TRIM Ref. 2011/552663.

22 *EDF / AREVA GDA Human Factor Issue: Heterogeneous Boron Dilution*, AMEC Report 16895-707-000-RPT-0014 Issue F-BPE, August 2012. TRIM Ref. 2012/436940

23 *Dilution Tests on Juliette Mock-up description of Facility and Tests Grids – April 2012, PEPD-F DC 17 Rev B,* EDF and AREVA, 26 April 2012. TRIM Ref. 2012/180188

24 *Unborated Slug of Water Assessment.* GRS-V-HSE-WP08-01. GRS. November 2010. TRIM Ref. 2011/143816.

25 *PKL III Tests on Heterogeneous Boron Dilution following SB-LOCA (Cold leg Break/Cold Leg SI) – Applicability to Reactor Scale.* May 2009. NTCTP-G/2008/en/0003.
TRIM Ref. 2011/94276

26 *Parameterization of buoyancy effects in generic PWR boron dilution scenarios*
International Conference on Nuclear Engineering ICONE-14-89480
July 17-20, TRIM Ref. 2013/22896

Annex 1

Deliverables and Associated Technical Queries Raised During Close-out Phase

GI-UKEPR-FS-01 Revision 0 – Heterogeneous Boron Dilution Safety case – EDF and AREVA Deliverables

GDA Issue Action	Fault Studies Area	Document Ref.	Title	Ref.
GI-UKEPR-FS-01.A1	External Heterogeneous Dilution Faults	PEPR-F DC 67	External Heterogeneous Boron Dilution Fault Schedule	13
GI-UKEPR-FS-01.A1	External Heterogeneous Dilution Faults	PEPR-F DC 70	Counter Measures against Heterogeneous Dilution Initiators	14
GI-UKEPR-FS-01.A1	Validation Evidence	PEPD-F DC 13	CFD Simulation of the Juliette Tests – STAR-CD – Physical Validation for External and Inherent Dilution	15
GI-UKEPR-FS-01.A1	Validation Evidence	PEPD-F DC 17	Dilution Tests on Juliette Mock-up description of Facility and Test Grids (Response to TQ-EPR-1560)	28
GI-UKEPR-FS-01.A1	External Heterogeneous Dilution Faults	PEPR-G DC 100032	Heterogeneous Boron Dilution resulting from an improper Reactor Coolant Pump start-up	16
GI-UKEPR-FS-01.A1	ALARP Review	PEPR-F DC 97	Design Improvements for Heterogeneous Boron Dilution Faults	17
GI-UKEPR-FS-01.A1	Inherent Heterogeneous Dilution Faults	PEPR-F DC 24	Safety Case for the Inherent Boron Dilution following LOCA	18
GI-UKEPR-FS-01.A1	External Heterogeneous Dilution Faults	PEPC-F DC 70	Safety Case for Heterogeneous Boron Dilution Fault (Response to TQ-EPR-1540 included in Chapter 16.4 PCSR update)	19

Annex 1

Deliverables and Associated Technical Queries Raised During Close-out Phase

GI-UKEPR-FS-01 Revision 0 – Heterogeneous Boron Dilution Safety Case – Technical Queries Raised

TQ Reference	GDA Issue Action	Related Submission	Description
TQ-EPR-1473	GI-UKEPR-FS-01.A1	PEPR-F DC 24	References for Boron Dilution Safety Case
TQ-EPR-1535	GI-UKEPR-FS-01.A1	PEPR-F DC 67	PSA Model for Boron Dilution Safety Case
TQ-EPR-1540	GI-UKEPR-FS-01.A1	PEPR-F DC 67 PEPR-F DC 70	Comments on Boron Dilution Fault Schedule
TQ-EPR-1557	GI-UKEPR-FS-01.A1	PEPR-F DC 24 PEPR-G DC 100032	Reference data for independent confirmatory analysis on EPRTM for the Boron Dilution Safety Case
TQ-EPR-1560	GI-UKEPR-FS-01.A1	PEPR-F DC 24 PEPR-G DC 100032 PEPD-F DC 13	PIRT and Scaling Analysis to support the Experimental Validation of the Boron Dilution Safety Case
TQ-EPR-1608	GI-UKEPR-FS-01.A1	PEPR-F DC 24	Inherent boron dilution following LOCA – sensitivity studies to operator action
TQ-EPR-1612	GI-UKEPR-FS-01.A1	PEPR-F DC 24 PEPR-G DC 100032	Reference data for independent confirmatory analysis on EPRTM for the Boron Dilution Safety Case

Annex 2

GDA Assessment Findings Arising from GDA Close-out for GI-UKEPR-FS-01 Revison 0

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-FS-30	The future licensee shall provide a revised PSA for external heterogeneous boron dilution faults.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-31	The future licensee shall explicitly demonstrate that the design basis safety case for external heterogeneous boron dilution faults meets the requirements of the PCC analysis rules presented in the PCSR.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-32	The future licensee shall demonstrate the functional capability of the CVCS letdown line to purge an unborated slug from a loop on the primary circuit. Ideally, the demonstration should take the form of a test performed upon either a full scaled test rig or an EPR™ reactor plant during commissioning.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-33	The future licensee shall review the feasibility of providing additional interlocks on the RHR system to ensure the system is purged with borated water from the IRWST prior to injection into the RCS and to ensure that the RHR is used to purge the hot and cold legs of loop 1 prior to RCP restart.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-34	The future licensee shall implement the human factors issue register recommendations for design and procedure features from the human factors analyses to support the heterogeneous boron dilution safety case, or provide a justification as to why these are not required to meet ALARP requirements.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-35	The future licensee shall review the design of the C&I interlock systems to ensure that adequate diversity is provided for frequent heterogeneous boron dilution faults.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-36	The future licensee shall perform PIRT and scaling analyses for the Juliette test rig to confirm its applicability for providing validation evidence of the important thermal hydraulic phenomena associated with heterogeneous boron dilution faults and to confirm safety margins.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site

Annex 2

GDA Assessment Findings Arising from GDA Close-out for GI-UKEPR-FS-01 Revison 0

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-FS-37	The future licensee shall provide further justification for the flow resistance data assumed in the CFD modelling of the flow distribution device.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-38	The future licensee shall provide further justification for not selecting failure of an additional train of the safety injection system as the most onerous single failure for the inherent heterogeneous boron dilution safety case.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-39	The future licensee shall perform PIRT and scaling analyses for the PKL test rig to confirm its applicability for providing validation evidence of the important thermal hydraulic phenomena associated with heterogeneous boron dilution faults.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site
AF-UKEPR-FS-40	The future licensee shall provide further justification for the CFD modelling of the boundary conditions assumed in the cold leg loops for the inherent boron dilution transient analysis studies.	Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site

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.

GDA Issue, **GI-UKEPR-FS-01** Revision 0 – Fault Studies – UK EPR™

EDF AND AREVA UK EPR™ GENERIC DESIGN ASSESSMENT

GDA ISSUE

HETEROGENEOUS BORON DILUTION SAFETY CASE

GI-UKEPR-FS-01 REVISION 0

<table>
<tr><td colspan="2">Technical Area</td><td colspan="2">FAULT STUDIES</td></tr>
<tr><td colspan="2">Related Technical Areas</td><td colspan="2">Probabilistic Safety Assessment
Reactor Chemistry</td></tr>
<tr><td>GDA Issue Reference</td><td>GI-UKEPR-FS-01</td><td>GDA Issue Action Reference</td><td>GI-UKEPR-FS-01.A1</td></tr>
<tr><td>GDA Issue</td><td colspan="3">A safety case for heterogeneous boron dilution events is required. Both external dilution events and intrinsic dilution mechanisms from certain accident situations need to be addressed.</td></tr>
<tr><td>GDA Issue Action</td><td colspan="3">EDF and AREVA to provide ONR with a safety case for heterogeneous boron dilution faults. This needs to consider both external and intrinsic faults.

ONR’s expectation is that faults are identified as being within the design basis based on their initiating frequency and their unmitigated consequences. Arguments that heterogeneous boron dilution faults are practically eliminated and do not need a full design basis analysis treatment due to probabilistic arguments taking benefit for engineered safety measures are unlikely to be accepted.

CFD analysis is a developing methodology, which offers insights into complex scenarios like heterogeneous boron dilution faults. However it can be sensitive to many variables, for example the skill of the practitioner, fine details of the model, the assumed boundary conditions etc. Validation of the CFD model is both important and difficult. ONR therefore encourages EDF and AREVA not to provide a safety case heavily reliant on claims derived directly from CFD analysis.

ONR’s assessment of the heterogeneous boron dilution safety case will inevitably generate questions and request further evidence. EDF and AREVA shall respond to ONR’s queries on the supplied safety case and provide further evidence, especially related to:
EDF and AREVA are claiming that the size of any un-borated slug of water will be limited by safety classified boron meters. EDF and AREVA need to provide evidence that these devices are capable of delivering this function to the requisite reliability.
For those faults where the size of an un-borated slug is restricted by other means, for example following a steam generator tube plugging error, EDF and AREVA also need to provide evidence they too are capable of delivering this function to the requisite reliability. A heavy reliance on administrative controls is likely to be subject to scrutiny by ONR.
For dilution events resulting from intrinsic mechanisms, EDF and AREVA will need to provide evidence of adequate validation for any CFD derived claims used as part of a multi-legged safety case.
EDF and AREVA shall update the PCSR in accordance with the agreed safety case.

With agreement from the Regulator this action may be completed by alternative means.</td></tr>
</table>