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-RC-01 Revision 1 – Combustible Gas Control Systems

Assessment Report: ONR-GDA-AR-12-019
Revision 0
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EXECUTIVE SUMMARY

This report presents the close-out of part of the Office for Nuclear Regulation's (an agency of HSE) Generic Design Assessment (GDA) within the area of Reactor Chemistry. The report specifically addresses the GDA Issue **GI-UKEPR-RC-01 Revision 1** generated as a result of the GDA Step 4 Reactor Chemistry Assessment of the UK EPR™. The Step 4 Reactor Chemistry assessment concluded that the UK EPR™ reactor was suitable for construction in the UK subject to satisfactory resolution of a number of GDA Issues. On the basis of the claims, arguments and evidence presented to the end of Step 4, I considered that the UK EPR™ safety case related to combustible gas control required further work in three discrete areas before I could be satisfied for GDA. These areas all relate to the performance of the Passive Auto-catalytic Recombiners (PARs), which are an integral part of the UK EPR™ Combustible Gas Control System (CGCS), and are aspects which need to be considered as part of the suite of supporting analysis for UK EPR™, namely:

- Operation of the CGCS with reduced PAR performance.
- Analysis under bounding accident conditions.
- Effect of PAR operation on the production of volatile iodine in the containment.

To address this GDA Issue, and associated three Actions, EDF and AREVA provided additional information, through a series of analysis reports, responses to technical queries and through technical meetings. The main deliverables provided in response to this GDA Issue included:

- A sensitivity study which determines the effects of a reduced PAR performance on the hydrogen distribution in containment.
- A suite of reports which provide the computational validation procedure of the EPR™ combustible gas control concept, including under bounding accident conditions. These reports consider topics such as the distribution of hydrogen in the containment and its removal by recombiners during the in-vessel phases, thermal loads from recombination and laminar deflagration of hydrogen accumulated in the containment dome, the potential for fast deflagration and its consequences with regard to the dynamic pressure on internal walls and the containment shell and whether the combustible gases which are produced during ex-vessel phases burn close to their release location or if there is a risk of accumulation of these gases in the upper containment regions.
- A sensitivity study which examines the potential increase in radiological releases to the environment caused by interaction of the recombiners with iodine, in the event of an accident which involves core melting.

From my assessment, I have concluded that:

- The results of the sensitivity study for reduced PAR performance indicate that the PARs are able to undergo a significant reduction in their overall effectiveness and still maintain the design intentions of the system and this situation does not lead to conditions which should threaten the containment integrity. The applied reduction in PAR performance incorporated in the model is relatively simple in nature, and therefore complexities relating to local effects are not captured, however the results show that the system as a whole provides significant margin in operational capability with respect to the most demanding accident scenarios. Furthermore, the analyses carried out have provided highly useful additional understanding of the behaviour of the CGCS and the way in which a reduction in performance will be partially compensated by the remaining capacity of the system, provided the PARs are not operating in a saturated regime. The results indicate that a system wide reduction in

performance in the order of 25% does not result in a cliff-edge in performance, even when considering the most penalising accident scenario identified.

- In order to demonstrate the performance of the CGCS under bounding conditions EDF and AREVA provided their analysis for the Flamanville 3 (FA3) reference plant. EDF and AREVA have confirmed the expectation that the licensee will provide site specific, rather than generic analysis for any EPR™ to be built in the UK. The FA3 analysis presented has been used to build confidence in the approach, to satisfy the GDA Issue Action and ultimately to demonstrate that the claims, arguments and evidence presented in the generic UK EPR™ PCSR remain sound. In assessing this analysis I consider that:
    1. It is thorough and provides confidence that the results are robust, the methodology adopted is appropriate and the resulting data has been used intelligently.
    2. EDF and AREVA logically consider the main risks and conclude they are successfully avoided or are within the capabilities of the design.
    3. The results show the importance of the PAR system in decreasing the combustible gas concentration in the medium and long-term and that while the PAR system is dimensioned to account for those scenarios which form the basis of the design, it remains adequate to respond to more aggravated penalising cases.
    4. I have identified several areas where additional development in the safety case is required as site specific work progresses. These do not undermine the validity of the results presented and I have raised Assessment Findings to ensure these are resolved satisfactorily.
    5. Ultimately, the response to this GDA Issue Action confirms that the generic PCSR claims are met and that the CGCS has the capability to meet the demands that are likely to be placed upon it under bounding conditions.
- The effect of the recombiners on the production of volatile iodine in UK EPR™ were analysed by EDF and AREVA to estimate the impact of any conversion of aerosol forms of iodine to volatile forms during a severe accident. This analysis used information on the recombiner performance derived from the detailed CGCS analysis and a range of assumed iodine conversion rates. A specific analysis code was used, which differs from the PCSR by incorporating a detailed treatment of the iodine chemistry. This detailed chemistry changes the predicted form of the iodine in the containment, compared to the assumptions in the PCSR, but also decreases the total amounts predicted to be released to the environment and even assuming a pessimistic conversion rate for the iodine predicts releases to the environment which are lower than claimed by the PCSR. While there are some inherent uncertainties in this approach, sufficient margin has been demonstrated and the use of pessimistic assumptions in the PCSR has been demonstrated to be bounding for the effect of recombiners. Overall, the claims made in the PCSR have been demonstrated.
- In response to this GDA Issue, EDF and AREVA updated the PCSR. I have reviewed these updates and am content that they accurately reflect the responses to the Issue Actions.

Overall, based on my assessment undertaken in accordance with ONR procedures, I consider the responses to be satisfactory and sufficient for closing the GDA Issue. This assessment has resulted in 13 new Assessment Findings which will need to be resolved by a future UK EPR™ licensee on a site specific basis.

LIST OF ABBREVIATIONS

AICC	Adiabatic Isochoric Complete Combustion
AREVA	AREVA NP SAS
"*Bounding*" scenario	EDF and AREVA use "*bounding*" scenarios to demonstrate the robustness of the combustible gas control system, and to show that no "cliff edge" effects exist. For "*bounding*" scenarios EDF and AREVA still require the containment integrity to be demonstrated. The "*bounding*" scenarios are chosen among the different core melt scenarios but feature some form of additional aggravation, such as a delayed primary circuit depressurisation. These scenarios are selected irrespective of their probability of occurrence. See also "*Representative*" scenarios.
CFD	Computational Fluid Dynamics
CGCS	Combustible Gas Control System [EDF coding system – ETY]
CHRS	Containment Heat Removal System [EDF coding system – EVU]
CL	Cold Leg
CMSS	Core-Melt Stabilisation System
DDT	Deflagration to Detonation Transition
EBU	Eddy Break-Up (combustion model)
EDF	Groupe Electricité de France
EPR™	AREVA pressurised water reactor design
FA3	Flamanville 3
FC	Fast Cooldown
GDA	Generic Design Assessment
HL	Hot Leg
HSE	(The) Health and Safety Executive
HSL	(The) Health and Safety Laboratory
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
IRWST	In-containment Refuelling Water Storage Tank
LBLOCA	Large Break Loss of Coolant Accident
LOOP	Loss of Off-Site Power
LP	Lumped Parameter (code)
MAAP	Modular Accident Analysis Program
MCCI	Molten Core-Concrete Interaction
MOX	Mixed-Oxide (fuel)
NRC	Nuclear Regulatory Commission (US)
OECD	Organisation for Economic Cooperation and Development
ONR	Office for Nuclear Regulation
PAR	Passive Autocatalytic Recombiner
PC	Partial Cooldown
PCSR	Pre-Construction Safety Report

PSA	Probabilistic Safety Analysis
PWR	Pressurised Water Reactor
PZR	Pressuriser
"*Representative*" scenario	EDF and AREVA use "*representative*" scenarios as the basis for the design of the combustible gas control system, to validate the severe accident management and mitigation measures, to demonstrate that the measures work as designed and to demonstrate that the integrity and leak rate of the containment are maintained. They consist of core melt scenarios in which the depressurisation of the primary circuit is actuated and works as intended. These scenarios are selected with regard to their likelihood. See also "*Bounding*" scenarios.
RO	Regulatory Observation
ROA	Regulatory Observation Action
RP	Requesting Party
RPV	Reactor Pressure Vessel
SAP	Safety Assessment Principle
SBLOCA	Small Break Loss of Coolant Accident
SBO	Station Black-Out
TAG	(Office for Nuclear Regulation) Technical Assessment Guide
TQ	Technical Query
UK	United Kingdom
UK EPR™	EDF and AREVA UK specific pressurised water reactor design

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1 INTRODUCTION

1.1 Background

1 This report presents the assessment conducted as part of the close-out of the Office for Nuclear Regulation (ONR), an agency of the Health and Safety Executive (HSE), Generic Design Assessment (GDA) within the area of Reactor Chemistry. The report specifically addresses the GDA Issue **GI-UKEPR-RC-01** Revision 1 and associated GDA Issue Actions (Ref. 1) generated as a result of the GDA Step 4 Reactor Chemistry assessment of the UK EPR™ (Ref. 2), related to the control of combustible gases. The assessment has focussed on the deliverables identified within the EDF and AREVA resolution plans (Ref. 3) published in response to the GDA Issue and on further assessment undertaken of those deliverables.

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

4 The Step 4 assessments concluded that the UK EPR™ reactor was suitable for construction in the UK subject to resolution of 31 GDA Issues. The purpose of this report is to provide the assessment which underpins the judgement made in closing GDA Issue **GI-UKEPR-RC-01**.

1.2 Methodology

5 This assessment has been undertaken in line with the requirements of the Office for Nuclear Regulation (ONR) HOW2 PI/FWD – Issue 3 (Ref. 4) which sets down the process of assessment within ONR. The Safety Assessment Principles (SAPs) (Ref. 5) have been used as the basis for this assessment. Ultimately, the goal of assessment is to reach an independent and informed judgment on the adequacy of a nuclear safety case.

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

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

1.3 Structure

8 The assessment report structure differs slightly from the structure adopted for the previous reports produced within GDA, most notably from the Step 4 Reactor Chemistry assessment (Ref. 2). While previous reports have made extensive use of sampling, this present report builds on the previous work during GDA and focuses on the resolution of the GDA Issues. As such this report is structured around the assessment of **GI-UKEPR-RC-01** rather than a report detailing close-out of all GDA Issues associated with this technical area.

9 The reasoning behind adopting this reporting approach is to allow closure of GDA Issues as the work is completed rather than waiting for the completion of all the GDA work in the Reactor Chemistry technical area.

2 ONR'S ASSESSMENT STRATEGY FOR REACTOR CHEMISTRY

10 The intended assessment strategy for close-out of GDA for the Reactor Chemistry topic area was set out in an assessment plan (Ref. 6) that identified the intended scope of the assessment and the standards and criteria that would be applied. This is summarised below:

2.1 Assessment Scope

11 This report presents only the assessment undertaken for resolution of Reactor Chemistry GDA Issue **GI-UKEPR-RC-01**, related to the combustible gas control systems (Ref. 1).

12 This report does not represent the complete assessment of UK EPR™ in the Reactor Chemistry topic area for GDA, or even the complete assessment of the combustible gas control systems. It is recommended that this report be read in conjunction with the Step 3 and Step 4 Reactor Chemistry assessments of the EDF and AREVA UK EPR™ (Refs 7 and 2) in order to appreciate the totality of the assessment undertaken as part of the GDA process. Section 3 of this report does provide a brief overview of the background to **GI-UKEPR-RC-01**.

13 Similarly, this assessment report does not revisit aspects of assessment already undertaken and accepted as being adequate during previous stages of GDA. However, should the assessment of EDF and AREVA's responses to the GDA Issue highlight shortfalls not previously identified during Step 4 or cast doubt on previously accepted arguments, 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 the site specific phase. As such the possibility of further Assessment Findings being generated as a result of this present assessment is not precluded.

14 Table 1 summarises **GI-UKEPR-RC-01** and its associated GDA Issue Actions generated as a result of the Step 4 Reactor Chemistry assessment. Annex 2 of this report contains the full text of the GDA Issue and Actions. Ref. 8 provides further background and explanatory information on the GDA Issue and Actions. EDF and AREVA have produced individual resolution plans for each of the GDA Issues which detail the methods by which they intended to resolve the Issues through identified timescales and deliverables; see Ref. 3.

GDA Issue Number	GDA Issue Description	Summary of GDA Issue Action	GDA Issue Resolution Plan and Reference
GI-UKEPR-RC-01	Combustible Gas Control Systems	Action 1 – EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the operation of the UK EPR™ Combustible Gas Control System (CGCS) with reduced performance of the Passive Autocatalytic Recombiners (PARs).	Resolution Plan for GI-UKEPR-RC01, GI-UKEPR-RC01-RP, Rev 0, 05.07.2011. (Ref. 3)
		Action 2 – EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the performance of the UK EPR™ Combustible Gas Control System (CGCS) in case of a bounding accident scenario.	
		Action 3 – EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the potential impact of operation of the UK EPR™ CGCS on iodine volatility in containment.	

Table 1: GI-UKEPR-RC-01, associated actions and resolution plans

15 A number of other assessment areas have provided input into the overall assessment of this Reactor Chemistry GDA Issue. This report is consistent with that assessment. Where necessary, for example for more significant assessment items, this is reported in more detail elsewhere as referenced in the assessment section of this report (Section 4).

2.2 Assessment Methodology

16 This report has been prepared in accordance with relevant ONR guidance (Refs 4 and 9) in coordination with the other assessment disciplines and the scope defined in the assessment plan (Ref. 6).

17 The assessment process consists of examining the evidence provided by EDF and AREVA in responding to the GDA Issue Actions. This is then assessed against the expectations and requirements of the SAPs and other guidance considered appropriate. Further details on the information that supported this assessment are given in Section 2.4 of this report.

18 The basis of the assessment undertaken to prepare this report is therefore:

- Submissions made to ONR in accordance with the resolution plans.
- Updates to the submission / PCSR / supporting documentation.
- The Design Reference that relates to the submission / PCSR as set out in UK EPR™ GDA Project Instruction UKEPR-I-002 (Ref. 10).

- Consideration of internal and international standards and guidance, international experience, operational feedback and expertise and assessments performed by other regulators, especially their findings.
- Interaction with other relevant technical areas (where appropriate).
- Raising and issuing of Technical Queries (TQs) as appropriate, followed by assessment of Requesting Party (RP) responses.
- Holding necessary technical meetings to progress the identified lines of enquiry.

19 Consistent with the GDA deadlines and to provide ONR with information for use in my assessment of **GI-UKEPR-RC-01**, I procured a programme of work involving a number of Technical Support Contractors (TSC). Further details of this support programme, and its relevance to the assessment conducted is given in Section 2.5 of this report.

2.3 Assessment Approach

20 The approach to the closure of GDA for the UK EPR™ is described in greater detail in the Reactor Chemistry assessment plan (Ref. 6) and is based upon the assessment methodology described above. The closure of each Reactor Chemistry GDA Issue is reflected in a standalone assessment report, which will describe the closure of the GDA Issue from the position established at the end of Step 4 (this report).

21 The overall strategy for closure of GDA is to build upon the assessment conducted during Step 4 and earlier, focussing on the detailed examination of the evidence presented by EDF and AREVA to support the satisfactory resolution of the GDA Issue Actions.

22 The following subsections provide an overview of the outcome from each of the information exchange mechanisms in further detail.

2.3.1 Technical Queries

23 A total of 6 Technical Queries (TQs) were raised with EDF and AREVA for the Reactor Chemistry assessment during close-out of **GI-UKEPR-RC-01** for UK EPR™. Refer to (Ref. 11).

24 The responses provided by EDF and AREVA to the TQs were assessed by ONR as part of this assessment. Commentary on the most important and relevant TQ responses is included in the assessment section later in this report as appropriate. The responses provided by EDF and AREVA to these actions supplied further evidence supporting the overall judgement on the adequacy of resolution of the GDA Issue.

2.3.2 Technical Meetings

25 Provisions were made for a series of technical meetings with EDF and AREVA during assessment of the **GI-UKEPR-RC-01** responses. These meetings occurred at appropriate points during 2011 and 2012 when most of the assessment took place. Approximately 5 days of main technical exchange meetings were undertaken, in addition to numerous teleconferences and smaller meetings, as necessary.

26 The principal focus of the meetings was to discuss progress and responses, to facilitate technical exchanges and to hold discussions with EDF and AREVA technical experts on emergent issues. A further key output was the direct interaction between EDF, AREVA and TSC experts to allow for dialogue and the ready exchange of information to enable TSC contracts to be fulfilled.

2.3.3 TSC Outputs

27 As detailed in Section 2.5, a number of technical support contracts were placed to review aspects of the EDF and AREVA responses to the GDA Issue Actions. The outputs from these contracts were mainly in the form of reports summarising the review work undertaken by the TSC in completing the task and containing expert conclusions and recommendations. Outputs from these contracts were used as an input into the assessment of UK EPR™ undertaken by ONR and are an input into the conclusions of this report. See Para. 71 for further details.

2.4 Standards and Criteria

28 The following section outlines the relevant standards and criteria that have informed the Reactor Chemistry assessment during close-out of **GI-UKEPR-RC-01** for UK EPR™.

2.4.1 Safety Assessment Principles

29 Of all of the standards and criteria that inform the assessment, it is the selection of the relevant SAPs (Ref. 5) that plays a key role in determining the scope of assessments in ONR. The SAPs considered relevant to the close-out assessment are listed in Table 9. These SAPs are a sub-set of those considered throughout the Step 4 assessment, as relevant to **GI-UKEPR-RC-01**.

2.4.2 Other ONR Guidance

30 Assessment was conducted to relevant ONR internal standards and guidance (Refs 4 and 9 and Table 10).

2.4.3 External Standards and Guidance

31 Generally, external standards and guidance specific to Reactor Chemistry are very limited in number.

32 The International Atomic Energy Authority (IAEA) has prepared guidance for the containment systems of nuclear power plants (Ref. 12) and this will be used as advisory during the assessment. This document is authoritative, wide-reaching and consistent with the assessment, but does not specifically address the points raised by the GDA Issues Actions so is not expected to contribute significantly to the assessment of **GI-UKEPR-RC-01**.

33 A review of WENRA (Western European Nuclear Regulators' Association) levels (Ref. 13) found none specific to Reactor Chemistry.

2.5 Use of Technical Support Contractors

34 Technical Support Contractors (TSCs) were engaged to assist with the Reactor Chemistry assessment work during Step 4 and this process continued during the GDA close-out stage.

35 Whilst the TSCs undertake detailed technical reviews, these are completed under close direction and supervision by ONR and the regulatory judgment on the adequacy or

otherwise of the UK EPR™ safety submissions is made exclusively by ONR. The TSC outputs were used as an input to this decision making process. The TSC reports are referenced in this report under the relevant assessment section, as appropriate.

36 Visibility of TSC work and feedback on progress and outcomes of TSC work was provided to EDF and AREVA throughout the process, including copies of the TSC outputs and reports.

2.6 Out of Scope Items

37 EDF and AREVA have identified no additional items as out of scope other than those identified during the Step 4 assessment.

2.7 Support from Other Assessment Areas

38 Due to the close links to the Severe Accidents assessment area I have worked closely with the relevant ONR Inspector for Actions 1 and 2. The Severe Accidents aspects of this GDA Issue are summarised in (Ref. 14), which I have considered as part of my assessment.

2.8 Working with Other Regulators

39 It has not been necessary to work with other regulators as part of my assessment.

3 BACKGROUND TO THE GDA ISSUE AND EDF AND AREVA'S RESPONSES

3.1 Overview of the EDF and AREVA Safety Case for Combustible Gas Control

40 The assessment of risks arising from nuclear facilities needs to consider those arising both from normal operation and from accident conditions. Conservative design, good operational practices, and adequate maintenance and testing should minimise the likelihood of accidents. Nuclear facilities are therefore designed to cope with, or are shown to withstand, a wide range of faults without unacceptable consequences by virtue of the facility's inherent characteristics or safety measures. EDF and AREVA provide information in the PCSR on a range of design basis and beyond design basis faults in UK EPR™, including severe accidents. The design of UK EPR™ has many engineered safety systems which are claimed to avoid and ultimately mitigate such scenarios. It is important to note that EDF and AREVA claim that severe accidents (i.e. those resulting in core damage) are "*virtually excluded*" and the design of UK EPR™ has been optimised to minimise the risk of accidents.

41 A severe accident generally arises due to the fact that, even when the nuclear reaction is stopped, the core of a Pressurised Water Reactor (PWR) still contains sufficient energy to require a period of cooling. Should this cooling fail or be sufficiently impaired the heat release can be high enough to damage the fuel, degrade the reactor core and ultimately lead to releases of radioactive species or flammable gases to the containment. In these circumstances it is important that the containment structure itself remains intact, especially early in the sequence, as this becomes the last barrier between radiological releases to the environment and ultimately to people. The EDF and AREVA safety strategy for these unlikely situations is two fold:

- "*Practical elimination*" of highly energetic phenomena which have the potential to breach the containment early in the accident.
- Maintenance of containment integrity in the long term phase.

42 EDF and AREVA have included a number of safety systems in UK EPR™ which are specifically designed to mitigate such events, including the Core Melt Stabilisation System (CMSS), the Containment Heat Removal System (CHRS) and a system for depressurising the reactor. Such features are assessed in more detail in the Step 4 reports on Reactor Chemistry (Ref. 2) and Containment and Severe Accidents (Ref. 15).

43 During such severe accidents combustibles gases can be released into the containment. Firstly hydrogen, mainly from steam oxidation of the zirconium based fuel cladding during the in-vessel phases, and in the latter ex-vessel phase hydrogen and carbon monoxide, from interaction of the molten core with sacrificial concrete used in the CMSS. In order to avoid challenges to the containment integrity from combustion of these gases EDF and AREVA have included a Combustible Gas Control System (CGCS) into the plant design. The UK EPR™ strategy for containment combustible gas management is described in the PCSR (Refs 16 and 17) and the corresponding SDM (Ref. 18). The specific aims of the CGCS are to:

- Prevent fast combustion that might challenge containment integrity.
- Reduce the combustible gas concentrations below flammability limits within 12 hours.

44 The containment arrangement in UK EPR™ is also relevant. The UK EPR™ design presented for GDA features a "*two-room*" containment where the containment area is divided into "*accessible*" and "*inaccessible*" parts during normal operations. This separation is convenient for plant operations, but complicates the combustible gas management during an accident by delaying dilution and mixing. In certain accident

sequences, gas is released into the smaller (16,000 m^3) inaccessible part, initially resulting in much larger concentrations in these areas. To counter this effect the containment reverts back to a "*one-room*" containment under accident conditions via operation of a series of mixing dampers and rupture panels (the CONVECT system). Efficient mixing and dilution facilitated by the CONVECT system is required for the PARs to achieve maximum depletion of combustible gases. This "two-room" arrangement is shown in Figure 1 below;

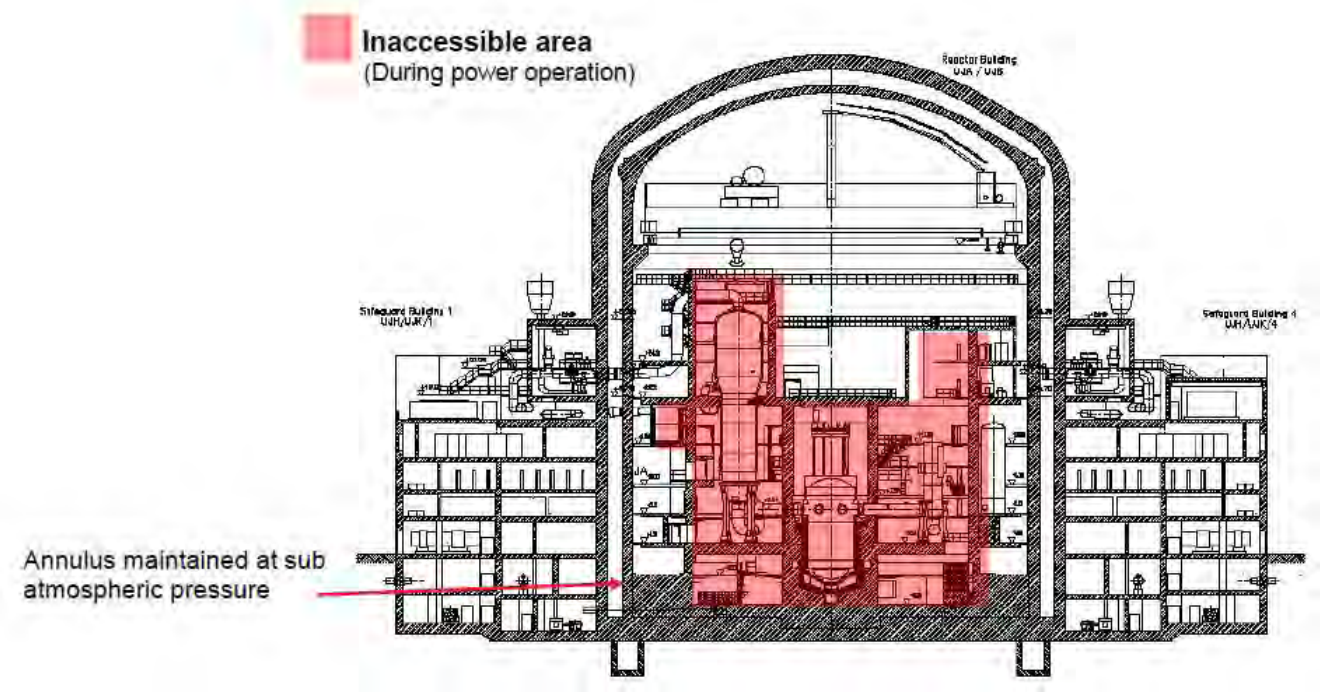

Figure 1: Illustration of the EPR™ "two-room" concept

45 Several sub-systems form the CGCS, and have specific functions such as combustible gas removal or mixing. The devices used for removal of the combustible gases in UK EPR™ are Passive Autocatalytic Recombiners (PARs). PARs use catalytic material to oxidise hydrogen and carbon monoxide and operate passively, requiring no external inputs to function (other than sufficient oxygen in the gas mixture). UK EPR™ features a total of 47 catalytic recombiners distributed throughout the containment. The PARs are installed in both the "*accessible*" part (main operating floor and annular rooms) as well as in the "*inaccessible*" part (Steam Generator compartments, Pressuriser compartment etc.). The PARs are installed at a range of heights within containment, from the floor above the main coolant pipes to the polar crane. EDF and AREVA have arranged the PAR locations on the basis of both design basis and severe accident events; however the system is sized on the basis of a severe accident event. Two different sizes of PARs are used with correspondingly different depletion rates (expressed for hydrogen); 41 "*large*" (5.4 kg hr^{-1}) and six "*small*" (1.2 kg hr^{-1}). The combined depletion rate for the entire system at full capacity is claimed as around 220 kg hr^{-1} at 0.15 MPa and 4% vol. hydrogen. At this rate all of the hydrogen produced from core degradation would be removed in around 6 hours. The UK EPR™ PAR design comprises a metal housing with a gas inlet at the bottom and a lateral gas outlet at the top. Numerous catalytic plates are arranged parallel to each other and vertically in the bottom of the unit.

46 EDF and AREVA claim that the UK EPR™ CGCS, and hence the PARs, are designed so that the pressure and temperature created inside the containment will not result in containment failure as a consequence of a hydrogen release during a severe accident. It is notable that the safety case for EPR™ relates to hydrogen. As discussed more fully in Section 4.1.1.7. of my assessment, in their analysis EDF and AREVA convert any carbon monoxide to an equivalent of hydrogen. Thus references to "hydrogen" that follow include any carbon monoxide derived hydrogen equivalents, unless specified otherwise. In order to meet this claim on the containment, EDF and AREVA require the following safety requirements to be met:

- The global hydrogen concentration is maintained below 10% based on the 80,000 m^3 free volume of the containment. Any region having a concentration of hydrogen above 10% vol. shall be small enough to prevent flame acceleration according to the σ and λ criteria.
- The maximum amount of hydrogen, resulting from the oxidation of all zirconium in the core, is reduced to a global average below 4% vol. within 12 hours.
- The Adiabatic Isochoric Complete Combustion (AICC) pressure is kept below the containment design pressure for representative scenarios that involve hydrogen combustion and below the test pressure for bounding scenarios.

47 In addition to their role in removing combustible gases, the incorporation of a large catalytic surface into the containment of UK EPR™ suggests that other potential reactions are possible, particularly during a severe accident when a range of other species are present and the PARs are operating at high temperatures. A large portion of the fission products that are released from fuel during an accident are in the form of metal iodides, which are relatively involatile and are efficiently captured and removed if they stay in this form. Other forms of iodine can be volatile and are inefficiently removed by such systems, even if they are present in much lower concentrations. It has been suggested by experimental programmes that the PARs could affect the decomposition of metal iodides. During and for a significant period following a severe accident iodine is a significant radiological concern and much effort is put into its management, including containment sprays and buffered sumps in UK EPR™. EDF and AREVA claim that any impact of the PARs on iodine volatility is bounded by the source term assumptions used in the analysis.

3.2 Assessment during GDA Step 4

48 My Assessment of the UK EPR™ combustible gas control safety case during Step 4 is reported in Ref. 2. The related containment and severe accidents assessment is reported in Ref. 15.

49 The primary aim of the Reactor Chemistry assessment of combustible gas control in UK EPR™ during Step 4 was to determine that the rates of combustible gas production credited in the safety case were reasonable and justified and that the chemical performance of the mitigation systems would meet the likely demands placed upon them. I sampled a number of aspects of the safety case in this regard, including:

- Justification for the design of the UK EPR™ CGCS.
- The intended modelling approach to demonstrate the suitability of the CGCS, including the modelling of combustible gas removal in the analysis.
- The chemical behaviour of PARs, including potential poisoning or degradation mechanisms and their associated experimental testing and background.

- The chemistry associated with combustion processes.

50 An important conclusion from the assessment is that the concept of PARs as a means of combustible gas control appears acceptable, provided the detailed supporting analysis can show that the safety requirements are met. It is significant to note that EDF and AREVA did not provide specific analysis for UK EPR™ in time for inclusion in the Step 4 assessment. This was the subject of Regulatory Observation 78, Action 2 (**RO-UKEPR-78.A2**) (Ref. 19), for which a response was not received until 8 April 2011 and hence was not assessed during Step 4. I also remained unconvinced over the arguments made for the effects of PARs on iodine control in UK EPR™, as no evidence that the analysis was bounding of this potential phenomena was provided during Step 4 and the PCSR does not mention any such effects.

51 The Step 4 assessment resulted in four Assessment Findings (namely **AF-UKEPR-RC-42**, **43**, **44** and **45**) and one GDA Issue specific to the control of combustible gases in UK EPR™. Generally, an adequate case was made for GDA in this area, subject to satisfactory resolution of the GDA Issue and associated actions. Full details of the conclusions of this assessment are reported in (Ref. 2), so are not repeated in detail here.

3.3 Summary of the GDA Issue and Actions

52 GDA Issue **GI-UKEPR-RC-01** and its associated three Actions are given in (Ref. 1). Further explanatory information on this Issue and Actions is provided in (Ref. 8)

53 On the basis of the claims, arguments and evidence presented to the end of Step 4, I considered that the UK EPR™ safety case related to combustible gas control required further work in three discrete areas before I could be satisfied for GDA. These areas all relate to the performance of the PARs and need to be considered as part of the suite of supporting analysis for UK EPR™, namely:

- Operation of the CGCS with reduced PAR performance.
- Analysis under bounding accident conditions.
- Effect of PAR operation on the production of volatile iodine in the containment.

54 I considered these aspects to be inadequately addressed in the UK EPR™ safety case at the end of Step 4.

3.4 EDF and AREVA Deliverables in Response to the GDA Issue Actions

55 The EDF and AREVA resolution plan for this Issue is given in (Ref. 3). This provides details of the deliverables EDF and AREVA intended to provide to respond to these Actions. The following section contains a brief description of the deliverables actually supplied in response to each GDA Issue Action.

3.4.1 Action 1 – Analysis with a Reduced PAR Performance

56 EDF and AREVA provided a single additional technical report in response to this Action, preceded by a letter justifying some of the choices made. These deliverables are described further below:

Letter EPR00909N - Deliverable for GI-UKEPR-RC01 – Combustible Gas Control – Action 1 – Bounding Scenario and selection of deactivated PARs

57 Letter EPR00909N (Ref. 20) was provided ahead of the sensitivity study report described below and includes two appendices which provided me with an early view of, and the potential to influence, two important aspects of the Action 1 response. The rationale and methodology for both of these aspects are described in detail in the letter:

- Scenario selection.
- Details of the reduction factor and the selection methodology for the deactivated recombiners.

PEPA-G/2011/en/1021 - Sensitivity analysis of a postulated reduced recombiner performance during severe accidents

58 This report (Ref. 21) presents the results of a sensitivity study of the hydrogen distribution inside the EPR™ containment atmosphere and the removal of hydrogen by recombination during the in-vessel phases of a severe accident, assuming a postulated reduced performance of the passive autocatalytic recombiners. The analysis uses the scenario identified in letter EPR00909N, and as used in the Action 2 responses (Refs 22, 23 and 24), and a modification to the recombiner model also described in letter EPR00909N. For this study three cases are investigated with the lumped-parameter containment code COCOSYS:

- The “base case” with all recombiners operating at the normal hydrogen depletion rate.
- A case with a reduced hydrogen depletion rate applied uniformly to all individual recombiners.
- A case where several recombiners are completely deactivated, with the remainder operating at the normal hydrogen depletion rate.

3.4.2 Action 2 – Analysis under a Bounding Accident Scenario

59 EDF and AREVA provided a suite of four technical reports in response to this Action. These were originally provided in response to **RO-UKEPR-78.A2** (Ref. 19). These deliverables are described further below:

PEPA-G/2011/en/1009 - Gas Distribution in the Containment during Severe Accident and Assessment of the Potential Hydrogen Combustion Risk

60 This report (Ref. 22) is the first in a series of four which cover the computational validation procedure of the EPR™ combustible gas control system. In this first report the distribution of hydrogen and other relevant species (such as steam) in the containment and its removal by recombiners during the in-vessel phase of a severe accident are analysed. Results are calculated mainly by the computational fluid dynamics (CFD) GASFLOW code but also with COCOSYS during long quasi-stationary phases in the accident progression. This report briefly describes the scenario selection process which results in the selection of three scenarios for the detailed analysis of the potential hydrogen risks. The analysis of gas distribution is used to investigate several aspects of the behaviour of EPR™ during such accidents, including operation of the CONVECT system, containment pressure, gas temperatures, hydrogen distribution and recombiner

performance. The gas distributions show that periods in time exist when conditions for hydrogen combustion prevail. The results are used to derive information for more detailed analysis of these periods in subsequent reports, by determining penalising conditions for the occurrence of such events.

PEPA-G/2011/en/1010 - Temperature Loads from Gas Release, Recombiner Operation and Slow Hydrogen Combustion in the Dome during a Severe Accident

61 This report (Ref. 23) provides the analysis for the temperature loads expected in EPR™

62 during the in-vessel phases of a severe accident. The analysis again uses GASFLOW and considers three important heat loads:

- The global response of the containment atmosphere to the injection of hot gases, steam and hot water from the primary circuit during the main release period (i.e. blowdown and core oxidation phase) is analysed, and the rise in pressure and gas temperature as well as the surface temperature of important structures is quantified.
- The thermal loads from the recombination of hydrogen, where hot exhaust gas plumes rise upwards from the operating recombiners, are also assessed both locally and in the containment dome.
- Based on the gas distribution results from Ref. 22, the times when the largest amount of hydrogen can possibly be burned are identified. In such cases involving combustion of a large mass of hydrogen in the dome, the peak temperatures and long-term loads are analysed, particularly for the sensitive steel liner.

PEPA-G/2011/en/1011 - Pressure Loads from Fast Hydrogen Combustion during a Severe Accident and Assessment of the Risk of a Deflagration-to-Detonation Transition

63 Based on the gas distribution results, if ignition in one of the confined equipment rooms is assumed at a time when high hydrogen concentrations are predicted there, fast combustion with potential flame acceleration towards a detonation cannot be excluded using empirical correlations based on experimental results. For such cases an analysis based on calculations with the fast deflagration code COM3D is conducted using conditions as determined from (Ref. 22). The effects of such an ignition of the hydrogen and the resulting dynamic pressure loads on internal wall and structures as well as on the containment shell are analysed in this report (Ref. 24).

PEPA-G/2011/en/1012 - Hydrogen Combustion after Reactor Vessel Failure during a Severe Accident

64 This report (Ref. 25) describes a generic analysis of the ex-vessel phases of a severe accident scenario in the EPR™ reactor. In addition to in-vessel risks, it is determined in this report whether the additional combustible gases which are produced during Molten Core-Concrete Interaction (MCCI) burn close to their release location or whether there is a risk of an accumulation of these gases in the upper containment regions. Due to the different requirements for selecting a bounding ex-vessel scenario the report describes analysis with COCOSYS to determine an appropriate scenario before performing more detailed analysis with GASFLOW. Results are presented on the global behaviour and combustion characteristics, for a "*generic*" EPR™.

3.4.3 Action 3 – Demonstration of the Impact of PARs on Iodine Volatility

65 EDF and AREVA provided a number of technical reports in response to this Action. The deliverables are described further below:

<u>DPAM-SEMIC-2011-353 – Dissociation of Iodine Aerosols into Gaseous Iodine in Hydrogen Recombiners – Impact on the Iodine Source Term</u>

66 This report (Ref. 26), produced by Institut de Radioprotection et de Sûreté Nucléaire (IRSN) for EDF, presents the results of a study using the ASTEC code to evaluate the impact of the additional volatile iodine source term produced from PARs inside the containment of a French 1300 MW_e PWR. The results from experimental tests performed in the THAI facility to estimate how much gaseous iodine could be produced in conditions representative of a nuclear accident are used as the basis of the study. Two cases are presented for one accident sequence, using a single iodine conversion rate and considering both operation and non-operation of the PARs.

<u>ENTEAG102129 - Addition to the document "dissociation of iodine aerosols into gaseous iodine in hydrogen recombiners - impact on iodine source term" DPAMSEMIC2011353</u>

67 This report (Ref. 27), produced in response to my assessment of Ref. 26, aims to demonstrate the applicability of the IRSN results to UK EPR™. This document first describes how the experimental results of the THAI tests can be applied to UK EPR™, and then describes how the results of the calculations made in the Ref. 26 can be applied to UK EPR™.

<u>002161-100-DE003-A BPE – Sensitivity Study of the potential impact of recombiners on volatile iodine release during a severe accident</u>

68 This report (Ref. 28), produced in response to my assessment of Refs 26 and 27, contains a sensitivity study of the impact of recombiners on environmental releases of iodine following an accident involving core melting. The calculations were performed with the IODE code which is part of the ASTEC suite developed by IRSN and GRS. The code calculates the evolution of the physical and chemical behaviour of iodine in a simplified reactor containment geometry comprising a single gas volume and a sump, with painted surfaces in contact with each of these. Under the influence of irradiation, a number of reactions occur which influence the amount and form of airborne iodine, which in turn determines the iodine source term to the environment. Sensitivity calculations were performed with different assumptions regarding the extent of conversion of aerosol to gaseous iodine species in the recombiners, ranging from zero (base case) to 10%. A further calculation was also performed to examine the effect of combustion on this process.

4 ONR'S ASSESSMENT

69 The following sections detail the specific assessment undertaken for GDA Issue **GI-UKEPR-RC-01** as identified by the Reactor Chemistry assessment in Step 4.

70 Each Action raised under the GDA Issue is reported as a discrete topic. As described earlier, this report does not represent the entirety of assessment conducted on these topics, with the Step 4 report (Ref. 2) providing further information. The sections follow the same outline structure:

- The main part of the section describes my assessment, detailing the work undertaken, external inputs into this assessment (e.g. TSC reports), the principal RP deliverables reviewed and the conclusions of the assessment.
- EDF and AREVA have updated the PCSR to reflect the outcomes of the GDA Issue Actions, and I review this.
- Finally, each GDA Issue Action is summarised, including my judgement on whether the Action has been adequately resolved, together with any areas where further work has been highlighted as necessary following GDA as Assessment Findings.

71 Assessment of the chemical performance of the combustible gas control systems is closely linked to the thermal-hydraulic behaviour of the containment under accidents when it may need to operate. As described in the UK EPR™ safety case an important pre-requisite for successful operation of the CGCS is an efficient mixing of the containment atmosphere. This mixing is directly influenced by operation of the PARs which create hot buoyant exhaust plumes which act to enhance atmospheric mixing. To ensure these effects are captured within the assessment I have worked closely with the ONR Containment and Severe Accidents inspector for Actions 1 and 2. The assessment that follows is consistent with this approach and the assessment note produced by the ONR Inspector for these topics (Ref. 14).

72 I commissioned TSC support to review the responses provided to this GDA Issue, see Refs 29, 30 and 31 for Action 1, Refs 30, 31 and 32 for Action 2 and Ref. 33 for Action 3. The assessment that follows is consistent with the conclusions of these reviews, as appropriate.

73 The assessment that follows discusses the responses to Action 2 first, as Action 1 is a sensitivity study based on the analysis presented in response to Action 2.

4.1 Action 2 – Analysis under a Bounding Accident Scenario

4.1.1 Assessment

74 As the UK EPR™ CGCS is based upon the use of PARs for combustible gas removal, the system will have an inherent overall removal rate for combustible gases based upon the size and quantity of installed equipment. There also isn't a single accident which can be said to describe all of the potential accident conditions under which the UK EPR™ CGCS may be expected to function. This is because the range of potential scenarios leads to many variations in the release rates of combustible gases, locations of release, timings of releases and other important parameters such as steam releases. This also means that, for example, the particular accident scenario that is the most relevant when considering temperature loads may not be the most appropriate if pressure loads were the objective of the analysis. Given these relationships, it is important that the safety case demonstrates that the system can meet the demands which are likely to be made of it should an accident occur using a best estimate basis; SAP FA.15 and associated para. 547 (Ref. 5).

75 In response to **GI-UKEPR-RC-01.A2**, EDF and AREVA indicated that the reports (Refs 22, 23, 24 and 25) provided in response to **RO-UKEPR-78.A2** (Ref. 19) contained the evidence required to satisfy this action. These reports were provided during Step 4, but too late for assessment. These reports are not analysis for UK EPR™, but for the reference design of Flamanville 3 (FA3). EDF and AREVA's intention in providing these reports in response to this GDA Issue Action is to demonstrate that suitable bounding calculations could be performed for UK EPR™. EDF and AREVA have confirmed the expectation that the licensee will provide an analysis on a site specific basis using the most up to date information, codes and analysis techniques. This will have benefits in ensuring that the safety case for an operational UK EPR™ will use the best available information and processes. This approach reinforces the requirements specified in Assessment Finding **AF-UKEPR-RC-42**, defined in the Step 4 Reactor Chemistry assessment report (Ref. 2), which requires the licensee to provide specific analysis for UK EPR™.

76 The calculations presented in the PSCR (Ref. 16) were performed for UK EPR™ during the design phase. Important differences to the calculations presented in response to **GI-UKEPR-RC-01.A2** (Refs 22, 23, 24 and 25) include a "*one-room*" containment design and a generic PAR arrangement. EDF and AREVA are aware of these differences and the argument made in the PCSR is that these differences are minor in terms of impact on the results of the analysis and ultimately on the substantiation of the safety claims.

77 Hence, in reviewing the responses to **GI-UKEPR-RC-01.A2**, I have considered not only the specific expectations of this Action in terms of providing an adequate demonstration of the performance of the UK EPR™ under bounding accident conditions, but also that the responses support the safety claims made in the generic PCSR.

4.1.1.1 Overall EDF and AREVA Approach

4.1.1.1.1 Determination of Combustion Risks and Resultant Hazards

78 In the event of a severe accident in UK EPR™ combustible gases are released to the containment atmosphere, where they mix with the air in the atmosphere and steam released from the primary circuit. Moreover, the mixing and distribution processes could drive to produce either well-mixed or inhomogeneous conditions (leading to stratification, local accumulation, etc.). If an ignition source were present the gas could burn in a number of different modes, with the way in which a cloud of combustible gas burns being dependant upon many often related variables such as mixture composition, local

geometry, turbulence or confinement. As the process is dynamic and constantly evolving over time, the conditions and hence potential combustion modes also change during the course of the accident. This means that the analysis of the combustible gas risks must consider effects which occur on a range of scales in both time and geometry.

79 The combustion regimes, from the point of view of the nuclear safety, can be broadly classified as deflagrations and detonations. Deflagrations are flames that travel at subsonic speeds relative to the unburnt gas, whereas a detonation is characterised by a combustion wave that travels at supersonic speeds. However, it is important to recognise that given a favourable set of conditions, and if subjected to hydrodynamic instabilities and turbulence, initially slow deflagrations may accelerate. Fast combustion regimes – fast deflagration (several hundred m s^{-1}), Deflagration-to-Detonation Transition (DDT) and detonations (more than 1000 m s^{-1}) – can then result. It is these latter phenomena, often resulting in significant dynamic pressure loadings, which increase the threat to containment integrity.

80 Hence, once it is established if a given mixture is over the flammable limit, the question then becomes how fast the resultant combustion is and does it have the potential to accelerate. Thus there are three basic steps for identifying the combustion regime (Ref. 34):

- Determine the flammability of the mixture (flammability criterion). The location of a given combustible gas mixture on the Shapiro ternary diagram (Figure 2) is a simple measure of determining whether a given gas mixture is flammable or even potentially detonable. The latter mode is less well defined in this approach, as there is some effect of scale on determining this boundary. In this diagram, the flammability and detonation zones are, respectively, delimited by the exterior (blue) and interior (red) curves.

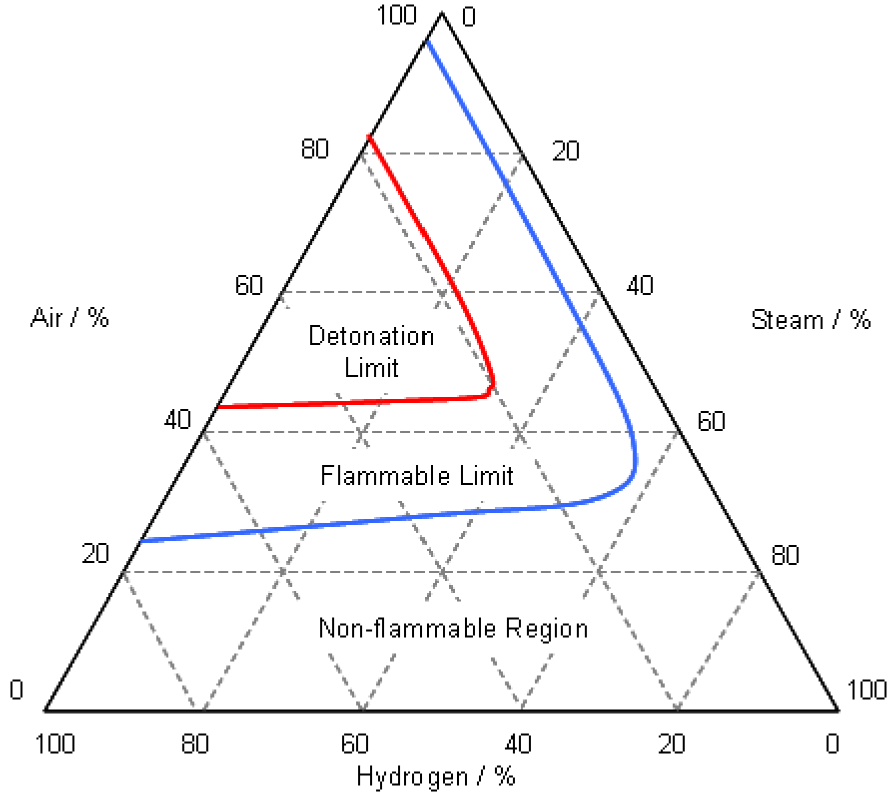

Figure 2: Typical Shapiro ternary diagram for hydrogen-air-steam

This shows that below around 4% vol. and above 75% vol. hydrogen the mixtures are not flammable, no matter what proportions of steam or air are also present. In between these boundaries the mixture could be non-flammable, flammable or even detonable dependant upon the other components present. For example, air-hydrogen mixtures above 4% vol. will combust provided they are not inerted by steam and are mixed with sufficient oxygen, but not completely. Above 8% vol. combustion will be complete. Above 10% vol. there is the possibility that the combustion can accelerate and become a detonation. Above 16% vol. direct detonation is possible, given a sufficient energy input (Ref. 35), although, as described later in my assessment, the direct initiation of a detonation is not possible within containment due to the high energy required (see Para. 122). The Shapiro diagram also demonstrates the important effect of steam on inerting what would otherwise be a flammable mixture. The determination of where a given gas mixture resides in this diagram is therefore an important indicator for the potential hazards that are possible.

- Determine the possibility of flame acceleration (σ criterion). The σ-criterion relates to flame acceleration. It represents the mixture's expansion factor, a ratio of fresh and burnt gas densities at constant pressure and is an intrinsic property of the mixture. The critical value of σ, beyond which flame acceleration is possible, depends on the initial gas composition, temperature and flame stability.
- Determine the possibility of DDT (λ criterion). The λ-criterion relates to DDT. In addition to fulfilling the σ-criterion, it is also necessary to fulfil the λ-criterion for DDT to occur. It is based on comparing a characteristic dimension of the geometry with the detonation cell size.

81 Importantly, these last two criteria are conservative prerequisites based on experimental results, that is, it is unlikely that flame acceleration or DDT would occur without fulfilling these criteria.

82 The EDF and AREVA approach is consistent with this methodology, as described more fully in subsequent sections of my assessment.

4.1.1.1.2 Comparison to Relevant Guidance and Good Practice

83 The OECD (Organisation for Economic Cooperation and Development) "*state of the art*" report on flame acceleration and DDT (Ref. 34) suggests a overall "*roadmap*" for evaluating the hydrogen risks to a given plant containment. This roadmap consists on several distinct sequential steps, including the following which are relevant to the analysis approach adopted:

i) Definition of a set of accident sequences of relevance to the nuclear plant design.

ii) Evaluation of the combustible gas and steam source terms for the postulated accident and release scenarios.

iii) Evaluation of the gas distribution and mixing within the compartments of the containment, on the basis of the defined source terms, including consideration of any mitigation measures.

iv) Evaluation of the flammability of the mixture in each area of the containment and application of flame acceleration and DDT criteria for a quantitative measure of the possibility of these events.

v) In some cases and despite the use of mitigation techniques, a risk for flame acceleration or DDT may still exist during some part of the transient considered. In those cases, a more detailed investigation with dedicated simulations of flames or detonations is needed in order to determine whether localised fast flames or detonations can threaten the containment integrity.

vi) Determination of the thermal and mechanical loads of the combustion processes (slow deflagration, fast deflagration or detonation) on the containment shell or other sensitive structures.

vii) Finally, evaluation of the structural response of the containment on the basis of the results of the previous step. If fast combustion modes cannot be excluded despite the risk mitigation system present, a detailed investigation of the local dynamic structural response is needed to demonstrate the containment integrity.

84 In order to cover these different requirements it is often necessary to use different analysis codes. Large scale effects over the long timescales of accident sequences are better suited to simplified Lumped Parameter (LP) codes. Conversely these do not offer the required accuracy to analyse the phenomena which occur on small time and spatial scale, such as local stratifications and fast combustions, which can be simulated in detail by more sophisticated Computational Fluid Dynamics (CFD) codes.

85 The EDF and AREVA approach given in the **GI-UKEPR-RC-01.A1** responses (Refs 22, 23, 24 and 25) is consistent with the OECD "*roadmap*" and consists of simulating a large number of sequences with a LP code (COCOSYS) to cover the different hydrogen release conditions expected during the accident (taken from MAAP4) and applying the CFD code (GASFLOW) to a selected number of sequences over short time windows in order to get an approach to the small-scale phenomena but avoiding an excessive computational time. Where the more localised CFD results indicate the potential for fast combustions these are further analysed with a dedicated combustion CFD code (COM3D). A summary of the computer codes used by EDF and AREVA is presented in Annex 3 of this report, with more detailed information given in Appendix 16A of the PCSR (Ref. 36).

86 The PCSR for UK EPR™ describes the approach to verifying the "*efficiency*" of the combustible gas control system (Ref. 16) (i.e. does the system meet its safety requirements) used by EDF and AREVA. This approach is the same as that assessed during Step 4 and as described in Section 4.6.3.2.1 of the Step 4 assessment report (Ref. 2). Briefly, this involves analysis of the hydrogen risks using a suite of computer codes, for a range of accident scenarios which are both "*representative*" (basis of the design) and "*bounding*" (demonstration of margins and avoidance of 'cliff edge' effects); see the list of abbreviations for a fuller definition of these terms used by EDF and AREVA. In this approach it is notable that the "*bounding*" scenarios are selected on deterministic rather than probabilistic criteria, whereas the selected "*representative*" scenarios are influenced by the likelihood of their occurrence. For this analysis EDF and AREVA claim to use a best estimate approach in the first instance, reverting to conservative assumptions if necessary.

4.1.1.1.3 Summary

87 I am content with this approach and agree with EDF and AREVA that this represents a sound basis upon which both the overall safety case for combustible gas control in UK EPR™ can be built and the response to **GI-UKEPR-RC-01.A2** could be made. It is clear that EDF and AREVA have put significant effort into the analysis of the CGCS in EPR™

and the presented analysis approach is consistent with modern developments in combustible gas safety justifications.

4.1.1.2 Scenario Selection and Definition of the Bounding Scenario

4.1.1.2.1 EDF and AREVA Scenario Selection Process

88 An important pre-requisite to satisfy this GDA Issue Action is the definition of an adequate scenario for analysis. In addition to the SAPs (Ref. 5) and Technical Assessment Guide (TAG) (Ref. 37), there is some other guidance available on such matters:

- IAEA Safety Guide No. NS-G-1.10, Design of Reactor Containment Systems for Nuclear Power Plants (Ref. 12) contains many relevant sections related to combustible gas control, including; "*6.24. … For new plants the amount of hydrogen expected to be generated should be estimated on the basis of the assumption of total oxidation of the fuel cladding.*"
- US NRC regulations (Ref. 38) state that new reactor designs "… *must limit hydrogen concentrations in containment during and following an accident that releases an equivalent amount of hydrogen as would be generated from a 100 percent fuel clad-coolant reaction, uniformly distributed, to less than 10 percent (by volume)…*".

89 EDF and AREVA have interpreted such requirements for UK EPR™ to mean oxidation of all of the fuel cladding throughout the entire accident sequence, rather than during a particular stage of the accident. Ultimately for severe accidents in UK EPR™ the vast majority of the zirconium will be oxidised, either by steam or during MCCI. For the PARs the most penalising conditions will results from high production rates or integrated masses of combustible gases, released to restricted volumes and in combination with conditions that are favourable for combustion or penalising for the PARs. The analysis presented in response to **GI-UKEPR-RC-01.A2** is consistent with defining the scenarios for detailed analysis in this manner.

90 The first report in the response, PEPA-G/2011/en/1009 (Ref. 22), calculates the distribution of hydrogen in the containment following a number of accident scenarios. This report draws heavily on both COCOSYS and GASFLOW calculations. The preceding stages of calculations using MAAP4 are not presented in this report, but are referenced and summarised. This is relevant to the scenario selection process, as it is at this first stage when the MAAP4 results are subjected to an initial selection of scenarios, from "*hundreds*" to a "*pre-selected set of 23 scenarios*". I required further confidence that this selection process was appropriate and I discussed these aspects further with EDF and AREVA during our technical meeting in September 2011.

91 Further information was subsequently provided in Ref. 39, in which EDF and AREVA outlined their methodology for selection of the accident scenarios for analysis. The scenarios included in the initial MAAP4 analysis cover all groups of accidents, including both with and without primary circuit breaks (e.g. LOCAs and LOOP scenarios), with breaks at each of the main postulated locations (hot leg, cold leg and pressuriser) and with parametric studies on aggravating factors such as break size and delayed depressurisation. The results of these analyses are examined and a number of "*rules*" are used to further refine this set of scenarios, such that the scenarios further selected for detailed study include cases from each of the main release paths to containment. The "*rules*" are designed to identify the scenario which produces the highest local concentration, including factors such as release rates and steam concentration. An example of the impact on hydrogen releases was given for a Small Break Loss of Coolant Accident (SBLOCA) analysis by varying the time of depressurisation past the 650 °C core

outlet temperature threshold. This demonstrated the importance of such a parametric approach, with up to 35% more hydrogen and twice the AICC pressure possible for an additional 10 minute delay.

92 I am content with these arguments for the scenario selection process. Recognition should also be given to AREVA as a competent organisation to perform these calculations having been involved in the basic EPR™ design phase, as well as site specific analysis (for FA3, OL3 and Taishan). On the basis of the systematic selection process and their previous experience it seems unlikely that EDF and AREVA have failed to identify an appropriate bounding scenario.

93 This process identifies three "*representative*" and one "*bounding*" scenarios for detailed analysis as part of the response. These scenarios involve releases to all of the potential release locations. As one of the "*representative*" and the "*bounding*" scenario share the same hot leg release location, EDF and AREVA further discount the "*representative*" scenario as they consider it to be covered by the "*bounding*" scenario analysis. Based on these arguments a SBLOCA in the hot leg, with delayed depressurisation is selected as the "*bounding*" case for hydrogen risks in UK EPR™.

94 The use of a "*bounding*" scenario is an important aspect of the EDF and AREVA case. It represents a penalising, aggravated scenario which is used to demonstrate the margins in the design, rather than be the basis for the design. For this reason, as will be described later in this report, it is often shown to be close to the limits of the design. This distinction is important and should be borne in mind.

4.1.1.2.2 Bounding Scenario Description

95 The report (Ref. 22) provides details of the accident progression. The "*bounding*" SBLOCA scenario is a rapidly progressing accident, with hydrogen release starting around 1 hour after the initiating event. This results in a total calculated release of around [redacted] kg during the entire in-vessel phase (approximately 88% of the theoretical maximum). The main release phase lasts around 1300 seconds, releasing around [redacted] kg of hydrogen with maximum release rates of up to [redacted] kg s^{-1} over the period. The hydrogen dissolved within the primary coolant is neglected as this represents only a few kg of additional release. This is illustrated in Figure 3 below (from MAAP), firstly for the overall in-vessel phase and then on a finer time scale for the main phase of release.

[redacted]

[redacted]

Figure 3: Hydrogen release characteristics during the in-vessel and main release phases for the "*bounding*" case from Ref. 22

96 Importantly for flammability hazards the corresponding steam releases are relatively low during the hydrogen release phase. The calculated containment pressure is [redacted] MPa if AICC is assumed, which is pessimistic for the containment as this assumes both complete combustion and no heat losses. This pressure is within the limits of the EPR™ design. The two remaining "*representative*" scenarios are shown to be bounded by this scenario, with lower hydrogen release rates, masses and AICC pressures. The benefit in the "*representative*" scenarios is to demonstrate the impact of release location on effects such as stratification and local concentrations. This is particularly relevant to the pressuriser break scenarios, where the release is at an elevated location and hence

stratification is more likely. These effects are discussed in more detail later in my assessment.

97 EDF and AREVA state that Large Break Loss of Coolant Accident (LBLOCA) accidents are not considered for hydrogen risk analysis, due to the large steam releases inerting the containment. No scenarios without any secondary cool down or for intact circuit faults (Such as Loss of Off-site Power (LOOP) scenario) are selected based on the MAAP4 results. Report PEPA-G/2011/en/1012 (Ref. 25), which contains the ex-vessel analysis, contains some analysis for both LBLOCA and LOOP scenarios. Both the masses and rates of combustible gases generated during the in-vessel phase of these scenarios are much smaller than the "*representative*" and "*bounding*" scenarios examined in Report PEPA-G/2011/en/1009 (Ref. 22). While the rate is lower, I queried if the atmosphere in inerted LBLOCA scenarios could become flammable again due to condensation or use of the spray system (see Ref. 39). EDF and AREVA confirmed that this would not occur, as the rate of hydrogen reduction by the PARs is sufficient to remove enough hydrogen before the condensation rate would de-inert the containment or the spray would be activated. This condensation would also reduce the overall pressure in containment. Similarly, activation of the sprays would act to further homogenise and reduce the overall pressure, allowing more margin before a detrimental overall pressure is reached. These arguments support EDF and AREVA's selection of the SBLOCA scenario as bounding for EPR™.

4.1.1.2.3 Comparison to the Generic UK EPR™ PCSR

98 The scenarios identified in the responses to **GI-UKEPR-RC-01.A2** (Refs 22, 23, 24 and 25) are different to these identified in the PCSR (Ref. 16). As described in Para. 75, this is a consequence of the different inputs and assumptions between the two sets of analysis. The PCSR identifies four "*representative*" and three "*bounding*" scenarios; however these are similar and in some cases identical to those identified for **GI-UKEPR-RC-01.A2** with some additional scenarios, as shown in Table 2 below.

PCSR Scenario (Ref. 16)	**Scenario Analysed in Detail in GI-UKEPR-RC-01 Responses** (Refs 22, 23, 24 and 25)
"*Representative*" Scenarios	
SBLOCA 2" CL FC	Yes
SBLOCA 2" HL FC	No
SBLOCA 3" PZR FC	Yes, but 2.5" break
SBLOCA 2" CL PC	No
"Bounding" Scenarios	
LOOP with reflood	Yes
SBLOCA 2" CL FC with reflood	No
SBLOCA 2" CL PC t?	No, but 2.5" HL break, 25 min delay

Note: FC = Fast Cooldown, PC = Partial Cooldown, CL = Cold Leg, HL = Hot Leg

Table 2: Comparison of PCSR and **GI-UKEPR-RC-01** scenarios

99 In addition, the analysis performed on those scenarios is different. Table 3 below shows a comparison of the analysis performed on the different scenarios for the PCSR and **GI-UKEPR-RC-01** responses. The highlighted case in each column represents the "*worst case*" from those analysed (i.e. the bounding scenario), which in most cases are different between the PCSR and GDA Issue responses.

Scenario	AICC Pressure		Pressure loads from slow combustion		Pressure loads from fast combustion		Thermal loads from Recombination		Thermal loads from Combustion		Ex-vessel phases	
	PCSR (Ref. 16)	**RC-01** (Ref. 22)	**PCSR** (Ref. 16)	**RC-01** (Ref. 23)	**PCSR** (Ref. 16)	**RC-01** (Ref. 24)	**PCSR** (Ref. 16)	**RC-01** (Ref. 23)	**PCSR** (Ref. 16)	**RC-01** (Ref. 23)	**PCSR** (Ref. 16)	**RC-01** (Ref. 25)
"*Representative*" Scenarios												
SBLOCA 2" CL FC	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
SBLOCA 2" HL FC	Y	Y										
SBLOCA 3" PZR FC (2.5" for RC-01)	Y	Y		Y	Y	Y		Y		Y		
SBLOCA 2" CL PC	Y	Y	Y								Y	
LBLOCA 12" HL PC	Y	Y										Y
LOOP 650	Y	Y										Y
"Bounding" Scenarios												
LOOP with reflood	Y	Y					Y					
SBLOCA 2" CL FC with reflood	Y	Y			Y		Y					
SBLOCA 2" CL PC t?	Y	Y	Y		Y		Y		Y			
SBLOCA 2.5" HL PC t25	Y	Y		Y		Y		Y		Y		

Table 3: Comparison of PCSR and **GI-UKEPR-RC-01** analysis, including the most penalising cases

100 I queried a number of the most important of these differences in detail, see Ref. 39. EDF and AREVA recognise these differences, and claim that these are due to developments and refinements in the codes and analysis procedures over the time period between the two sets of analysis. This is not to suggest that the results of the PCSR analysis are invalidated, rather that the responses to **GI-UKEPR-RC-01.A2** are the most up to date.

4.1.1.2.4 Summary

101 Overall, I am content that EDF and AREVA have identified suitable bounding scenarios for analysis of the combustible gas risks in UK EPR™. While there are significant differences between the analysis in the PCSR and the **GI-UKEPR-RC01.A2** responses, the most important aspect to consider is the confirmation that the overall safety claims made in the PCSR are met, irrespective of which particular analysis or scenario is considered. I review the most relevant of these in the subsequent sections of my assessment.

4.1.1.3 Model Set-up and Application

102 Before discussing the results of this analysis in detail, there are some general points about the analysis described in the **GI-UKEPR-RC-01.A2** responses that are relevant. These are discussed now, rather than later in my assessment as they are generic to the analysis presented. They are only mentioned again later, under each of the more detailed sections, where they have particular relevance to the results. It is possible that some of these aspects are covered in other documentation produced for FA3, but EDF and AREVA did supply any reports other than those provided under **GI-UKEPR-RC-01.A2** (Refs 22, 23, 24 and 25) in order to resolve the GDA Issue.

4.1.1.3.1 Comparison to Relevant Guidance and Good Practice

103 The use of multiple codes to form the suite of analysis is a recognised technique for complex containment models (see for example Ref. 34). The approach adopted by EDF and AREVA is consistent with the safety cases provided for other plants which use recombiners for combustible gas control, see Ref. 40 for example which relates to German PWRs, which were the original plants to incorporate PARs and where much of the development for this type of approach occurred. At the end of Step 4 I was content that an adequate case could be made for UK EPR™ on this basis and, having now assessed the responses, I remain confident this is the case.

104 However, it remains important that when complex computer codes, such as CFD, are relied upon heavily as part of a safety justification that their use should be justified and adequately documented. This is consistent with the expectations of SAP FA.22 (Ref. 5), in relation to the methods of calculation, and T/AST/042 (Ref. 41) and the associated Health and Safety Laboratory (HSL) report (Ref. 42). In addition, many external documents exist which stress the importance of this type of justification, particularly with CFD codes which are know to be susceptible to uncertainties due to effects such as user competence, initial set-up and selected phenomenological models (see Refs 35, 43 and 44). I have considered the expectations of this guidance, as appropriate, in assessing the **GI-UKEPR-RC-01.A2** responses. This indicated a number of aspects which I discussed with EDF and AREVA as part of my assessment:

- *<u>Comparison of COCOSYS and GASFLOW</u>* – in addition to more specific queries on these codes, as discussed later in my assessment, additional reassurance on their adequacy could be gained by comparing the results from these two codes (within the limitations of the codes). Only very limited comparisons can be found in the **GI-UKEPR-RC-01.A2** responses, and they are not explicit comparisons. I asked EDF and AREVA for a number of discrete comparisons in TQ-EPR-1543 (Ref. 11). The response to this TQ did not provide the information I requested on a number of points. This was due to the fact that the GASFLOW calculations had already been preformed and hence all that could be provided was further post-processing of the existing results. This meant that unless a particular parameter was originally selected, it could not be further interrogated now. Similarly it was not possible to compare nodes in COCOSYS to the same volumes in GASFLOW, as such segregations had not been built into the original GASFLOW analysis. These factors limited the response provided. To attempt to alleviate these restrictions EDF and AREVA did provide various comparisons for pressure, temperature, steam, hydrogen, recombiner performance and convective flows using other means such as GASFLOW monitor points and by averaging data within areas which have a hydrogen level above a set threshold. The response is detailed, and some differences are seen which are due to differences in the codes and the particular physical models employed (such as the treatment of momentum), however the general trends show are that:

1. Both codes predict the same general behaviour and trends.
2. Comparisons between average or integrated values on containment scale are reasonable. As the scale becomes smaller so the comparisons diverge.
3. Comparisons are better when the level of inhomegeneity is small and hence rates of change are also small. As the inhomegeneity increases so the comparisons diverge.

This is exemplified by the comparisons shown in Table 4 below, which compares the maximum differences between the COCOSYS and GASFLOW results for the "*bounding*" SBLOCA scenario from Ref. 22:

Parameter	**Comparison of COCOSYS and GASFLOW results** (TQ-EPR-1543 (Ref. 11))	
	Difference	**Relative / %**
"*Global*" Parameter		
Pressure	[redacted] MPa	[redacted]
Average Temperature	[redacted] °C	[redacted]
Total Steam Mass	[redacted] kg	[redacted]
Total Hydrogen Mass	[redacted] kg	[redacted]
Total Recombined Hydrogen Mass	[redacted] kg	[redacted]
"Local"Parameter		
Temperature (in the dome)	[redacted] °C	[redacted]
Steam Concentration (in the dome)	[redacted] % vol.	[redacted]
Hydrogen Concentration (in the dome)	[redacted] % vol.	[redacted]
Recombined Hydrogen Mass (in SG tower loop 2)	[redacted] kg	[redacted]
Volume Flow (through pressure equilibration ceilings)	[redacted] m^3	[redacted]

Table 4: Comparisons between COCOSYS and GASFLOW results for the "*bounding*" case in Ref. 22 (from TQ-EPR-1543 (Ref. 11))

On the basis of the response to TQ-EPR-1543 (Ref. 11), I conclude that;

i) Such behaviour is to be expected for any comparison between a LP and CFD code and is the reason why more sophisticated CFD codes are used for determining local effects.

ii) On the whole, this response showed that COCOSYS and GASFLOW compare reasonably well, within limits, at least at the global scale for homogenous states.

iii) It is clear that such comparisons for local parameters are much more divergent, on the basis of the evidence as presented. However, there are some suggestions that this too could yield a reasonable comparison, if dedicated comparisons were to be made. It is also relevant to consider that the reliance placed upon the COCOSYS results for local effects is limited in the EDF and AREVA responses for **GI-UKEPR-RC-01.A2**. On this basis I am content that sufficient has been provided to conclude that these differences do not undermine the information provided in the responses, or the claims supported by it.

iv) An element which could not be provided in the response was information on the range of values within a particular volume in GASFLOW, which may have provided useful information on the effects of CFD code discretisation described further below.

- *Time-shifts in GASFLOW calculations* – to minimise the computing time where a large time lag exists between the initial blowdown and core melting phases EDF and AREVA effectively "skip" this time period in the GASFLOW calculations. This applies to both of the "*representative*" scenarios (but not the "*bounding*" SBLOCA scenario which is much quicker). EDF and AREVA claim that this period is "quasi-stationary" with little or no change in the containment conditions. Data is presented to show this is the case for hydrogen, but not for other relevant parameters. I asked EDF and AREVA to provide some confirmatory data on a number of points in TQ-EPR-1546 (Ref. 11). The response provided additional data on the behaviour of the plant to steam releases and liner temperatures during the "quasi-stationary" period. This analysis shows that, for the SBLOCA 2" CL FC scenario considered, the steam concentrations and liner temperature are marginally overestimated by this assumption, which is conservative for the safety case. This response provided confidence in the suitability and application of this approach.
- *CFD code discretisation* – all CFD analysis requires a balance to be struck between the computing time and the accuracy when determining the number of steps, either spatially or temporally. I queried if EDF and AREVA had undertaken a sensitivity study for these aspects as part of the set-up for GASFLOW and COM3D, particularly where the results show the potential for detrimental effects. EDF and AREVA argued that all the codes are used within their validation, which is to say that the discretisation used is able to accurately model the experimental testing used to validate the code. This is not the same as undertaking a sensitivity study for the specific EPR™ set-up to ensure that it can capture all the relevant effects in UK EPR™ (see for example Refs 43 and 44). Similar considerations for COCOSYS are discussed and assessed in Section 4.2, under **GI-UKEPR-RC-01.A1**.

105 The above are examples of the type of justification I would expect to see in the combustible gas control safety case for UK EPR™, particularly as it is reliant on complex

CFD codes. This is not just a simple case of assurance that the codes are used within their validation, but also a demonstration that the specific application of the codes to UK EPR™ is appropriate and “fit for purpose”. For example I would expect that consideration would be given to undertaking a sensitivity study for the specific set-up to ensure that it can capture all the relevant effects in UK EPR™. I am content that sufficient evidence has been provided by EDF and AREVA at this time, in relation to the generic safety case and the response to **GI-UKEPR-RC-01.A2**. As described earlier in Para. 74, it is expected that the future licensee will provided site specific analysis and hence I would expect these aspects to be developed further during this phase. As such, I consider these to be Assessment Findings, **AF-UKEPR-RC-56** and **AF-UKEPR-RC-57**:

AF-UKEPR-RC-56: *The licensee shall complete and document, as part of the site specific analysis, a:*

- *Verification and validation of the codes used to support the safety case for combustible gas control, including a comparison of the analysis to relevant good practice guidelines for CFD use.*
- *Review of inter-code comparisons where the analysis procedure calculates the same data in different codes.*

This Assessment Finding should be completed before fuel is first loaded into the reactor.

Required Timescale: Fuel load

AF-UKEPR-RC-57: *The licensee shall demonstrate the adequacy of the CFD codes descretisation as part of the site specific analysis, especially for those phenomena where high spatial or temporal accuracy is required. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required Timescale: Fuel load

4.1.1.3.2 Recombiner Performance

106 During Step 4 I examined how the various codes used by EDF and AREVA model the recombiners removing combustible gases during use (see Ref. 2). While there are some simplifications in the approach adopted, I was content that this model was an adequate compromise between complexity and adequacy. This conclusion was based upon arguments presented by EDF and AREVA that the simplifications have only limited impact on the overall results. For determining factors such as temperature loads, I remain content with this approximation. For use in simplified LP codes such as COCOSYS this remains an adequate model.

107 However, having now assessed the detailed results from the local GASFLOW calculations I believe that further work should be done in the site specific phase to investigate the assumption of 100% depletion through the PAR influencing the results for effects such as gas distributions, stratification or plume flows. Recent experimental tests on AREVA type PARs show around 40% of the hydrogen entering a given PAR can remain un-reacted at the outlet (Ref. 45). A similar, but perhaps different, effect would also be seen for other combustible gases such as carbon monoxide; refer to Section 4.1.1.7. of my report. I queried this aspect with EDF and AREVA (see Ref. 11). Despite

not examining this aspect by analysis EDF and AREVA still claim any effects would be small. I do not believe that the results of such effects can be predicted a priori and I believe that some analysis of this, or at least a fuller justification for not doing so, is needed as part of developing the site specific safety case for UK EPR™. This analysis should be sufficient to be able to determine the risks on both the global and local scale. The uncertainty caused by this simplification should be considered in the context of its use in a "*bounding*" scenario for the analysis, which is a conservative assessment. It is also relevant that none of the codes, as currently implemented by EDF and AREVA in the **GI-UKEPR-RC-01.A2** responses, would be able to adequately model this effect. On balance, I judge that further consideration needs to be given to this potential effect in the site specific analysis for a UK EPR™, but am content that this approach is adequate for resolution of **GI-UKEPR-RC-01.A2**. As such I consider this to be an Assessment Finding, **AF-UKEPR-RC-58**:

> ***AF-UKEPR-RC-58:*** *The licensee shall include a demonstration of the impacts of allowing unreacted combustible gases to exit the PARs as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required Timescale:*** Fuel load

4.1.1.3.3 Summary

108 I have compared the specific application of the codes in the **GI-UKEPR-RC-01.A2** responses to relevant guidance and good practice for use of CFD codes in safety justifications. Generally, this has shown that EDF and AREVA have appropriately applied the codes and have intelligently used the results. I have however, identified several areas where further development is required as the safety case is progressed during the site specific phase. These are mainly related to the verification and validation of the codes specifically to UK EPR™. I am content these do not undermine the validity of the responses to resolve this GDA Issue Action.

4.1.1.4 Gas Distribution, Combustion modes and Recombiner Performance

4.1.1.4.1 Overview

109 Report PEPA-G/2011/en/1009 (Ref. 22) primarily deals with the gas distribution in containment during the in-vessel phases of the accident scenarios considered. The report is comprehensive and summarises a number of analyses with both COCOSYS and GASFLOW. The results of the analyses are examined systematically in terms of hydrogen risks and effects on the plant. The report presents a number of relevant observations and results derived from the analysis; those most relevant to the GDA Issue are assessed further below, preceded by a sub-section which discusses several detailed aspects of the modelling which are relevant.

4.1.1.4.2 Modelling Approach and Assumptions

110 The vast majority of the report is based upon GASFLOW results, as described earlier (Section 4.1.1.2). EDF and AREVA also make use of the lumped parameter code COCOSYS to model the entire accident sequence and derive global results, such as the long-term depletion rate or AICC pressure. I note that the nodalisation of EPR™ used in these COCOSYS calculations is rather simplistic, containing 30 nodes, with the single

dome node having more volume than all the remaining 29 nodes combined. Ref. 40 indicates that other uses of this code for safety documentation have often used many more nodes (for example a 3 loop PWR used 165 nodes and a German KONVOI PWR used 182 nodes). However I judge that the EDF and AREVA approach is adequate in the context of the current GDA Issue action because;

- The reliance placed on the COCOSYS results for safety purposes were higher in these latter, non EPR™ cases. As above, the majority of the EPR™ case is instead based on GASFLOW.
- The response to TQ-1543 (Ref. 11), as discussed in Para. 103, showed that COCOSYS and GASFLOW agreed reasonably well on global aspects, which provides some degree of validation for the relevant COCOSYS results.
- EDF and AREVA base their analysis around the more sophisticated GASFLOW calculations for local effects.

111 This aspect is much more relevant to the sensitivity study related to **GI-UKEPR-RC-01.A1**, where only COCOSYS analysis is performed, see Section 4.2.

112 Similarly, as described in Para. 103, it is important that the nodalisation used within the GASFLOW CFD calculations is adequate. The number of nodes should be sufficient for the representation of the geometry of the flow domain and the expected flow phenomena in that domain. This is clearly more important in areas where small spatial resolution is required. Relevant good practice guidelines (for example, Refs 34, 35, 43 and 44) recommend that it should be demonstrated that the final result of the calculations is (almost) independent of the nodal scheme that is used. The response to TQ-EPR-1543 (Ref. 11), as discussed in Para. 103, was less clear on these aspects and EDF and AREVA confirm they have not undertaken such an analysis. This is not to suggest that the results themselves are compromised, on the contrary EDF and AREVA are confident that their nodal scheme is adequate and that it represents current "*best practice*", instead this is another area where I believe that further justification will be needed as the safety case develops. As such I consider this to be part of Assessment Finding **AF-UKEPR-RC-57**, described earlier.

113 Another important choice in the GASFLOW analysis presented is the turbulence model used. Generally, it is possible to use either an algebraic or k-ε turbulence model in GASFLOW. The k-ε model is more accurate, but requires a very small numerical time-step, leading to large computing times and thus EDF and AREVA use the simplified algebraic model. As this could influence how the gas is distributed, I queried the impact of this simplification in my technical meetings with EDF and AREVA in both September and November 2011 (see Ref. 39). EDF and AREVA claim that this approach leads to reasonable estimates in areas of high turbulence but overestimates in areas of low flows, thus is conservative overall. I asked if analysis had been performed to confirm this claim. EDF and AREVA replied that it is neither possible to apply a spatial or temporal separation of turbulence models (e.g. algebraic modelling for the release area/time and k-ε modelling for the rest of the containment volume/time) nor to perform an entire simulation with the k-ε turbulence model. I accept that this is the case for the **GI-UKEPR-RC-01.A2** responses.

114 In order to understand the likely scale of effect this could cause my TSC performed a parametric study of the turbulence model in GASFLOW, using the THAI HM-2 experiment (Ref. 30). This experiment used the 60m^3 THAI test vessel. The aim of this experiment was to validate the use of helium as a hydrogen substitute in such tests and as such used a much simpler geometry than UK EPR™. An example of the results from this study is presented below:

[redacted]

Figure 4: Comparison of experimental results and GASFLOW analysis of the THAI HM-2 test using the algebraic and k-ε turbulence models from Ref. 30.

115 I do not believe it is appropriate to examine the results of this TSC study in too great a detail; rather it is useful in demonstrating that the choice of turbulence model does indeed have a noticeable effect, even in this much simpler simulation. It was also evident that the EDF and AREVA claim of over-estimating turbulence using this model appears to be supported. On this basis, I am content that the arguments provided by EDF and AREVA approach are adequate for resolving the GDA Issue

116 However, I believe that further evidence should be provided on the impact of this choice as part of the site specific analysis, should its use be retained. An investigation into the effects of this choice using a suitable two-equation turbulence model (e.g. k-ε, SST) would provide additional evidence for the adequacy of this assumption. This analysis should be sufficient to reveal the effect on gas distributions and the resultant combustion risks, both on the global and local scale. To overcome some of the calculation difficulties, such a comparison could be performed for a limited duration, when the distribution is potentially most dependant upon the turbulence (e.g. during the blow-down phase) but should consider at least one accident sequence from the safety case. I am content that this can be resolved as part of the site specific analysis, hence I consider this to be an Assessment Finding, **AF-UKEPR-RC-59**.

AF-UKEPR-RC-59: *The licensee shall demonstrate that the use of a simplified algebraic turbulence model is adequate as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

117 As well as being important in determining the gas distributions, the turbulence level is an important input to the fast combustion calculations as described in Section 4.1.1.6.

4.1.1.4.3 Results – CONVECT System

118 The first important result suggested by the analysis in Ref. 22 is that the CONVECT system of foils and dampers opens sufficiently prior to or during the release of large amounts of hydrogen to allow atmospheric mixing of the containment. For the “*bounding*” SBLOCA scenario the analysis suggests this occurs within 1200 seconds, over 3600 seconds before the peak hydrogen release occurs. The analysis also shows the different volumetric flow rates through the mixing dampers between the different scenarios, which suggest that the “*bounding*” SBLOCA analysis exhibits the strongest convection in the cases examined. EDF and AREVA cite a previous analysis with partial failure of the CONVECT system as evidence for the adequacy of the CONVECT system. I did not review these calculations in relation to this GDA Issue, but note that this was considered as part of the Step 4 Containment and Severe Accidents assessment (Ref. 15), specifically in **AF-UKEPR-CSA-05**.

4.1.1.4.4 Results – Gas Distributions

119 The general trend for gas distribution in the Ref. 22 analysis shows that the released hydrogen initially accumulates around the break location and in the large upper dome area, where it produces a relatively homogenised but stratified upper hydrogen cloud. As the accident progresses these higher concentration clouds mix with the remaining volumes in the annular and equipment rooms, further diluting the average hydrogen content. For cases where convection is strongest this process is quicker and more pronounced. For all the scenarios examined the rates of atmospheric mixing are sufficient to prevent large areas with very high hydrogen concentrations developing. For the “*bounding*” SBLOCA case (which has the highest levels of convection) this progresses to such an extent that, within 30 minutes of the main release, the lower rooms actually have higher concentrations than the dome. This is due to the preferential location of the PARs in the upper regions, and the correspondingly higher level of hydrogen removal this causes. This is shown in Figure 5 below (from GASFLOW) which shows the developing hydrogen concentrations in two perpendicular vertical slices through the containment at 15 minute intervals.

[redacted]

[redacted]

[redacted]

Figure 5: Hydrogen concentration in vertical slices shortly after peak hydrogen release and approximately 15 and 30 minutes later for the "*bounding*" case from Ref. 22

120 The difference in the rates of atmospheric mixing does make important differences to the analysis, as this effectively dictates what combustion modes need to be considered and when for each scenario (see the following sub-section, Para. 121 onwards) as described earlier in Section 4.1.1.1. For example, despite rapidly releasing over [redacted] kg of hydrogen early in the scenario, the "*bounding*" SBLOCA analysis results show that it is quickly diluted into the containment volume, resulting in a hydrogen cloud with over 4% vol. hydrogen that occupies almost all of the containment volume (i.e. almost 80,000 m^3). At the same time, the corresponding cloud with over 10% vol. hydrogen is much smaller, but initially occupies most of the dome volume (i.e. around [redacted] m^3). This latter high concentration area is seen to be rapidly removed to under the 4% vol. level within a further 15 minutes. The mass (upper figure) and volume (lower figure) in clouds with different hydrogen concentrations are shown in Figure 6 below (from GASFLOW), for the "*bounding*" SBLOCA scenario:

[redacted]

[redacted]

Figure 6: Hydrogen mass and volume within various concentration clouds within containment for the "*bounding*" case from Ref. 22

121 In contrast the "*representative*" scenario with a break at the pressuriser has much weaker convection, due to the elevated release location, and a stratified atmosphere persists for much longer in the area surrounding the break. Arguments are made later in the EDF and AREVA report as to why this is not as penalising as might be suggested by considering the hydrogen distribution alone. In this scenario, other releases from the break accumulate in the pressuriser compartment along with hydrogen, meaning that the steam content is often sufficient to render the mixture inert despite the high hydrogen levels. This is a reasonable argument.

4.1.1.4.5 Results – Combustion Risks

122 The distribution of combustible gases is important in determining the extent and form of combustion that could result. As described previously, Section 4.1.1.1, hydrogen above 4% vol. will combust provided it is not inerted by steam and is mixed with sufficient oxygen, but not completely. Above 8% vol. combustion will be complete. Above 10% vol. there is the possibility that the combustion can accelerate and become a detonation. Above 16% direct detonation is possible, given a sufficient energy input. In general, the analysis shows that there are time periods where such combustible gas clouds exist. Data is presented which show the time history of the various cloud volumes which contain more than 4, 8, 10 and 16% vol. Hydrogen, see Figure 6. EDF and AREVA examine these results to determine what further analysis is necessary:

- For the "*bounding*" SBLOCA scenario, the results indicate that a global (slow) combustion has the potential to occur. Similarly, the "*representative*" scenarios show large areas where hydrogen above 4% vol. persists for appreciable times. Using Sharipo ternary diagrams, the report relates the risk of combustion to the mass of hydrogen present in the various compartments over time. Analysis of the impact of such a slow combustion is presented in a separate report (Ref. 23), assessed in Section 4.1.1.5 of my report.
- Analysis of the extent of higher concentration areas suggest that flame acceleration cannot be excluded in areas of the containment including the dome and accessible rooms for the "*bounding*" SBLOCA scenario. Similarly, EDF and AREVA cannot discount such combustions in the "*representative*" scenarios. However the volume, mass and time that higher concentration areas exist in the "*representative*" scenarios are an order of magnitude lower than for the "*bounding*" SBLOCA case. More detailed analysis of these phases of the accidents using both the GASFLOW and COM3D codes is presented in a separate report (Ref. 24), assessed in Section 4.1.1.6 of my report.

123 EDF and AREVA do not explicitly consider the direct detonation of hydrogen in their report. In TQ-EPR-1545 (Ref. 11), I queried why direct detonation of hydrogen had not been considered in the calculations as several periods exist where the gas composition is such that it is within the detonable region, for both the "*representative*" and "*bounding*" scenarios. EDF and AREVA responded that a sufficient source of energy is not available within the containment to initiate such reactions directly, given the large (several KJ (i.e. equivalent to a blasting cap used as a detonator for explosives and several orders of magnitude larger than a spark)) energy input needed and the rapid increase in energy needs when ideal mixtures of hydrogen and oxygen are not present. According to tests performed by Sandia the critical ignition energies for hydrogen-air mixtures with 20, 18.5 and 17.4% vol. hydrogen correspond to about 30g, 150g and 460 g of tetryl high explosive respectively (Ref. 46). This is consistent with the IAEA guidance (Ref. 35) which states that "*direct initiation of a detonation is not possible within containment due to the high energy required*". On this basis I am content that such analysis is not needed in the UK EPR™ safety case.

124 As described above, despite the incorporation of a large number of PARs into the EPR™ design, several periods exists where elevated hydrogen concentrations are possible. While EDF and AREVA do go on to perform additional analysis to confirm the consequences for these periods, I note that the ALARP arguments regarding if anything further could be done to stop such conditions even being reached are weak. The UK EPR™ PCSR states that "*… several solutions were considered including recombiners and igniters to prevent global detonation or deflagration due to high hydrogen concentrations. Passive autocatalytic recombiners were ultimately selected for this*

purpose." For example; a concept utilising a combination of hydrogen igniters and PARs known as the "*dual concept*" was recently reported by the IAEA in Ref. 35. Such an approach was originally developed and tested in Germany and is currently implemented at Loviisa 1 and 2 in Finland (76 PARs / 20 igniters) and for the Korean APR1400 PWR design (26 PARs / 10 "*glow plug*" igniters). The analysis of this type of system indicates that such an approach could be effective in controlling combustible gas concentrations. As is common this approach offers both benefits and disadvantages:

- The main benefit being that this concept recognises that in the most demanding accident conditions, where the recombiners may not be able to keep up with the high hydrogen release rates, the igniters may be used for initiating combustion at the flammability limits and to prevent formation of a rich mixture, with avoidance of the resultant risks.
- Conversely, this option utilises both active and passive technology to control the hydrogen concentration within the containment and assumes that adequate power supply is available to energise the igniters in accident condition such as LOOP and Station Black-Out (SBO) that may lead to severe accident conditions. This concept can potentially add complexity to the overall mitigation system which requires further consideration.

125 I judge that further examination of such options should be made by the licensee, on an ALARP basis, as part of the detailed site specific design phase to determine if further defence in depth measures could be applied for those times where combustible gas concentrations are potentially highest. This is also related to **AF-UKEPR-CSA-23**, from the Step 4 Containments and Severe Accidents assessment (Ref. 15). Hence I consider this to be an Assessment Finding, **AF-UKEPR-RC-60**.

> ***AF-UKEPR-RC-60:*** *The licensee shall review reasonable practicable design improvements that could be made to UK EPR™ to mitigate against hydrogen accumulation in severe accident conditions within the containment. This Assessment Finding should be completed before the containment is pressure tested.*
>
> ***Required timescale:*** *Containment Pressure test*

4.1.1.4.6 Results – PAR Performance

126 In addition to gas distributions and potential combustion modes, this report provides information on the performance of the PARs. Without the PARs it can be shown that a release of around 800 kg of hydrogen, at 0.15 MPa and 100 °C, evenly distributed throughout the containment volume would result in an average hydrogen concentration of over 10% vol., sufficient to put the containment at risk of a global combustion. Such masses of hydrogen are predicted for a number of severe accident scenarios, including the "*bounding*" SBLOCA case which is predicted to release a total of [redacted] kg during the in-vessel phase, with an initial rapid release of around [redacted] kg followed by several small releases and a final slower release of around a further [redacted] kg. The fact that such global concentration are not reached in the EPR™ analysis presented, very simply demonstrates that the PARs are effective in reducing the hydrogen concentrations to less hazardous levels, at least on the global scale.

127 A simple measure of the effectiveness of the PARs at removing the hydrogen is to compare the mass of hydrogen in containment to the released mass. For the "*bounding*"

SBLOCA analysis the maximum amount of hydrogen present in the containment at any time in the accident is calculated to be [redacted] kg. At this same time the PARs have removed a total of [redacted] kg of hydrogen, or 9%. This peak occurs very soon in the accident, shortly after the peak hydrogen release period. As the accident progresses the amount of hydrogen removed by the PARs increases to around [redacted] kg by the time of the second major release, even further increasing to around [redacted] kg when the residual mass of hydrogen peaks for a second time (to around [redacted] kg) as a result of this second main release. Maximum average recombination rates of up to [redacted] kg hr^{-1} are predicted. This is shown in Figure 7, below. Note that this figure is from the COCOSYS simulations while the figures above are from the GASFLOW results; hence there are minor differences due to code to code comparisons, as described previously (Para. 103).

[redacted]

Figure 7: Hydrogen release and recombination characteristics for the "*bounding*" case from Ref. 22

128 It is notable that while the two "*representative*" scenarios analysed show much larger differences between the residual and total hydrogen released to containment at the time of maximum concentration (around 40% removed), the residual masses of hydrogen in containment are much lower at around [redacted] to [redacted] kg. Maximum average recombination rates of around [redacted] kg hr^{-1} are predicted. These lower values are primarily due to the much lower hydrogen release rates, and hence lower demand on the PARs. This further reinforces the argument for the conservative nature of the "*bounding*" SBLOCA case.

129 As well as global CGCS performance, information is also presented on the performance of individual recombiners. This is more difficult to interpret as the performance can be transient, depending on the local conditions. What is clear is that a number of the recombiner "*groups*" show similar performance across the individual PARs within that group. Those that exhibit this behaviour are those not subject to direct leaks paths, but experience hydrogen from global convection (i.e. those on the polar crane or annular rooms). This type of behaviour further reduces the vulnerability of the CGCS to failure or

degradation of individual recombiners. A number of the PARs do show very high peak recombination rates (over [redacted] g s^{-1}), but such rates are often transient with peak rates of around [redacted] g s^{-1} more common. This behaviour is relevant to the sensitivity study provided in response to **GI-UKEPR-RC-01.A1**, see Section 4.2.

4.1.1.4.7 Comparison to the Generic UK EPR™ PCSR

130 Several of the results described in Ref. 22 directly relate to the claims made in the generic UK EPR™ PCSR (Ref. 16). I compare these explicitly to the PCSR claims below;

- "A*verage hydrogen concentration does not exceed 10% by volume for any scenario*." The maximum average hydrogen concentration predicted by EDF and AREVA is significantly less than this, [redacted]% vol.
- "*AICC pressure is at no time greater than 5.5 Bar* [0.55 MPa] *for representative scenarios.*" The maximum AICC pressure predicted by EDF and AREVA for the "*representative*" scenarios examined is around half of this, [redacted] MPa.
- "*AICC pressure can reach 6.3 Bar* [0.63 MPa] *for a bounding scenario…"* The maximum AICC pressure predicted by EDF and AREVA for the "*bounding*" SBLOCA scenario is [redacted] MPa, below the PCSR claim.
- "*Recombination rate of hydrogen is several hundred kg/hour…*" and "*The maximum amount of hydrogen, resulting from the oxidation of all zirconium in the core, is reduced to a global average below 4% vol. within 12 hours*." The maximum individual and average recombination rates predicted by EDF and AREVA are [redacted] and [redacted] kg hr^{-1} respectively. Global average hydrogen concentrations are only infrequently above 4% vol. and can be seen to reduce below this level in several thousand seconds at most, well within 12 hours. Those periods above this level are assessed in subsequent sections of my report below.

131 Hence, despite the above comments, and the difference in scenarios and analysis assumptions between the two sets of analysis, it can be seen that the relevant PCSR claims are indeed substantiated by the responses to **GI-UKEPR-RC-01.A2**.

4.1.1.4.8 Summary

132 The response provided by EDF and AREVA shows how the hydrogen distribution in the containment of EPR™ changes throughout the course of a severe accident and how this influences the resultant combustion risks. The approach adopted is appropriate to the GDA Issue Action, including under bounding accident conditions. The analysis does show that several periods exist where gas mixtures which are rich in combustible gases are produced. I have raised an Assessment Finding for the licensee to justify if ALARP modifications could be made to remove these periods. Overall, there is a degree of conservatism in the approach. The analysis also confirms that, despite differences in the underlying analysis between the PCSR and the **GI-UKEPR-RC-01.A2** responses, the relevant PCSR claims are still supported by the evidence presented.

4.1.1.5 Temperature Loads

4.1.1.5.1 Overview

133 During a severe accident, the heat generated within the containment could have important consequences on the integrity of the inner steel liner in particular. There are several potential sources of significant heat input that should be considered. Report PEPA-G/2011/en/1010 (Ref. 23) analyses the containment temperature loads as a result of the release of hot gases and water from the primary circuit, as well as the operation of the PARs and postulated slow hydrogen combustion in the containment dome, all building upon the gas distribution results generated in Ref. 22.

134 The comments made earlier, regarding the assumptions and simplification EDF and AREVA have applied to the COCOSYS and GASFLOW calculations, therefore propagate through to the results presented in this report as well.

135 Neither the combustible gas control PCSR chapter (Ref. 16), nor the responses to **GI-UKEPR-RC-01.A2** details what the critical containment temperature loads are in UK EPR™. Without this information it is not possible to judge what margin is available in the results presented. I queried these aspects in TQ-EPR-1542 (Ref. 11). EDF and AREVA responded by indicating that the steel containment liner has been designed to tolerate temperatures of up to [redacted] °C, with occasional short lived transients above this. The response also quoted Ref. 47, which contains analysis to bound the potential thermal and pressure loads for the EPR™ civil structures during severe accidents. This analysis is of a similar vintage to that described in the PCSR and also concluded that inner concrete structure temperatures may reach up to [redacted] °C due to combustion and [redacted] °C due to recombination. These values are used as part of the EPR™ design process.

136 The results presented in Ref. 23 show that the release of hot gas and steam is not the primary driving force for increasing the liner temperature, however it does act to generally heat the containment before any recombination or combustion occurs. The main source of heat is due to the reaction of hydrogen with oxygen, either in the PARs or during combustion. Both need to be considered separately as the energy is dispersed in different rates over different areas.

4.1.1.5.2 Results – Thermal Loads from the PARs

137 An examination of the data shows that the PARs generally operate at near constant average rates once the main hydrogen peak has occurred, with the "*bounding*" SBLOCA scenario exhibiting around twice the rates seen in the "*representative*" cases. This means the energy input from recombination is similarly constant, on the containment scale. However, a number of individual PARs will experience higher rates due to their proximity to the postulated break or hydrogen source.

138 The PAR recombination model was examined in detail during Step 4 of GDA, see Section 4.6.3 of Ref. 2. Overall, I concluded that while the model may not represent what is actually occurring in a given PAR unit, it is a reasonable simplification upon which to perform such analysis. Due to the way the model is constructed and how the initial test data was produced, this may underestimate the outlet hydrogen concentrations and flows but overestimate the outlet gas temperature from individual PARs. Such effects are considered negligible by EDF and AREVA and are likely to cancel when considered on containment scale, but perhaps not on the local scale. I believe that any such effect would be similar in scale to that caused by recombiner "*saturation*" described in Para. 140 that follows.

139 The "*bounding*" SBLOCA scenario shows average containment gas temperature increases of around 30 °C, or up to around 40 °C in the dome. This demonstrates both the degree of mixing and the efficiency with which the containment mass absorbs the heat produced. However, such estimates do not consider "hotspots" as might be generated in the local environment close to PARs. EDF and AREVA consider these in detail later in the same report, which shows that the PARs in the "*bounding*" SBLOCA scenario, generally achieve maximum exhaust gas temperatures in the range of [redacted] to [redacted] °C, with the highest individual PAR exhaust reaching [redacted] °C, at the location close to the break. This effect is seen in the analysis of the liner temperatures, which shows "hotspots" in areas above the polar crane PARs and SG compartments of up to [redacted] °C. See Figure 8 below (from GASFLOW).

[redacted]

Figure 8: Maximum liner surface temperature without combustion for the "*bounding*" case from Ref. 23

140 When combustion is also considered these "hotspots" are lost within the much larger and hotter area of the dome encompassed by the combustion, particularly in the "*bounding*" SBLOCA scenario; see Figure 9 that follows in a later section.

141 An important assumption in the PAR model is the "*saturation*" limit of 8% vol. hydrogen above which the PAR is assumed to operate at a constant rate (given sufficient oxygen). EDF and AREVA have applied this limit to all the analysis presented for **GI-UKEPR-RC-01**. Such an assumption is conservative for gas distributions (potentially leaving some non-combusted gas) but conversely not for temperature loads. For example, it can be calculated that allowing a PAR to operate up to 10% vol. hydrogen would increase the recombination rate (or energy released) by 25% according to the governing PAR model defined by EDF and AREVA (Ref. 48). Considering the critical temperature loads defined in the response to TQ-EPR-1542 (Ref. 11) and the above analysis results it is possible that the liner could see temperatures closer to [redacted] °C, albeit for short durations and over only small areas. As described below, this remains less than the corresponding loads when a penalising slow combustion is considered.

142 Irrespective of this extra energy, EDF and AREVA's predicted PAR temperatures may be sufficient to cause ignition of combustible plumes in areas around the PARs, see Ref. 49. I queried the potential for the PARs to operate as igniters. EDF and AREVA claim that while this is not modelled in the current analysis, it can be considered bounded by the case which considers ignition under penalising conditions. If ignition at PARs was explicitly considered any temperature or pressure loads from such a slow combustion should be lower than those considered in the current analysis. The high PAR exhaust temperatures described above make small slow combustions at PAR outlets likely, but explicit modelling of this is unnecessary for the EDF and AREVA approach for EPR™.

4.1.1.5.3 Results – Thermal Loads from Combustion

143 In terms of slow combustion the questions of where and when the ignition occurs are important. Slow combustions are not a problem provided the structures and equipment can be shown to tolerate the consequences in terms of temperature and pressure. The AICC pressure bounds the potential pressure loads; see para. 95. Such simple calculations cannot be used to predict temperature loads effectively.

144 The most important area to protect in any PWR is the containment shell itself, as this represents the last barrier to environmental releases. As such slow combustions in inner rooms of the containment are not of as much concern as areas close to the shell, such as the dome and annular compartments which are important to consider. It is not possible to predict when ignition may occur in reality, as the gas is below the auto-ignition temperature (around 500 °C) and must therefore ignite as a consequence of some unknown, random event during the accident. To encompass such effects EDF and AREVA chose an artificial time of ignition for their calculations, which is based on maximising the mass of hydrogen in both the overall containment and the dome specifically. Ignition is chosen to occur at one of the PARs in the dome, due to the hot operating temperature. I accept these arguments as reasonable for maximising the temperature loads on the containment shell and note that such an approach will lead to a conservative analysis of thermal loads from combustion.

145 Analysis is performed for both "*representative*" and the single "*bounding*" scenario from Ref. 22. In all cases the volume of the dome cloud with over 4% vol. hydrogen is comparable at around 30000 m^3, but the mass of hydrogen is highest for the "*bounding*" SBLOCA scenario at around [redacted] kg, around twice the mass of the "*representative*" scenarios.

146 The combustion model used in the GASFLOW calculations uses a modified Arrhenius approach to determine the rate parameter for use in the calculation of the rate of combustion. This is a simplified approach to combustion and does not consider any detailed chemistry. EDF and AREVA choose to disable the auto-ignition criteria for these calculations, which is conservative for the temperature releases as this allows gas volumes to combust which are below this threshold and means the combustion does not "burn-out" as might be expected. It is notable that EDF and AREVA do not use this same assumption for the ex-vessel phase of the accident, see Section 4.1.1.7, potentially affecting the temperatures predicted. Despite these simplifications the overall rate remains heavily dependant on the gas temperature, so hotter gas does combust much quicker. This approach does lead to some artefacts in the modelling, including no real information on flame propagation. This may have implications for the mass of combusted hydrogen, as flame propagation could lead to increased mixing. EDF and AREVA claim that this is an overall conservative approach. My TSC considered that while GASFLOW is well suited for predicting gas distributions it is not as reliable for combustion processes

(Ref. 31). EDF and AREVA acknowledge and discuss these limitations in Ref. 23. These potential detriments have to be balanced against the other assumptions used in the analysis, such as performing the determination for a bounding scenario and considering other pessimisms such as maximising the hydrogen available at the time and location of ignition and disabling the auto-ignition threshold. On balance I judge that this is a reasonable simplification to make for the response to **GI-UKEPR-RC-01.A2**.

147 However, as the temperature loads from combustion are entirely dependant upon the amount of hydrogen burnt, I consider it to be appropriate for additional evidence to be provided during the site specific phase to demonstrate that the GASFLOW results are indeed bounding in this regard. This could be achieved, for example, by repeating the analysis with a dedicated combustion code, using the same boundary conditions and ignition point, and comparing the masses of hydrogen burnt. This analysis should confirm that the defined limits for the containment steel liner are respected, or evidence should be presented to show that the structure can tolerate the loads predicted. I consider this to be an Assessment Finding, **AF-UKEPR-RC-61**, to be resolved as part of the site specific analysis:

> ***AF-UKEPR-RC-61:*** *The licensee shall demonstrate as part of the site specific analysis that the GASFLOW results are adequate to bound the temperature loads predicted during combustion, in terms of the amount of hydrogen burnt. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load*

148 The analysis in Ref. 22 shows that for the "*bounding*" SBLOCA analysis combustion is complete in only a few seconds, burning [redacted] kg of hydrogen (or 64% of that present). This is a much higher mass and shorter timescale than both "*representative*" scenarios. This results in a flame speed of several hundred m s^{-1}, putting this in the fast combustion regime, but it is artificially accelerated by the simplified combustion model used so is not a reliable measure of potential flame acceleration, but is conservative for temperature loads. This artificially high combustion speed supports my judgement in Para. 143, that the EDF and AREVA application of GASFLOW to predict temperature loads from combustion for the **GI-UKEPR-RC-01.A2** responses is adequate.

149 This analysis shows that, with combustion in the dome, the gas temperature rapidly peaks at over [redacted] °C, resulting in a peak liner surface temperature of [redacted] °C in the dome, although this rapidly decreases and stabilises to below [redacted] °C in a further 20 seconds, but stays marginally above [redacted] °C for over 1000 seconds. Temperatures in the more sensitive vertical sections of the liner, where penetrations are located, are lower still. The peak liner temperatures at various times following combustion are shown in Figure 9 below. The top picture is at the time of maximum thermal load, whereas the bottom picture is for 10 seconds later, demonstrating the rapid cooling of the liner following such combustion.

[redacted]

[redacted]

Figure 9: Maximum liner surface temperature with combustion for the "*bounding*" case from Ref. 23, at the time of peak temperatures and 10 seconds later

150 For the potentially sensitive steel liner the results are generally consistent with the critical temperature loads defined in the response to TQ-EPR-1542 (Ref. 11). However there appears to be a short period where the [redacted] °C limit is exceeded, confined to the dome area. In response to TQ-EPR-1542 (Ref. 11) EDF and AREVA confirm that such short lived transients are considered as part of the liner qualification. I am satisfied with this response in the context of the present GDA Issue Action but would expect a future

licensee to explicitly consider such excursions as part of Assessment Finding **AF-UKEPR-RC-61**, defined above.

151 Peak surface temperatures for the concrete and steel structures inside containment are also presented, both of around [redacted] °C. These thermal loads for the internal concrete structures are notably higher than those defined in response to TQ-EPR-1542 (Ref. 11). While the loads remain below [redacted] °C and [redacted] °C without and with combustion for both "*representative*" cases, the peak temperature rises above [redacted] °C for around 200 seconds without combustion or for 900 seconds if combustion is also included for the "*bounding*" SBLOCA scenario. This occurs over only a small surface area of the internal walls of the SG tower. The TQ-EPR-1542 (Ref. 11) response again suggested that such effects are considered in the design of the internal structures, and the report referenced in the TQ response does indeed consider the thermal loads caused by exposure to [redacted] °C gas for 1800 seconds, which is significantly hotter for longer than the Ref. 23 analysis, as described earlier in Para. 148. On this basis I am content with this response.

4.1.1.5.4 Comparison to the Generic UK EPR™ PCSR

152 The PCSR (Ref. 16) assesses the temperature loads for a number of alternate scenarios. This used an early version of GASFLOW which did not model heat transfer from gas to walls effectively, meaning wall temperatures are under-predicted. Thus while the liner temperatures predicted without combustion in the PCSR are lower than those given in PEPA-G/2011/en/1010 (Ref. 23) and described above, the gas temperatures are relatively consistent. Several cases are examined for combustion temperature loads, including a comparable SBLOCA scenario. Despite these differences the relevant claims in the PCSR related to temperature loads are substantiated by the EDF and AREVA analysis presented in PEPA-G/2011/en/2010:

- "*Temperature loads on the containment shell resulting from recombination are below* [redacted] *°C*." As described above this result was calculated with an ineffective heat transfer model, hence the **GI-UKEPR-RC-01** response results are higher at [redacted] °C, and potentially higher still if the PAR 8% vol. limit is revisited. However, even then margin still exists according to the response to TQ-EPR-1542 (Ref. 11), which gives confidence that the PCSR claim remains valid.
- "*Temperature loads on the containment shell are below* [redacted] *°C for representative scenarios when considering combustion of in-vessel generated hydrogen…"* EDF and AREVA calculate a maximum liner temperature of [redacted] °C for the "*representative*" scenarios analysed, significantly lower than the PCSR claim.
- "*Peak temperature on the containment shell from combustion is around* [redacted] *°C for bounding scenarios ((SBLOCA) with delayed depressurisation, steel liner explicitly modelled). However, this peak temperature is only reached in the dome and involves only an area of around 10 m^2*." Again, while the **GI-UKEPR-RC-01** response calculates higher temperatures, of [redacted] °C, this is a short lived transient peak over a small area of the dome which quickly falls to less than [redacted] °C. The response to TQ-EPR-1542 (Ref. 11) also gives confidence that this transient is not significant and are considered as part of qualification for the liner, supporting the PCSR claim.
- "*Combustion temperatures are considerably lower in the cylindrical part of the containment where the penetrations for ducts, material hatch and personnel airlock are located.*" EDF and AREVA predict lower maximum liner temperatures in the

upper cylindrical regions of around [redacted] °C and [redacted] °C in the "*representative*" and "*bounding*" scenarios respectively, and 20-30 °C less in lower areas.

4.1.1.5.5 Summary

153 I am content that EDF and AREVA have provided an adequate justification for the temperature loads expected during the in-vessel phases of a severe accident in EPR™ in the context of the present GDA Issue Action. The results show that without combustion, the temperature loads predicted on walls and structures are moderate with the loads from recombiners explicitly considered. Combustion loads can be significantly higher but are often transient and short-lived, and are only present in the dome away from more sensitive areas. Such transients are considered as part of qualification for the liner. The results support the claims made within the generic UK EPR™ PCSR.

4.1.1.6 Fast Combustion Risks and Pressure Loads

4.1.1.6.1 Overview

154 As with temperature loads, pressures generated during a severe accident have the potential to threaten the containment integrity or to damage internal structures or equipment. Pressures generated by hydrogen combustion can be significant, if the flame speed is fast, particularly if higher than the speed of sound. This can result either from a direct detonation or from a slower combustion that accelerates due to turbulent mixing (Deflagration to Detonation Transition (DDT)).

155 As described previously (Para. 122) direct detonations are considered extremely unlikely in EPR™ due to the high energy input required. The approach taken by EDF and AREVA to assess the potential for fast combustions is to use the gas distribution analysis from Ref. 22 to determine the likelihood of both flame acceleration and DDT based upon experimentally derived criteria, σ and λ. As described in more detail in the Step 4 assessment report (Ref. 2), σ is a conservative indicator of the likelihood of flame acceleration, based upon the properties of the mixture. Fulfilment of the σ criteria does not indicate that flame acceleration will always occur, but it is highly unlikely to occur without fulfilment of this criterion. Similarly, λ is a measure of the susceptibility of the gas to detonation. Again, meeting both the σ and λ criteria (i.e. the flame must be both accelerable and detonable) does not mean that DDT will occur, only that it is possible.

4.1.1.6.2 Modelling Approach and Assumptions

156 EDF and AREVA conduct analysis for all three scenarios described in Ref. 22 (two "*representative* and one "*bounding*"), plus one further case where the "*representative*" pressuriser break scenario has an artificially diminished steam content. This latter case further enhances the conditions for flame acceleration and is used to demonstrate the avoidance of any "cliff-edge" effects. The gas distribution results from Ref. 22 do show that for all the cases examined there are times when the gas compositions are such that flame acceleration has the potential to occur. In PEPA-G/2011/en/1011 (Ref. 24), the fast combustion CFD code COM3D is used to model the combustion of hydrogen at the location and time that results in the most challenging conditions for the production of flame acceleration. The analysis also provides information regarding whether flame acceleration towards a deflagration-to-detonation transition (DDT) presents a risk to the containment. Such combustion will be more problematic in confined areas which contain obstacles causing turbulence, such as the equipment rooms in UK EPR™. For all the

scenarios considered these are exactly where the hydrogen release from the primary circuit occurs, hence the necessity of detailed and specific analysis. This is consistent with the OECD “roadmap” for evaluating the hydrogen risks to a given plant containment, described in Section 4.1.1.1.

157 This is an important aspect of the EDF and AREVA safety case for combustible gases as there is no “empirical” reasons to suggest flame acceleration does not occur and instead the case is reliant on complex CFD analysis to show that the flame speeds remain benign, requiring a suitable level of confidence in the analysis.

158 Before describing the results in detail it is relevant to note that there are several assumptions and simplifications in the way that the EPR™ fast combustion modelling was performed, any or all of which could have an influence on the results predicted by EDF and AREVA:

- Combustion model - COM3D uses a modified eddy break-up (EBU) combustion model, which means that the rate of burning is dependant upon the turbulence and not the chemical kinetics. This model is very commonly applied in such calculations, mostly due to its relative simplicity. As with all modelling of such complex phenomena, results should be treated with a note of caution. For example, the OECD “state of the art” report on flame acceleration and DDT (Ref. 34) states of the EBU model that; “*eddy break-up modelling provides a crude first approach to turbulent combustion simulations when the primary interest is in (i) worst-case estimates for high-intensity turbulence and (ii) details of the flame acceleration history from ignition to high-speed combustion are irrelevant*” and that “*much more sophisticated modelling is required to obtain true predictive capabilities both for flame acceleration and the kinetics-dominated high-turbulence intensity regime responsible for potential transition to detonation*”. Thus it is recognised that while the EBU model provides inaccurate but indicative estimates for flame speeds, it is a recognised and well known technique. I queried this approach with EDF and AREVA, who confirmed that they consider the modified EBU model to be appropriate and believe its application to EPR™ bounded by its validation (Ref. 50). The main validation uncertainty relates to tests at higher temperatures (as predicted for EPR™), but this is a general deficiency in the model, not specifically related to EPR™. Overall while the modified EBU model has deficiencies its use in the present analysis appears justified provided due cognisance is given to its limitations.
- Turbulence model - Unlike GASFLOW, COM3D uses the k-ε turbulence model which is more appropriate. However, as described in Para. 112 the choice of applying the algebraic model in GASFLOW could influence both the initial distributions but also more specifically the initial turbulence conditions transferred to COM3D. While EDF and AREVA claim that transfer of the data between the two numerical methods is easy, they have not demonstrated that the assumption in GASFLOW results in an adequate input for COM3D. As the combustion process is highly reliant on the turbulence level this assumption has the potentially to significantly affect the results of the analysis. However, as described previously (Para. 112), there are valid reasons why EDF and AREVA have applied this approach in the current analysis. It is also evident that the EDF and AREVA claim, that this model overestimates the turbulence level appears to be supported by my TSCs calculations. An overestimate of initial turbulence would lead to a pessimistic determination of flame speeds. As such I judge that this approach is satisfactory in the context of resolving the current GDA Issue Action but would expect a future UK EPR™ licensee to review this aspect as part of Assessment Finding **AF-UKEPR-RC-59**.

- Nodalisation - Similarly, the nodal scheme applied in COM3D is important in terms of assuring that the model can adequately resolve all the relevant phenomena at the chosen scale. It is especially important to the COM3D calculations as there is no other means available within the safety case to assess the likelihood of DDT, hence there needs to be a high level of confidence in the calculations. This should include consideration of what obstacles or structures have been modelled in the analysis, which may increase or decrease the possibility of flame acceleration. EDF and AREVA state that the most important obstacles for flame acceleration in EPR™ are the walking grids, which are claimed to be modelled accurately. I am content with these arguments for the resolution of this GDA Issue Action, but would expect a future licensee to review these aspects further as part of Assessment Finding **AF-UKEPR-RC-57**.
- Geometry - EDF and AREVA assume that all the doors in the containment are open at the time of combustion. My concern was that this might not necessarily be conservative should this lead to reflections and channelling of the flame front. EDF and AREVA confirmed that they have repeated such analysis assuming closed doors in the past, which showed decreased flame speeds due to enhanced gas mixing. While I have not reviewed these calculations in detail, I am content that these effects have been considered by EDF and AREVA and accept their argument that they have been conservative as reasonable. I am content that sufficient has been provided in relation to the present GDA Issue Action.
- Calculation times - The analysis presented in the report runs for less than 10 seconds for all the scenarios. I queried why the analysis was stopped after this period, as the analysis appeared to show on-going combustion at the termination. EDF and AREVA stated that this is because the flames have exited the equipment rooms long before this point and have thus entered the dome and other containment regions where they decelerate. Although the combustion rates may be high at these points, this is due to on-going slow combustion in large areas of the containment, not accelerated flames (i.e. a large mass burning slowly as opposed to a small mass burning quickly). EDF and AREVA consider that extended periods of analysis may be possible in the future with increased computing resources. I am content with the justification given for this aspect and accept these arguments.

4.1.1.6.3 Results – Occurrence of Flame Acceleration

159 To bound their calculations EDF and AREVA chose the ignition time based upon the GASFLOW results, which are interrogated to show the area of the cloud with a σ index above 1. This analysis shows that the σ index > 1 cloud (i.e. the volume potentially susceptible to flame acceleration) encompasses the gas cloud which contains above 16% vol. hydrogen, and occasionally encompasses areas of the 10 and 8% vol. clouds, but never extends to an area comparable to the 4% vol. cloud. This limits the areas susceptible to flame acceleration. Additionally, EDF and AREVA chose the time of ignition such that the mass of hydrogen present within the potentially susceptible cloud is maximised. Using this approach, the combustion is calculated at the time when the potential for accelerated flames is highest, with ignition at the location which gives the longest run-up distance inside the affected rooms. Both effects would act to maximise the possibility of producing flame acceleration, further pessimising the results. EDF and AREVA argue that ignition from outside the equipment rooms are bounded by the cases of ignition inside the rooms, which is a reasonable argument

160 The “*bounding*” scenario has a mass and volume of hydrogen in the σ >1 cloud of around ten times that analysed for the “*representative*” pressuriser break scenario, as shown in Figure 10 below (from GASFLOW). As can be seen the maximum extent of the potentially accelerable gas cloud extends to a large part of the dome in the “*bounding*” case (upper figure), but is confined to small areas in the upper SG towers in the “*representative*” pressuriser break case (lower figure):

[redacted]

[redacted]

Figure 10: Extent of σ-index cloud above 1 at the time of ignition for the “*bounding*” case and “*representative*” pressuriser break case from Ref. 25

161 Despite this difference, the "*representative*" pressuriser break case is shown to be the worst case in terms of flame speeds and pressure loads across the containment shell. This is due to the stratification that has occurred in the scenario and the resultant rapid combustion this produces. EDF and AREVA also analyse the "*representative*" pressuriser break case with the global average steam content reduced by 10% to provide an artificial bounding case. This additional aggravation nearly doubles the calculated maximum flame speeds.

162 In all cases analysed, including the artificially aggravated reduced steam content case, the calculations show that the flame is initially accelerated within the confined equipment rooms, but slows again when it reaches the (relatively) unconfined dome area. Peak flame speeds are up to several hundred m s^{-1} are predicted by the analysis, but remain below the speeds needed before DDT is possible. Even the aggravated pressuriser SBLOCA scenario with reduced steam content remains below this limit. Thus on this basis EDF and AREVA claim that DDT does not occur in EPR™ and they do not make claims and arguments regarding fulfilment or otherwise of the λ criteria for DDT.

163 While the argument is made that the dome cannot support accelerated flames due to the large open areas, an area of the dome which has a geometry potentially susceptible to flame acceleration is within the polar crane support structures and this area is further assessed by EDF and AREVA. Similar to the cases examined with ignition in the equipment rooms, ignition is selected based on the time and location of the most penalising combustion. As the polar crane concentrations are effectively identical to those seen within the dome itself, albeit with slight variations due to mixing, the "*bounding*" SBLOCA scenario is considered. It is shown that the σ index is never above 1 in the polar crane structure, avoiding the possibility of flame acceleration and DDT and therefore no detailed COM3D analysis is performed.

164 As part of my assessment I had several queries in the analysis of flame speeds undertaken by EDF and AREVA:

- Due to modelling constraints EDF and AREVA are not able to reliably predict the flame speed in the very early phases of the combustion. Predicted flame speeds are well above the critical limit at these times, but are discounted by EDF and AREVA as unreliable. This is a consequence of the combustion modelling as described in Para. 157.
- It has been shown through international validation exercises (for example, Ref. 51) that CFD codes are only able to predict flame speeds with large uncertainties, when trying to predict experimental results using such codes. The calculated flame speeds for the aggravated pressuriser break scenario may be within the range for DDT when uncertainties are considered, although the other scenarios are almost certainly not. EDF and AREVA claim that they are able to accurately predict the peak flame speeds in such exercises (or even over-predict), even if the precise time or location of occurrence is more uncertain. This should result in an overall conservative safety analysis. The results in Ref. 51 do tend to agree with this argument, although this is only for a single, relatively simple case.

165 I discussed the flame speed calculations with EDF and AREVA who agreed that this was an area of some uncertainty due to limitations in the modelling; however they also argued that the pressure loads predicted by the analysis support the claim of no significant flame acceleration. EDF and AREVA claim that the analysis of flame speed is only used to support the conclusions of the pressure loads analysis described below.

166 EDF and AREVA provided further information on flame speeds in Ref. 52, in response to discussions during our Technical Meetings. This response examines data from fixed temperature monitor points in GASFLOW to determine the time that a flame front reaches them (i.e. temperatures above a define threshold which would be indicative of a flame). As these monitor points are a defined distance from the ignition source it is possible to use them to estimate the flame speeds. This response re-examines the data from the aggravated Pressuriser break scenario with reduced steam content considered in Ref. 25. The main assumption in this approach is that the flame propagation is mainly in the vertical direction; significant horizontal propagation needs to be factored into the results otherwise significantly overestimated flame speeds will result. The results of this analysis indicate that:

- In those areas around the main coolant pump of Loop 3 (where ignition occurs), significant horizontal flame acceleration is observed; conversely the vertical acceleration is limited. Some of this is an artefact of the ignition location being close to several narrow connections between compartments in this particular scenario. Flame speeds are highest close to the ignition location and slow as the flame front moves away. There is a gradual decrease in flame velocities as the distance from the ignition increases, only altered by any obstacles en-route.
- No significant flame acceleration or combustion is observed in the SG tower.
- In all instances no flame speeds are above or close to the pessimistic limit for DDT.

167 While this response re-evaluates existing data generated for another purpose, it does tend to support the overall EDF and AREVA position that no detrimental flame acceleration occurs even for the most penalising case and what flame acceleration does occur rapidly slows.

168 Hence, while there are some weaknesses in the evidence presented by EDF and AREVA to support the claim that flame acceleration does not occur, this needs to be balanced against the other pessimisms inherent in the analysis, particularly the use of an artificially aggravated case. On the balance of evidence presented, I judge that EDF and AREVA's claim that detrimental flame acceleration does not occur is reasonable in term of supporting the current GDA Issue Action. I would expect site specific analysis for UK EPR™ to refine the calculations (for example by presenting evidence also for the λ criteria and a more detailed and specific examination of flame speeds). I consider this to be an Assessment Finding, **AF-UKEPR-RC-62**, and it is related to **AF-UKEPR-CSA-23** from the Step 4 Containment and Severe Accident assessment report (Ref. 15) and **AF-UKEPR-RC-60**, raised in Section 4.1.1.4 above, is also related:

> ***AF-UKEPR-RC-62:*** *The licensee shall provide additional evidence to support the claims made on the avoidance of detrimental flame acceleration as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load*

4.1.1.6.4 Results – Pressure and Temperature Loads from Fast Combustion

169 The pressure from fast combustion analysis is not bounded by the corresponding slow combustion analysis. This is because even though the fast combustion started in the equipment rooms slows considerably when entering the dome, it still retains some velocity compared to a combustion initiating in the dome itself. The "*representative*"

pressuriser break SBLOCA scenario proves to be the worst case examined. The calculated pressure loads on the containment shell are below the AICC pressure, which is itself below the design pressure. Dynamic loads are small at less than [redacted] MPa. Similarly, the peak pressure differences across the internal walls which may be more prone to increased pressures due to dead-ends and restrictions remain well below [redacted] MPa. The pressure loads calculated by COM3D are further conservative due to the adiabatic approximation used in the code.

170 EDF and AREVA claim that the absence of dynamic pressure loads is further evidence to indicate that detrimental flame acceleration does not occur.

171 It is not possible to use the COM3D calculations to examine the temperature loads due to the adiabatic approximation used in the combustion model. However, comparison of the gas temperatures in the dome for the three examined scenarios shows similar results to the slow combustion calculations performed with GASFLOW. This is perhaps not surprising as the mode of combustion (fast or slow) has no effect on the energy released, only the mass, area and timescale over which it occurs. Predicted gas temperatures in equipment rooms are lowest in the "*bounding*" SBLOCA scenario and highest in the "*representative*" pressuriser break case, at around [redacted] °C. On the basis of this analysis EDF and AREVA claim that the slow combustion calculations bound the potential temperature loads. It can be seen that the GASFLOW (slow combustion) results are indeed higher than those predicted by COM3D (fast combustion). The main exception being the "*representative*" pressuriser break scenario, however this is itself bounded by the "*bounding*" scenario temperature loads. On the basis of this evidence, I am content with this argument.

4.1.1.6.5 Comparison to the Generic UK EPR™ PCSR

172 The PCSR (Ref. 16) discusses the analysis from four scenarios, two "*representative*" and two "*bounding*", which are different to those considered as part of the **GI-UKEPR-RC-01** responses although the most penalising case identified is very similar; see Table 3. Irrespective of these scenario differences, the results in the PCSR are presented in only general terms, with little detailed information on, for example, flame speeds and pressure histories. More detailed information is provided by the associated PCSR reference (Ref. 53) which does predict some "*mild*" flame acceleration, but flame speeds remain sub-sonic. However, it is notable that the PCSR analysis predicts both much larger dynamic pressures across internal walls, of up to [redacted] MPa (compared to [redacted] MPa in the corresponding **GI-UKEPR-RC-01** scenario), and larger pressure spikes on the containment shell (up to [redacted] MPa – still below the AICC pressure) mainly as a result of flame deceleration in the dome. These differences do not affect the validity of the main claim made in the PCSR regarding pressure loads from accelerated flames, which is:

- "*Dynamic loads on the containment shell are benign. Pressurisation is bounded by AICC pressure. Although the flame accelerates in the SG tower, it decelerates in the dome, which results in small dynamic loads on the containment shell.*" The results presented in Ref. 24 by EDF and AREVA do indeed predict dynamic loads less than the AICC pressure on the containment shell as a result of an initially accelerated combustion which slows in the dome.

4.1.1.6.6 Summary

173 EDF and AREVA have provided a detailed analysis for flame acceleration risks in EPR™. The results of this work show that flame acceleration could occur in EPR™, but the flame

speeds predicted are lower than the levels needed to initiate DDT even for an artificially aggravated case. EDF and AREVA predict an initially accelerated combustion that slows in the dome resulting in dynamic loads less than the AICC pressure on the containment shell and temperature loads less than those calculated for slow combustion events. The use of an artificially aggravated case is a particular strength in the safety case. On the balance of evidence presented I am content that sufficient evidence has been provided to conclude that detrimental flame acceleration is a highly unlikely situation in EPR™. I have identified some areas related to this analysis where further development of the safety case will be needed by a future UK EPR™ licensee, so have raised these as Assessment Findings. I am content that the claims made in the generic UK EPR™ PCSR are supported by this response.

4.1.1.7 Ex-vessel Analysis

4.1.1.7.1 Overview

174 Report PEPA-G/2011/en/1012 (Ref. 25) details the analysis conducted to bound the ex-vessel phase of a severe accident in EPR™.

175 Before describing the analysis it is useful to briefly describe the accident progression expected for a severe accident which involves an ex-vessel phase in UK EPR™, as this has a number of consequences for the resulting combustible gas hazards. The ex-vessel phase starts once the Reactor Pressure Vessel (RPV) fails and the molten corium it contains is transferred to the reactor pit, which surrounds the RPV. Ultimately the corium is transferred to the spreading area where it is cooled by adding water from the IRWST (In-containment Reactor Water Storage Tank) and submerging the melt. To get there it must first pass though the melt discharge channel, which is separated from the pit via a melt gate, the purpose of which is the temporarily retain the corium in the pit before allowing its onward travel. The pit and spreader are both lined with a layer of sacrificial concrete which reacts with the corium, to reduce its chemical reactivity, to promote its stabilisation and to cool the mixture by dissipating the heat. These structures form an important part of the Core Melt Stabilisation System (CMSS). This process not only generates further hydrogen but also produces combustible carbon monoxide, carbon dioxide and steam and also affects the timing, release rates and release locations for these species. This arrangement is shown schematically in Figure 11 below (from Ref. 16):

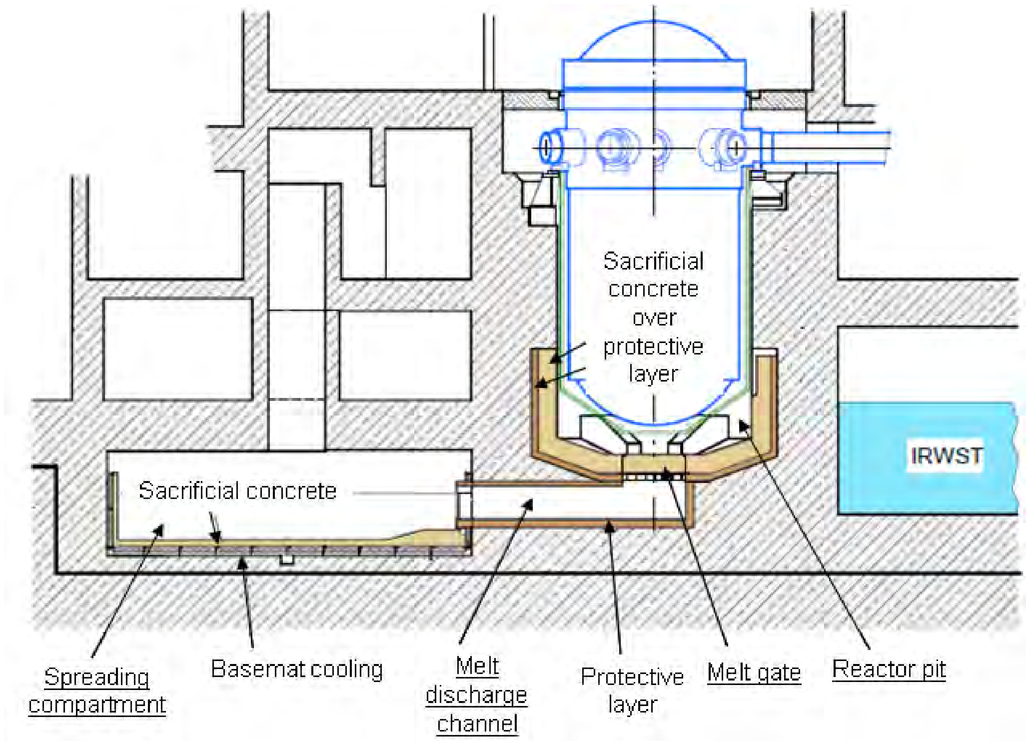

Figure 11: Main components of the EPR™ core melt stabilisation system (Ref. 16)

176 The analysis reported by EDF and AREVA again uses COCOSYS and GASFLOW to model the containment response to the combustible gas releases, taking an additional input from COSACO which determines the interaction between the molten corium and sacrificial concrete in the CMSS. This latter code provides the rates of gas generation for input to COCOSYS and GASFLOW.

177 As previously, the general points made earlier regarding COCOSYS and GASFLOW (see Section 4.1.1.3) remain relevant.

4.1.1.7.2 Scenario Selection

178 The scenarios analysed for the ex-vessel phase are distinctly different from those of the in-vessel phase. This is because the penalising in-vessel case, where the mass and rate of hydrogen release is maximised, is not bounding of the ex-vessel phase (i.e. to bound the in-vessel phase scenarios are chosen with the highest levels of fuel oxidation, thus producing more hydrogen. To bound the ex-vessel phase the opposite is true, with scenarios chosen which minimise the in-vessel oxidation allowing greater levels of combustible gas generation in this latter period). This is an important pessimism in the EPR™ case as it is not possible to have both a bounding in-vessel and ex-vessel phase using this approach. The report (Ref. 25) describes three initial "*generic*" scenarios; LBLOCA, LOOP and a "*representative*" SBLOCA scenario from the in-vessel phase. These represent a fast, intermediate and slow rate of accident progression respectively. These are initially analysed with COCOSYS.

179 The actual analysis presented is based on a generic EPR™ reactor for the initial MAAP4 input, not FA3 or UK EPR™, unlike that presented in the other responses (Refs 22, 23 and 24) or the PCSR (Ref. 16). Some information is presented on the comparison of the "*generic*" results to the plant specific (FA3) analysis; results for the amount of hydrogen

generated in-vessel vary by +5%, +18% and -20% between the "*generic*" and FA3 analysis for the three cases examined. The origin of these discrepancies are due to the lower thermal power assumed in the "*generic*" analysis (4300 MW compared to 4500 MW) and advances in the codes and analysis methods between the two data sets. I also noted that the peak hydrogen mass in containment for the SBLOCA cold leg break was larger in this report than Ref. 22 by 25 kg, when I would expect them to be identical. I queried this difference in TQ-EPR-1544 (Ref. 11). EDF and AREVA confirmed this difference was due to the difference between "*generic*" and FA3 specific cases. Overall, I am content that these differences are minor and have only a small impact on the analysis and hence the safety case.

180 What is apparent from this analysis is that the ex-vessel phase is not as affected by the particular accident scenario as the corresponding in-vessel phase. Despite differences in the in-vessel phases, in terms of rates and mass of hydrogen generated, the ex-vessel phases for all three scenarios analysed show very similar results in terms of the overall mass of combustible gases released (around [redacted] kg hydrogen and [redacted] kg carbon monoxide), ratio of hydrogen to carbon monoxide at any given time and release profile over the course of the accident. Differences exist in the rates and timings of the individual phases. This is demonstrated in Figure 12 below (from COCOSYS), which shows the combustible gas release profiles for the LBLOCA, LOOP and SBLOCA scenarios considered by EDF and AREVA:

[redacted]

Figure 12: Comparison of combustible gas release profiles for the ex-vessel scenarios considered in Ref. 25

181 This similarity is not surprising given that this phase of the accident is dictated by the reaction of corium and sacrificial concrete, which in turn is dictated by the heat energy in the corium (which influences the rate of reaction) and masses of un-oxidised zirconium and concrete (which influence the mass and rate of combustible gas produced).

182 Based on these initial COCOSYS results EDF and AREVA select the LOOP scenario as the "*bounding*" case for further detailed analysis with GASFLOW.

183 I agree that a LBLOCA analysis is very unlikely and is not relevant on a probabilistic basis. EDF and AREVA also chose to discard the SBLOCA scenario, on what appears to be mainly motivated by the extra computational time required for the SBLOCA case. I note that the corresponding in-vessel phase of the SBLOCA scenario has already been calculated with GASFLOW as part of Ref. 22.

184 As described previously, scenario selection is an important pre-requisite. It is also apparent from the presented COCOSYS results in Ref. 25 that the SBLOCA case may be more penalising for latter combustion risks. In particular there appears to be a time period (< 1000 seconds) where average conditions in the reactor pit are in the flammable region as the steam content in the pit also remains below inerted levels for over 10000 seconds following RPV failure. As this data is only the average for a particular volume, EDF and AREVA themselves state that "*It should be noted again that the averaging of compartment conditions in the lumped-parameter code COCOSYS makes these results meaningless for the prediction of a combustion, as locally high concentrations of combustible gases can not be properly resolved*" and also "*… in the diagram* [Shapiro three phase combustion diagram for the ex-vessel phase] *… the contribution from carbon monoxide as a combustible gas is not taken into account*". These are also general statements that could apply to the other scenarios considered however both the LBLOCA and LOOP scenario do not need to consider this possibility because the reactor pit remains steam inerted through this period. Overall, these calculations alone cannot be used to assess the risks of combustion in the reactor pit for the SBLOCA case.

185 This is perhaps a consequence of the aims for the analysis presented in Ref. 25, which is to "*show that hydrogen and CO burn near the location where they are released so that there is no risk of accumulation*". In other words this report is not a complete assessment of the hazards associated with the combustible gas risks during the ex-vessel phases of a severe accident in EPR™, for example thermal or pressure loads resulting from these phases, the inference throughout the report being that these are bounded by the in-vessel phase results. Other information of relevance is instead found in the references to the generic PCSR (Ref. 16), which contains an analysis for a similar SBLOCA case. As such I consider this as part of my assessment that follows.

186 However, while I consider that sufficient evidence has been provided in the context of the present GDA Issue Action, I believe that the scenario selection procedure for the ex-vessel phase should be supplemented with additional supporting information for the final scenario selection decision, including consideration of combustion risks at the local scale, when site specific analysis is performed for UK EPR™. I consider this to be an Assessment Finding, **AF-UKEPR-RC-63**:

> ***AF-UKEPR-RC-63:*** *The licensee shall justify the scenario selection for the ex-vessel phases of a severe accident, including consideration of combustion risks at the local scale, as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load*

4.1.1.7.3 Bounding Scenario Description

187 The report (Ref. 25) provides details of the accident progression for the chosen "*bounding*" LOOP scenario. This accident exhibits steady hydrogen (including carbon monoxide equivalents) releases of around [redacted] kg s^{-1} throughout the accident, with

short lived peaks of up to [redacted] kg s^{-1} observed at the start of the MCCI in both the reactor pit and spreading area. These rates are much lower than those seen in the in-vessel phase. Steam releases throughout the ex-vessel phase are very large. This is shown in Figure 13 below (from GASFLOW).

[redacted]

Figure 13: Combustible gas releases for the LOOP scenario from Ref. 25.

4.1.1.7.4 Results – Combustible Gas Removal and Resultant Hazards

188 The GASFLOW results for the "*bounding*" LOOP scenario in Ref. 25 show that combustion is the dominant removal mechanism in the ex-vessel phases of the accident. Around [redacted] kg of hydrogen (including carbon monoxide equivalents) is removed, with only around [redacted] kg of this removed by recombination in the PARs, at the time the analysis is stopped. At the point when the analysis is stopped the corium is quenched and no more combustible gases are produced from MCCI. The total mass of hydrogen (including carbon monoxide equivalents) present in the containment peaks approximately 45 minutes before this at around [redacted] kg, which is lower than that seen in the "*bounding*" SBLOCA analysis used for the in-vessel phases.

189 There are two very strong effects which are dominating the behaviour of the gases in containment during the ex-vessel phase:

- Combustible gases released during the MCCI phase are burned close to the release location in a standing flame, principally near the reactor pit (throughout almost all of the ex-vessel release phase) and at the exit of the exhaust chimney to the spreading area (once melt flows to the spreader). This creates a large hot buoyant flow driving convection. This process is such that the analysis suggests some of the unreacted hydrogen remaining from the in-vessel phase is also combusted in this process, further depleting it.
- Large steam releases similarly drive convection, particularly during quenching of the corium in the spreading area.

190 Local concentrations of combustible gases are generally low (< 4% vol.) but can be very high in areas around the release locations at certain times (for example the spreading

area is > 50% vol. shortly after opening of the gate). The results show that, at the time of greatest stratification (shortly after melt gate opening), the cloud with more than 2% vol. hydrogen fills almost the entire containment, but the cloud of more than 4% vol. is confined to the reactor pit, spreading area and connections to adjacent compartments. The fact that these high concentration areas are confined to the CMSS areas support the EDF and AREVA argument that standing flames are consuming the released hydrogen close to the release sites. The fact that the 2% vol. cloud extends to fill almost the entire containment is an artefact of the simple combustion model used which does not allow combustion when gases are below the flammability limit (4% vol.); in reality these gases would also burn to some extent. This underestimates the local temperatures but increases the distribution of combustible gases away from the release sites. Due to steam production and oxygen depletion during quenching combustion in the spreading area directly is prevented.

191 Another important assumption applied by EDF and AREVA is that throughout the GASFLOW calculations the carbon monoxide released is converted to hydrogen equivalents for the calculations on an energy basis (i.e. 1g of CO is equal to 0.083g of hydrogen). This is reasonable for an energy basis, but does lead to some further assumptions in the analysis. The OECD has published a report on the effects of CO under severe accidents (Ref. 54) which further discusses some of the potential consequences of this assumption. I discussed these points with EDF and AREVA:

- CO clearly has different material properties than hydrogen. This could impact on the distribution of gases within the containment, but is not expected to be significant when balanced against the other assumptions used in the analysis, particularly the bounding case analysed.
- In order to allow GASFLOW to simulate a standing flame, EDF and AREVA assume that "*the mixture of hydrogen and oxygen in a cell burn if the combustion conditions based on the ternary diagram for hydrogen, oxygen and steam are fulfilled*". However, the mixture will also contain carbon monoxide plus potentially some carbon dioxide, thus affecting the validity of the flammability limits. The OECD report (Ref. 54) states that these effects can be calculated using Le Chatelier's rule and that "*the presence of CO widens the flammability of hydrogen*". This needs to be balanced against the diluting effects of CO_2. Overall, I do not consider that this effect will have a significant impact on the results of the analysis as presented, but I would expect this case to be presented explicitly for any UK EPR™ site specific analysis, Assessment Finding **AF-UKEPR-RC-64**:

  AF-UKEPR-RC-64: *The licensee shall demonstrate that the assumption that carbon monoxide is treated as hydrogen does not negatively impact on the flammability of the gas mixture as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

  Required timescale: *Fuel Load*

- While flame speeds and detonability may be affected by mixtures containing both hydrogen and CO, the calculation performed by EDF and AREVA suggest that conditions for fast flames or detonations are not approached and hence this has no consequence on the analysis results. This is related to Assessment Finding **AF-UKEPR-RC-45** from the Step 4 assessment report (Ref. 2).

- By converting carbon monoxide to hydrogen there is no carbon dioxide produced from either combustion or recombination, but more steam. Whereas steam is condensable and the mass from hydrogen is small compared to steam from flashing of the primary coolant and quenching of the melt, carbon dioxide is not condensable and will act to increase the containment pressure. The analysis in Ref. 25 shows that around [redacted] kg of carbon dioxide are produced from MCCI alone, if carbon monoxide was considered an additional [redacted] kg would be produced. Overall, such an increase would be negligible for the containment compared to other sources of pressure.
- The amount of oxygen consumed by reaction with hydrogen as opposed to carbon monoxide is comparable in this regard (in fact assuming hydrogen is marginally conservative) so the results predicted by GASFLOW for oxygen depletion are adequate in this regard.
- As described earlier in Para. 106, the assumption of 100% depletion of all combustible gases that enter a given PAR could potentially affect the predicted results of the analysis. This is equally applicable to carbon monoxide which may in fact have a lower depletion than hydrogen for the same conditions. I consider that consideration of this effect is part of Assessment Finding **AF-UKEPR-RC-58** defined earlier in my report.

192 As described previously, the ex-vessel analysis report provided in response to this GDA Issue Action (Ref. 25) mainly attempts to justify the assumption that standing flames are developed and that released gases do not accumulate. While this is an important claim, and providing evidence of such is important, it does so at the expense of not explicitly considering other risks posed during this phase. As such, I queried the effects of temperature loads in TQ-EPR-1542 (Ref. 11) as there are large parts of the containment which experience temperatures of greater than 150 °C, up to 1000 °C. Flame temperatures may well be very high, closer to 2000 °C. This is illustrated in Figure 14 below (from GASFLOW), which demonstrates how the area with temperatures above 500 °C expands and then contracts in the various areas of the CMSS as the accident progresses (from top to bottom - after vessel failure, after melt gate opening, at the end of quenching and following quenching):

[redacted]

[redacted]

[redacted]

[redacted]

Figure 14: Cloud with gas temperatures above 500 °C after vessel failure, after melt gate opening, at the end of quenching and following quenching for the LOOP scenario from Ref. 25

193 In response, EDF and AREVA agreed that PEPA-G/2011/en/1012 (Ref. 25) does not represent such thermal loads accurately but also claim that the areas where such standing flames may develop are sufficiently distanced from the liner and do not contain any sensitive structures. EDF and AREVA also conclude in their response that:

- While the loads on civil structures are considered elsewhere, they cite Ref. 47 which details the containment loads from MCCI gas combustion. This report does not consider loads from standing flames above the reactor pit, but does consider the exhaust chimney from the spreader. EDF and AREVA consider this former case to be covered by the loads caused by the corium itself in the pit. The analysis for the exhaust chimney predicts temperatures of over [redacted] °C at the concrete surface. This analysis is not of the same vintage as the **GI-UKEPR-RC-01** responses and considers a different scenario. The overriding assumption made in Ref. 47 is that such flames only develop in the 10 minutes when the MCCI in the spreading area is "*dry*" (i.e. in the period between start of MCCI in the spreader and the beginning of water quenching). It is not clear from PEPA-G/2011/en/1012 what duration is expected for these flames and, as described in Para. 145, the simple combustion model in GASFLOW may underestimate the extent of combustion and hence the resultant temperature loads, hence it is not apparent how relevant the results presented in Ref. 47 actually are.

- While the results presented in PEPA-G/2011/en/1012 show that the containment liner may experience temperature loads of greater than [redacted] °C for short time periods, EDF and AREVA confirmed in their response to TQ-EPR-1542 that a new calculation performed for FA3 shows that the temperature remains below this limit throughout the ex-vessel phase. I am content with this response. Similar data would be needed as part of the site specific analysis for UK EPR™, taking account of the point raised in Para. 145 regarding the adequacy of GASFLOW combustion modelling.

194 The PCSR (Ref. 16) also contains some information on temperature loads generated during the ex-vessel phases. As with all the PCSR analyses, this is of an earlier vintage to the GDA Issue responses and considers a different scenario, in this case an SBLOCA. The PCSR considers combustion in the reactor pit and spreading area, with the latter considered to bound the former as, even though a similar mass of combustible gases are burnt, the duration is shorter. The predicted maximum temperatures for the internal steel and concrete structures and containment liner are [redacted], [redacted] and [redacted] °C respectively. For the potentially sensitive steel liner there appears to be a short period where the [redacted] °C limit is exceeded, as is evident in the PEPA-G/2011/en/1012 results. Again, the response to TQ-EPR-1542 (Ref. 11) confirms that revised calculations have shown this is an artefact of the earlier analysis and this limit is indeed respected throughout the ex-vessel phase.

195 Considering the GDA Issue, TQ responses and PCSR analysis in combination, I am content that sufficient evidence has been provided on thermal loads in the context of the current GDA Issue Action. However, as the generation of standing flames is an important consequence of the EPR™ design I believe that the licensee should address and accurately quantify the temperatures loads from ex-vessel hydrogen combustion, including their effects, as part of the site specific analysis. This should address the discrepancies highlighted above. I am content that it is appropriate to address this as part of producing site specific assessments and I therefore consider this to be an Assessment Finding, **AF-UKEPR-RC-65**:

> ***AF-UKEPR-RC-65:*** *The licensee shall quantify the temperatures loads from ex-vessel hydrogen combustion as part of the site specific analysis. This should demonstrate the effects of combustion in standing flames on thermal loads. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load*

196 Due to combustion in standing flames, pressure loads are mainly generated as a result of corium quenching and the resultant steam production. Pressures in the containment rise sharply and steadily during this phase from around [redacted] MPa to [redacted] MPa, and fall steadily thereafter. Due to the similarity of the LOOP scenario to other scenarios, similar pressure rises could be expected for other scenarios. Such pressures are below the design limits for the containment.

4.1.1.7.5 Comparison to the Generic UK EPR™ PCSR

197 The main claim made in the PCSR regarding ex-vessel phases is:

- "*Ex-vessel generated hydrogen may lead to containment shell temperature of at most* [redacted] *°C due to continuous combustion (standing flame). These temperatures are reached in the dome only.*" Despite both the PCSR and GDA Issue responses indicating that temperatures are above [redacted] °C during certain periods of the ex-vessel phases, in response to TQ-EPR-1542 (Ref. 11) EDF and AREVA claim that revised calculations show that liner temperatures remain below [redacted] °C throughout the ex-vessel phases, giving margin to the PCSR claim.

4.1.1.7.6 Summary

198 EDF and AREVA analyse the ex-vessel phases of a severe accident in EPR™ to show that combustible gases, which now include CO from MCCI, are combusted close to their release location and do not accumulate in other areas of the containment. I am content that this important assumption has been shown to be the case. The response to the GDA Issue Action is weaker at presenting the holistic safety review of the risks during these phases but in combination with the PCSR I am content that an overall case has been made. I have raised a number of Assessment Findings to seek improvements to these aspects for any future EPR™ constructed in the UK. The claim made in the generic PCSR for UK EPR™ is supported.

4.1.2 PCSR Update

199 EDF and AREVA did not plan to update the consolidated Step 4 PCSR (Ref. 16) in response to **GI-UKEPR-RC-01.A2**, as defined in their resolution plan (Ref. 3).

200 However, as part of my assessment of the **GI-UKEPR-RC-01.A2** responses I have reviewed the claims, arguments and evidence presented against those from the PSCR. As described in Sections 4.1.1.4 to 4.1.1.7 above, while there are some differences in the precise values and evidence, the overall intent of the PCSR is met. On this basis I agree that the PCSR does not need updating as a result of **GI-UKEPR-RC-01.A2** however, as site specific analysis will be preformed (as noted in Assessment Finding **AF-UKEPR-RC-42**), the site specific PCSR will need further development.

201 As part of my review I do note that the effect of activation of the containment spray system on the hydrogen risks is not covered in the **GI-UKEPR-RC-01.A2** responses. This is considered in the PCSR. The PCSR quotes Ref. 55, which is an analysis of the effects of the containment spray for a "*bounding*" SBLOCA scenario. This analysis considers earlier activation of the spray system at a penalising time, rather than considering the 12 hour "grace" period normally considered for the other PCSR analysis. The overall conclusion of this report is that this earlier, penalising activation of the spray system does not negatively impact on the hydrogen risks, and potentially has a beneficial impact

resulting from greater homogenisation. I am content that these arguments are credible and that it is not necessary to further consider these aspects as part of the GDA Issue responses.

202 However, AREVA note in Ref. 55 that "*Although it is expected that the main conclusion remain valid for other scenarios, a confirmation for scenarios with significant different steam concentration … seems recommendable*". I agree with this general conclusion and believe that this can be applied to other scenarios, however as the PCSR analysis is of a different vintage and uses a different scenario (hence a different steam concentration), I judge that this aspect should be reviewed and justified as part of any site specific analysis, Assessment Finding **AF-UKEPR-RC-66**. This analysis should be consistent with the overall safety case and should include a range of scenarios which cover the steam concentrations possible in containment and variations in the timing of operation of the spray. This aspect is therefore best resolved as part of the site specific analysis:

> ***AF-UKEPR-RC-66:*** *The licensee shall demonstrate the impact of operation of the containment spray system on the combustible gas risks as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load*

4.1.3 Summary of the Assessment of the Action 2 Responses

203 In response to this GDA Issue Action, EDF and AREVA provided a series of reports which detail the computational assessment of the risks associated with combustible gas generation during both the in-vessel and ex-vessel phases of a severe accident in EPR™ (Refs 22, 23, 24 and 25). I have assessed these reports and in conclusion I note that:

- The overall structure and approach in these reports is appropriate to the GDA Issue Action and the safety case gap it seeks to address. The reports contain a high level of detail which builds confidence that the results are robust, the methodology adopted is appropriate and the resulting data has been used intelligently.
- The results presented are for the reference plant, FA3, not a generic UK EPR™, although it should be recognised that the design reference point for both plants is common. EDF and AREVA have confirmed the expectation that the licensee will provide site specific analysis for any EPR™ to be built in the UK. I am content with this approach as it means that the safety case will use the most modern and up to date analysis and techniques. This would also remove some of the difficulties experienced during the assessment in terms of reconciling analysis results from many different sources, which often use different assumptions and inputs, allowing a consistent and more transparent case to be made. The FA3 analysis presented has been used to build confidence in the fundamental approach, to satisfy the GDA Issue Action requiring analysis under bounding conditions and ultimately to demonstrate that that the claims, arguments and evidence presented in the generic UK EPR™ PCSR remains sound.
- The overall EDF and AREVA approach, of using initial Lumped Parameter codes followed by increasingly more detailed CFD codes, has been demonstrated to be appropriate and is consistent with relevant international guidance in many regards. Throughout my assessment I noted several areas where detailed aspects of the models need further evidence or development. I do not judge these to be sufficient

to undermine the overall conclusions of the report, but these should be addressed by the licensee as part of the site specific analysis for any UK EPR™.

- There were also several areas of the results where I found gaps in the information presented. This was mainly as a consequence of the "*scope*" for the FA3 analysis. I asked further queries on these areas and EDF and AREVA responded adequately to these queries, where this was possible within the bounds of the analysis undertaken. I have identified several areas where additional development in the safety case is needed and I have raised Assessment Findings to ensure these are resolved satisfactorily during the site specific phase.
- EDF and AREVA initially provided only limited information on the processes used to identify appropriate bounding scenarios for analysis. However, they responded appropriately to my questions and queries and I am satisfied that the process applied is appropriate resulting in a suitable selection. I am particularly encouraged by the use of a "*bounding*" case to demonstrate margins and the avoidance of cliff-edge effects.
- The analysis provides very useful information on the PAR performance in EPR™. It is clear that during periods with high release rates the CONVECT system and successful mixing of the containment atmosphere is important to minimise inhomogeneous concentrations of combustible gases, with the PARs becoming more important in the medium to long term as a means of reducing the risks associated with these gases. The analysis shows that the PAR system, while dimensioned to account for the "*representative*" cases, is adequate to respond to more aggravated penalising cases.
- EDF and AREVA consider the main potential safety risks, and conclude that:
    1. The risk of a global detonation is avoided in all scenarios.
    2. Without combustion, the temperature loads predicted on walls and structures are moderate with the loads from recombiners explicitly considered. Combustion loads can be significantly higher but are often transient and short-lived, and are only present in the dome away from more sensitive areas. Such transients are considered as part of qualification for the liner.
    3. Pressure loads predicted by slow combustions are below the AICC pressures, for which the EPR™ containment is designed.
    4. The analysis of the risks of flame acceleration, potentially leading to Deflagration to Detonation Transition (DDT), is analysed in some detail by EDF and AREVA because the gas distribution results show that such effects cannot be ruled out. This aspect of the EDF and AREVA case is entirely based on CFD analysis, hence there needs to be an adequate level of confidence that these results are reliable. EDF and AREVA predict an initially accelerated combustion slowing in the dome which results in dynamic loads less than the AICC pressure on the containment shell, temperature loads less than those calculated for slow combustion events and no occurrence of DDT. The use of an artificially aggravated case is a particular strength in the safety case. On the balance of evidence presented I am content that sufficient evidence has been provided to conclude that detrimental flame acceleration is a highly unlikely situation in EPR™.

5. Ex-vessel phases are analysed by EDF and AREVA to show that combustible gases, which now include CO from MCCI, are combusted close to their release location and do not accumulate in other areas of the containment. I am content that this important assumption has been shown to be the case.

- As the reports provided in response to this GDA Issue Action are not specific to UK EPR™, EDF and AREVA have not updated the PCSR. Nonetheless, I have reviewed the claims and arguments made in the PCSR against these responses and conclude that they remain valid.

204 On the basis of the evidence supplied by EDF and AREVA in response to **GI-UKEPR-RC-01.A2**, I am content that an adequate case has been made regarding the specific expectations of this GDA Issue Action. I have raised a number of Assessment Findings for the licensee to resolve as part of their site specific analysis. As such I am content that this GDA Issue Action can be closed.

4.1.4 Assessment Findings

205 Based upon the assessment of the **GI-UKEPR-RC-01.A2** responses described in Section 4.1 above, I have identified the following Assessment Findings which need to be addressed, as normal regulatory business, by the licensee, during the design, procurement, construction or commissioning phase of the new build project;

AF-UKEPR-RC-56: *The licensee shall complete and document, as part of the site specific analysis, a:*

- *Verification and validation of the codes used to support the safety case for combustible gas control, including a comparison of the analysis to relevant good practice guidelines for CFD use.*
- *Review of inter-code comparisons where the analysis procedure calculates the same data in different codes.*

This Assessment Finding should be completed before fuel is first loaded into the reactor.

Required Timescale: Fuel load

AF-UKEPR-RC-57: *The licensee shall demonstrate the adequacy of the CFD codes descretisation as part of the site specific analysis, especially for those phenomena where high spatial or temporal accuracy is required. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required Timescale: Fuel load

AF-UKEPR-RC-58: *The licensee shall include a demonstration of the impacts of allowing unreacted combustible gases to exit the PARs as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required Timescale: Fuel load

AF-UKEPR-RC-59: *The licensee shall demonstrate that the use of a simplified algebraic turbulence model is adequate as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-60: *The licensee shall review reasonable practicable design improvements that could be made to UK EPR™ to mitigate against hydrogen accumulation in severe accident conditions within the containment. This Assessment Finding should be completed before the containment is pressure tested.*

Required timescale: *Containment Pressure test*

AF-UKEPR-RC-61: *The licensee shall demonstrate as part of the site specific analysis that the GASFLOW results are adequate to bound the temperature loads predicted during combustion, in terms of the amount of hydrogen burnt. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-62: *The licensee shall provide additional evidence to support the claims made on the avoidance of detrimental flame acceleration as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-63: *The licensee shall justify the scenario selection for the ex-vessel phases of a severe accident, including consideration of combustion risks at the local scale, as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-64: *The licensee shall demonstrate that the assumption that carbon monoxide is treated as hydrogen does not negatively impact on the flammability of the gas mixture as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-65: *The licensee shall quantify the temperatures loads from ex-vessel hydrogen combustion as part of the site specific analysis. This should demonstrate the effects of combustion in standing flames on thermal loads. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

AF-UKEPR-RC-66: *The licensee shall demonstrate the impact of operation of the containment spray system on the combustible gas risks as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*

Required timescale: *Fuel Load*

4.2 Action 1 – Analysis with a Reduced PAR Performance

4.2.1 Assessment

206 The purpose of **GI-UKEPR-RC-01.A1** was for EDF and AREVA to demonstrate the performance of the CGCS with the PARs operating at reduced combustible gas removal efficiencies. An important assumption in the UK EPR™ safety case is that the PARs operate at 100% depletion efficiency at all times they are operational (and there remains sufficient oxygen present). This means that all of the combustible gas that enters the PAR is oxidised. The rate that the gas enters the PARs is derived from experimental results where the rate of hydrogen removal by a PAR in a fixed gas volume was measured and related back to the subsequent PAR flow necessary to match this measured removal rate (Ref. 48). This is a reasonable approach to determining information on the rate of combustible gas removal, but it does not provide any information on the efficiency of the PAR or the rates of gas entering the individual units. Conversely, it is likely that this approach actually underestimates the PAR flow rates, underestimating the mixing of the atmosphere that would result.

207 It is possible to hypothesise various mechanisms that could influence the performance of the PARs, such as catalytic poisoning or counter-current flows. There are many experimental results which have looked at various aspects of PAR performance, see Ref. 56 for example, including many such effects. I examined this evidence during Step 4 and concluded that while there is no evidence to suggest that a combustible gas control system based on PARs would be significantly degraded by such effects, some limited reduction in performance remained possible. Rather than try and rationalise this into particular phenomenology, I requested EDF and AREVA to demonstrate the performance of the CGCS with a reduced PAR performance to demonstrate the tolerance to this effect, irrespective of the precise cause.

208 To address this concern EDF and AREVA undertook to provide a specific analysis, using the similar methodologies as used for other UK EPR™ analyses, namely COCOSYS modelling of the containment. EDF and AREVA proposed to perform this work with a revised PAR model, which reduces the PAR performance by 25%. Additionally, they proposed to perform an analysis with a number of PARs completely removed such that the overall system performance was similarly reduced by around 25%. The published EDF and AREVA resolution plan, Ref. 3, contains further details on this approach.

4.2.1.1 Selection of Accident Scenario, Reduction Factor and Deactivated PARs

209 The first response provided in relation to **GI-UKEPR-RC-01.A1**, Ref. 20, contains two appendices which provide details on:

- Scenario selection for the sensitivity analysis.
- Selection of deactivated PARs.

210 The first of these describes the rationale for selecting the chosen "*bounding*" SBLOCA scenario. This is the same "*bounding*" analysis selected for the in-vessel phases of Action 2; hence the reasons for selection are as described in Section 4.1.1.2. I queried a number of points on this response in Letter EPR70343N (Ref. 57). EDF and AREVA provided responses to these as part of the sensitivity study report (Ref. 21). Overall, I am content with the arguments presented for selection of the chosen SBLOCA scenario for this study.

211 Similarly, I am content with the 25% reduction factor applied to the efficiency of the PARs. In the absence of an experimental or theoretical basis for a reduction factor, this appears a suitably bounding and penalising assumption on which to undertake the demonstration.

212 As described earlier in Para. 106, the EDF and AREVA PAR model does not allow for un-reacted hydrogen to exit a PAR. The application of this 25% reduction does not alter this boundary condition and hence this analysis does not respond to Assessment Finding **AF-UKEPR-RC-58**. Such an analysis is not possible with COCOSYS as currently applied by EDF and AREVA, so an alternative approach to that used for the response to **GI-UKEPR-RC-01.A1** would be required (for example, the use of GASFLOW).

213 While not requested, EDF and AREVA also provided a second sensitivity analysis, where a number of PARs are completely removed, to further demonstrate the system margins. EDF and AREVA presented their rationale used to select which PARs are removed as part of the second appendix of Ref. 20. The intent was to remove around 25% of the CGCS capacity. To do this EDF and AREVA suggested a statistical approach to recombiner removal, whereby the performance of individual PARs were ranked (based on the analysis in Ref. 22) and every fourth PAR deactivated. The proposed ranking procedure was based on the total integrated mass of hydrogen removed over the entire course of the analysis. I queried other potential measures and EDF and AREVA responded in the sensitivity study (Ref. 21) by also comparing;

- The integrated mass of hydrogen removed until shortly after the peak hydrogen generation phase.
- The peak hydrogen depletion rate.

214 This comparison showed that, irrespective of which ranking method was applied, the PARs selected by the EDF and AREVA method remain fairly evenly distributed throughout the rankings (i.e. they are not biased towards a particular area of the distributions). This suggests that the selection of PARs to deactivate is reasonable. However, it should be noted that some of this is due to the COCOSYS model, which groups the PARs into the various compartments within the containment model and acts to average the conditions experienced by the PARs in that group, see Section 4.2.1.2 that follows.

215 It is also notable that more penalising conditions could be chosen by removing PARs from a localised area or those with the highest rates. However, both of these are considered beyond the scope of the current Action and could be argued to be unlikely on a probabilistic basis. Overall, I am content with the methodology applied by EDF and AREVA for resolution of **GI-UKEPR-RC-01.A1**.

4.2.1.2 Modelling Approach

216 Ref. 21 provides details of the COCOSYS model used to undertake the sensitivity analysis. This is the standard model used by EDF and AREVA, including in their responses to **GI-UKEPR-RC-01.A2** (Refs 22, 23, 24 and 25). This model splits the containment volume into 30 nodes. The temperature, pressure, concentrations etc. within each individual node is averaged at any given time (i.e. gas entering or leaving a node is instantaneously averaged with the bulk). The nodes range in size from 84 m^3 (reactor pit) to over 45000 m^3 (dome), but each accurately represents an area within the containment (compare this to an average of 0.39 m^3 within each GASFLOW volume). The PARs are distributed throughout the various nodes, based upon their location in the plant design (e.g. the dome node contains eight PARs). This model has some important

consequences on the results of the sensitivity analysis and these should be understood before considering the results.

217 As the gas environment within a given node is the average of that node, it follows that the PARs within that node will all see exactly the same environment. This means that the performance of a group of four PARs within a given node will be affected in the same manner irrespective of whether one complete PAR is removed or all four PARs have their performance reduced by 25%. This is one factor which explains both:

- The insensitivity in deactivated recombiner selection described in Para. 213.
- The similarity in results between the reduced performance and deactivated PAR sensitivity studies, described further in Section 4.2.1.3. below.

218 While this model is more appropriate for the use of COCOSYS as undertaken for the main safety case (i.e. as in Refs 22, 23, 24 and 25) where the interest is in understanding containment performance on the global scale, for attempting to understand the (local) performance of recombiners this resolution is less appropriate. Ref. 22 contains information on the performance of individual recombiners as derived from the more detailed GASFLOW calculations. As described in Para. 128, this shows that some of the recombiner "*groups*" do indeed show similar performance for either mass or rates of hydrogen, but others do not. At worst individual recombiners within a group may vary by factors of around 2. This would suggest that:

- A selection scheme for the deactivated recombiners based on the GASFLOW results would be different to those selected or proposed in Ref. 21.
- Nodalisation of the COCOSYS model, taking account of the performance of individual PARs would lead to different results than those presented.

219 The response to TQ-EPR-1543 (Ref. 11), which requested a comparison for various results between COCOSYS and GASFLOW, showed that in general such comparisons are reasonable on the global or average level when the level of inhomegeneity is small. Should either of these conditions not be met then the results tend to vary to some degree. This has implications for the conclusions that can be drawn for the local effects of a reduced recombiner performance, see the section that follows.

220 I therefore consider that a more appropriate nodalisation scheme for COCOSYS could have been adopted by EDF and AREVA for this sensitivity study. This would be more akin to those previously used in such safety studies, see Ref. 40 for example. Ultimately however, it is the effect that these assumptions and simplifications have on the safety consequences of the results that are important. I consider these factors further when assessing the results of the sensitivity study below.

4.2.1.3 Effects of Reduced CGCS performance

4.2.1.3.1 Overview

221 Ref. 21 presents the results of the sensitivity analysis in terms of the global reduction in hydrogen mass, the variation in depletion rate, the overall hydrogen concentration, the local hydrogen concentrations in particular locations and the hydrogen depletion rates of the PAR units in different containment zones. The general approach is to compare the "*base*" case with the sensitivity cases. The "*base*" case refers to the analysis from Ref. 22, with 100% performance/no deactivation of PARs. EDF and AREVA present a thorough examination and explanation of the differences, although as described later the safety consequence of these differences is not adequately documented in the report and as such I requested further information via TQs in a number of areas.

4.2.1.3.2 Results – Global Aspects

222 The first result that is apparent from the report is that the results for the case with either a reduced PAR performance or the case with deactivated PARs are very similar. EDF and AREVA claim this as evidence for the global convection in UK EPR™. I do not agree that this is the case, although the results are clearly influenced by the mixing that occurs, but rather this is an artefact of the modelling approach described in Section 4.2.1.2. above. I believe that the two cases should differ more than the results presented by EDF and AREVA suggest, but perhaps not grossly so. I am content that this does not undermine the use of the analysis to satisfy the GDA Issue Action.

223 For simplicity, reference to the "*sensitivity*" case in the assessment that follows can be taken to refer to either the reduced performance or the deactivated PARs study, unless stated otherwise.

224 In terms of the global CGCS performance the effect of the sensitivity case is to reduce the overall system performance, but by margins less than the 25% reduction factor applied to the PARs. The actual performance reduction varies throughout the accident sequence, but does not approach the 25% level (except for the very early phases when the recombiners are not fully working) with a time-averaged reduction of 14%. This is due to the positive feedback mechanism which the recombiners display. As they do not operate at a constant capacity, but instead inherently vary their performance based on the time dependant local environment, the individual recombiners "*work harder*" as a result of the increased local hydrogen concentrations caused by inefficient or deactivated PARs. This behaviour lends further confidence to the adequacy of the UK EPR™ CGCS design. This effect should occur provided that the recombiners never operate in a saturated condition. This analysis does show that there is still margin remaining in the CGCS performance even under the most penalising conditions used for the "*bounding*" analysis and with a 25% reduction, as saturation is part of the underlying PAR model in COCOSYS.

225 The overall trend in the mass of hydrogen present in the containment is the same between the base and sensitivity cases, with an initial early peak and a latter second lower peak, both followed by gradual reductions by the PARs. At the time of the overall greatest mass of hydrogen the difference between the two cases is in the order of [redacted] kg or around 4% relative. This is maximised later in the sequence at around [redacted] kg, or around 30% relative. This difference decreases to around [redacted] kg by the time of RPV failure. Similarly the overall recombination performance shows reduced initial rates, but the rate of decrease is slower and they become higher in the sensitivity case for around the last 7000 seconds of the analysis (before RPV failure). The time-average difference is less than 10%. Both of these measures support the positive feedback described above. This is shown in Figure 15, below (from COCOSYS). Note that although this Figure appears to show only two cases (i.e. base and sensitivity cases), it does show all three cases. This is because both of the sensitivity cases (i.e. reduced performance or deactivated PARs) are so similar that there results overlap, appearing as a single dashed line.

[redacted]

Figure 15: Comparison of released, recombined and residual hydrogen mass in containment for the base and sensitivity cases from Ref. 21

226 There is a discrepancy in the peak mass of hydrogen present in the containment between this report and Ref. 22. I queried this discrepancy with EDF and AREVA in TQ-EPR-1544 (Ref. 11), who responded that this difference is due to the differences between COCOSYS (as in Ref. 21) and GASFLOW (as in Ref. 22) as described more fully in Para. 103. I am content that this difference does not affect the validity of the response.

227 EDF and AREVA discuss the impact of the sensitivity study on the recombiner performance in some detail. The analysis does indeed show that the PCSR claims are met in terms of:

- At all times a global hydrogen concentration of 10% vol. is avoided.
- At the time of RPV failure the hydrogen concentration is below 4% vol., avoiding the possibility of large scale combustions.

4.2.1.3.3 Results – Local Aspects

228 In contrast to the global aspects, the response is weaker at presenting the impact of the sensitivity study local risks to UK EPR™, namely temperature or pressure loads in either the in-vessel or ex-vessel phases. Having now assessed the ex-vessel analysis provided in response to **GI-UKEPR-RC-01.A2** (Ref. 25), see Section 4.1.1.7, I am content that consideration of ex-vessel phases is not required as the reliance on the PARs is much larger for the in-vessel phases. I consider the in-vessel local aspects further below.

229 As well as the masses of hydrogen the other important consideration is its concentration, both globally and locally. Generally the sensitivity case adds less than 1% vol. to the peak results in the base case. When the concentration remains below the flammability limit, this additional concentration makes no difference to the safety case claims. It is notable however that in several instances this additional hydrogen takes the average concentration within the flammable range (or in reality the cloud of flammable hydrogen

gets larger or contains a larger mass). These occur following the second main hydrogen release, due to the cumulative effect of the reduced recombiner performance at this time (i.e. the first, main peak does not experience such effects as the PARs are not yet acting efficiently at this time). While EDF and AREVA attempted to argue that such effects did not need to be considered as part of the sensitivity study, I did not agree and asked for further reassurance for the consequences of these increased hydrogen levels for three particular instances, as below.

4.2.1.3.4 Results – Slow Combustion

230 The analysis of slow combustion risks described in Ref. 23 and Section 4.1.1.5 is based upon combustion in the dome early in the accident sequence. I queried if this ignition time remained conservative, in TQ-EPR-1547 (Ref. 11), as the hydrogen concentration returns to the flammable range at the second peak release in the sensitivity case. In response EDF and AREVA provided additional data from the sensitivity analysis which showed the mass of hydrogen present within the dome throughout the in-vessel phase. This illustrated that the mass of hydrogen in the second peak remains less than the mass during the first peak hence the original calculation in Ref. 23 does indeed remain bounding for slow combustions.

4.2.1.3.5 Results – Fast Combustion

231 For fast combustion risks, as described in Ref. 24 and Section 4.1.1.6, the ignition is triggered early in the sequence. The criteria applied by EDF and AREVA to select the ignition time and location are that the σ-index cloud should be maximised, along with the mass of hydrogen within that cloud. For the "*base*" case no data is presented in PEPA-G/2011/en/1011 (Ref. 24) on times after 7000 seconds, which would show the development of any σ-index cloud during the second main release phase, although there is a clear decrease in the mass of hydrogen present during this period and the analysis shows that the development of such clouds is linked to strong releases which result in inhomogeneous atmospheres. As there is a much smaller difference between the hydrogen masses in containment for the first and second release phases for the sensitivity cases (around [redacted] kg instead of [redacted] kg), I queried if this assumption remained bounding in TQ-EPR-1547 (Ref. 11). EDF and AREVA responded to my TQ by arguing that the second main release need not be considered because:

- The GASFLOW results used to determine fast combustion risks are comparable to COCOSYS.
- The second peak in hydrogen mass does not surpass the first release peak.

232 As described previously, COCOSYS does not necessarily always compare well with GASFLOW for local effects and flame acceleration is not solely a product of the total hydrogen mass present. As such I do not accept these arguments as completely relevant or reasonable and did not consider that the response was adequate in this regard.

233 However, I also recognise that information to resolve this query is not available to EDF and AREVA from their COCOSYS calculations as part of the sensitivity study and that the fast combustion risks have been shown to be more penalising in the "*representative*" pressuriser break SBLOCA not considered as part of the response to **GI-UKEPR-RC-01.A1**. On balance, in the context of the present GDA Issue Action I consider that the analysis of flame acceleration for the pressuriser break with reduced steam content (in Ref. 25) should bound any effects caused by the increased hydrogen content due to the reduced recombiner performance. However, I believe that a more detailed justification for

this aspect should form part of any future site specific analysis and hence I have raised this as an Assessment Finding, **AF-UKEPR-RC-67**.

> ***AF-UKEPR-RC-67:*** *The licensee shall provide a justification for the effects of reduced PAR performance on combustion risks at the local scale as part of the site specific analysis.*
>
> ***Required timescale:*** *Fuel Load.*

4.2.1.3.6 Results – Thermal Loads from PARs

234 As described earlier, Para. 223, the remaining PARs in the sensitivity cases have a higher depletion rate as a result of compensating for the reduced overall system performance. While unlikely, if such an effect did occur then the hydrogen removal rate would be higher, leading to higher thermal loads near these PARs. Based on the results presented in the sensitivity study and the response to TQ-EPR-1542 (Ref. 11) I do not believe that this extra heat would be significant.

4.2.1.3.7 Summary

235 The sensitivity analysis provided by EDF and AREVA in response to **GI-UKEPR-RC-01.A1** demonstrate the effects of a reduced recombiner performance. Importantly this analysis shows that a reduction in performance, either uniformly applied to all recombiners or more locally confined to individual units, is partially compensated by the system such that the net effect is more benign than might be initially expected. This is an important and valuable attribute of the use of a combustible gas mitigation system based on PARs. While the response is less explicit in considering the impact of this reduced performance on the local scale, I am content that suitable arguments have been made to justify that the responses made under **GI-UKEPR-RC-01.A2** remain bounding, although I do believe that these arguments need to be formalised as part of the safety case and have raised this as an Assessment Finding for a future licensee to resolve as part of their site specific analysis.

4.2.2 PCSR Update

236 EDF and AREVA updated the consolidated Step 4 PCSR (Ref. 16) to account for the deliverables produced and assessment conducted for **GI-UKEPR-RC-01.A1**. This was sent to ONR as a draft version in letter EPR01043 (Ref. 58), which also included a roadmap for the changes. The relevant changes made can be summarised as:

- Addition of general information regarding detailed performance of recombiners.
- Addition of a reference to the recombiner sensitivity study report (Ref. 21) and summary of analysis.
- Moving of one paragraph on recombiner qualification tests to a different position in the text to ensure consistency.

237 I am content that these changes adequately reflect the responses provided to **GI-UKEPR-RC-01.A1** and the final version of the PCSR is appropriate (Ref. 59). The overall conclusion drawn by EDF and AREVA on the relevance and impact of the sensitivity study with reduced recombiner performance is consistent with my assessment as described above and my conclusions given below.

4.2.3 Summary of the Assessment of the Action 1 Responses

238 In response to this GDA Issue Action, EDF and AREVA provided a sensitivity study for the UK EPR™ CGCS with a postulated reduction in PAR performance (Ref. 21). I have assessed this report and in conclusion I note that:

- The overall structure and approach in this report is appropriate to the GDA Issue Action and the safety case gap it seeks to address.
- A suitable level of detail has been provided to provide background information, with additional details in terms of the results of the study. I found the presentation of the results of the study lacking in terms of information on the overall safety concerns (such as temperature or pressure loads) and as such I found it necessary to ask further queries on the results. EDF and AREVA responded adequately to these queries in the context of **GI-UKEPR-RC-01.A1**, except for a single point which I have raised as part of an Assessment Finding.
- Similarly, I noted some constraints in the modelling conducted and the justification for these. Particularly, EDF and AREVA did not appear to consider the impact of the limitations in applying their current COCOSYS model to this particular problem before undertaking the analysis. If the intention of EDF and AREVA was to perform analyses with a single reduction factor of 0.25, then a single GASFLOW run would have been preferable to multiple COCOSYS runs that are essentially variations on a theme. This would have provided significant useful detail in terms of the local effects of reduced performance, with the potential for repeating the supporting analyses of temperature loads, pressure loads and fast combustion, should these be deemed necessary. Despite these limitations I do not judge these to be sufficient to undermine the overall conclusions of the report.
- The most significant conclusions from the analysis are that, despite the increased hydrogen concentrations:

    1. Predicted global concentrations are well below 4% at the time of RPV failure and maintained below 10% at all times. In this respect, the design intentions of the CGCS are maintained.
    2. Regardless of the strengths and weaknesses of the sensitivity study, the overall results do indicate that the PARs are able to undergo a significant reduction in their effectiveness and still maintain the design intentions of the system. This situation does not lead to conditions which should threaten the containment integrity.
    3. Whilst the applied reduction in PAR performance incorporated in the model is relatively simple in nature, and therefore complexities relating to local effects are not well captured, the results show that the system as a whole provides significant margin in operational capability with respect to the most demanding accident scenarios.
    4. The analyses carried out have provided highly useful additional understanding of the behaviour of the CGCS and the way in which a postulated reduction in performance can be partially compensated by the remaining capacity of the system, provided the PARs are not operating in a saturated regime. The results indicate that a reduction in performance in the order of 25% does not result in such an effect, even under the most penalising "*bounding*" scenario.

- The update of the PCSR to account for this GDA Issue Action is appropriate.

239 On the basis of the evidence supplied by EDF and AREVA in response to **GI-UKEPR-RC-01.A1**, I am content that an adequate safety case has been made and, in conjunction with the updated PCSR, I am content that this GDA Issue Action can be closed.

4.2.4 Assessment Finding

240 Based upon the assessment of the **GI-UKEPR-RC-01.A1** responses described in Section 4.2 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, by the licensee, during the design, procurement, construction or commissioning phase of the new build project;

> ***AF-UKEPR-RC-67:*** *The licensee shall provide a justification for the effects of reduced PAR performance on combustion risks at the local scale as part of the site specific analysis. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load.*

4.3 Action 3 – Demonstration of the Impact of PARs on Iodine Volatility

4.3.1 Assessment

241 The release of radioactivity to the environment following a severe accident depends on the magnitude and the chemical and physical form of the radioactivity that is airborne in the containment as a function of time. Thus, once the amounts released into the containment is established, it is the subsequent behaviour of the released material within the containment that determines the source term to the environment; see SAP FA.18 and associated paragraphs (Ref. 5). For example, the type and quantity of aerosols can affect the performance of engineered safety systems (e.g. air cleaning systems) as well as the magnitude, dispersion and effects of any radioactive source term leaked to the environment.

242 Most of the radioactive material that is released into the containment atmosphere of a PWR during a severe reactor accident will be in the form of aerosols. It has been recognised for quite some time that the operation of PARs may induce changes in aerosols suspended in the containment during an accident (for example, Ref. 60).

243 Of this radioactive material, iodine can be of particular importance due to its radiological consequences. Subsequent phenomenological experiments have demonstrated that there is potential for PARs to generate volatile forms of iodine, namely molecular iodine, by thermal decomposition of metal-iodide species that would be present in such containment aerosols (Refs 61 and 62). It is likely that such chemical conversions will be reproduced in accident-representative conditions to some degree and initial (albeit limited) results from relevant experiments indicate high mitigation of this molecular-iodine production. Despite these apparent limitations such a conversion process, even when very limited, might make a noticeable contribution to the gas-phase iodine in the containment atmosphere.

244 During Step 4, I queried the potential for the PARs in UK EPR™ to affect fission product distribution in containment in a similar detrimental manner. EDF and AREVA responded by stating that while this potential effect is not included in the current UK EPR™ analysis, it can be considered "*negligible*" due to the bounding source term used for UK EPR™. EDF and AREVA indicated that a study of this effect was scheduled for 2011, but provided no further details. **GI-UKEPR-RC-01.A3** was raised to request EDF and AREVA to provide evidence to support this argument.

4.3.1.1 EDF and AREVA's Safety Case for the Radiological Consequences of Core-Melt Scenarios

245 EDF and AREVA describe how the objective of their radiological consequence calculations for core melt accidents is to show that, taking account of the specific UK EPR™ design provisions, the release of radioactive materials outside the plant remains within the radiological objectives for the plant. The safety case for UK EPR™ (Ref. 16) in this regard is based on two main claims:

- Only "*limited counter measures*" will be needed for UK EPR™ in case of a severe accident involving core melt. This means that there should be:
  - i) limited public sheltering duration,
  - ii) no emergency evacuation beyond the immediate plant vicinity,
  - iii) no permanent relocation, and;
  - iv) no long term food restrictions.

- The source term used for the assessment of the consequences of core melts is bounding and includes some "*margin*" to accommodate any increases in iodine caused by recombiner interactions.

246 The focus of **GI-UKEPR-RC-01.A3**, and hence the assessment that follows, is therefore to examine the evidence which shows that these claims are indeed met for UK EPR™, including consideration of the impact of the recombiners.

4.3.1.2 UK EPR™ Iodine Source Term for Core Melt Scenarios

247 Before describing the responses to this GDA Issue Action it is prudent to consider the EDF and AREVA approach to determining the radiological consequences of such severe accidents which involve core melting. This is detailed in Section 16.2.3 of the PCSR (Ref. 16) and was assessed briefly in the Step 4 Reactor Chemistry report (Ref. 2).

248 As for many of the accident analyses presented in the GDA PCSR, EDF and AREVA present two calculation methods and their corresponding results based on the German and French approaches respectively. EDF and AREVA state that the approach will be reviewed to address UK specific requirements later in the site specific phase.

249 For both methods EDF and AREVA base their calculation on a 4900 MW_{th} core, around 10% higher power than UK EPR™. During such an accident EDF and AREVA assume that the entire core inventory of iodine is released to the containment, mainly as aerosols but with small, but important fractions as elemental and organic iodine. It is these later species that are the main sources of iodine that are released to the environment during such an accident and the assumed quantities and treatment of these species is one of the main differences between the two methods. Both methods use the same assumptions regarding containment leak rates and similar assumptions for filtration efficiencies.

250 In the German method, EDF and AREVA assume instantaneous releases to the containment atmosphere at the start of the accident of elemental and organic iodine fractions of [redacted] and [redacted]% respectively (of the total core iodine inventory), with the remaining iodine released as aerosol. Once airborne inside the containment, the evolution of the source-term is calculated using a method recommended by IRSN based on the results of international experimental programmes such as VERCORS and PHEBUS. This method calculates the fraction of nuclear material remaining airborne in the containment by a summation of exponential decay terms which model agglomeration, sedimentation and deposition of the aerosol (by thermophoresis and Brownian diffusion). It assumes the sprays in UK EPR™ are not used and ignores deposition by diffusiophoresis. The parameters used for this calculation were derived from calculations using the AEROSOLS-B2 code. These calculations considered a number of pessimisms including the volume to surface ratio and the physical properties of the aerosols. A consequence of this approach is to predict airborne concentrations decreasing to infinitesimal levels at long times, so EDF and AREVA apply a minimum cut-off level for the long term (of [redacted]%).

251 Using these relationships it is calculated that the concentration of elemental (volatile) iodine in containment decreases rapidly from the initial [redacted]% to [redacted]% in around 3 hours. The concentration stays at this lower level for the remainder of the accident considered. EDF and AREVA also assume a similar concentration of organic iodine which is neither removed nor converted to other forms during the remainder of the accident. Thus the long-term airborne iodine concentration in containment is made up from [redacted]% volatile forms (elemental and organic) plus any unsettled aerosol. The concentration of aerosols also decrease exponentially but over a much longer timescale,

with around 30% of that originally released still in the atmosphere after 3 hours and over 5% still present after 2 days. The consequences for a given accident can thus be determined by integrating the airborne activity in containment multiplied by the assumed leak rate to the annulus (0.3% volume per day) over time, minus any mitigation provided by the annulus ventilation systems before discharge.

252 The French method, which is currently used by EDF for their French PWR fleet, is similar to that described above but the release assumptions are based on the US NRC NUREG-1465 (Ref. 63). This assumes 95% of the core iodine inventory is initially released as aerosol, with the remaining 5% assumed to be in elemental form. 3% of the elemental release (i.e. 0.15% of the core inventory) is assumed to convert to organic iodine very shortly after release. Similarly to the German method, the organic fraction is assumed as a steady state concentration which does not change while the elemental iodine fraction decreases due to deposition in the containment.

253 A comparison of the differing release fractions assumption between these two methods is shown below:

Iodine Form	Release Fraction (of Core Inventory)	
	UK EPR™ PCSR (Ref. 16)	NUREG-1465 (Ref. 63)
Aerosol	[redacted]	0.95
Elemental	[redacted]	0.05
Organic	[redacted]	0.0015 (from elemental fraction)

Table 5: Comparison between the UK EPR™ PCSR (Ref. 16) and NUREG-1465 (Ref. 63) release fractions for iodine for an accident involving core melt

254 Both of these approaches therefore do not rely on any detailed modelling of iodine chemical behaviour in the containment, instead relying on simple empirical relationships.

255 Due to differences in the calculations it is not possible to compare the results directly, however using these methods EDF and AREVA calculate that the releases of iodine (^{131}I) to the environment are:

- [redacted] TBq after 30 days for the German approach (which is made up of around 40% aerosol and 30% each of elemental and organic iodine).
- [redacted] % of the core inventory (by mass) of iodine using the French approach after 70 days

256 The overriding argument in both of these methods is that all iodine removed from the atmosphere is ultimately transferred to the IRWST, due to effects of condensation or sprays should they be activated, where it remains. Operation of the sprays may also have an effect on the combustion risks in the containment. Iodine is retained by the IRWST water due to the pH increase caused by the injection of sodium hydroxide. This is related to Assessment Finding **AF-UKEPR-RC-50** from the Step 4 Reactor Chemistry report (Ref. 2), which requests an analysis of the IRWST pH during such an accident.

257 Ultimately this means that the IRWST water will therefore contain the vast majority of the iodine released during such an accident. In UK EPR™ this water is used to quench the corium in the ex-vessel phase of the accident so a significant fraction of this is evaporated, with further potential evaporation possible dependant upon how the Containment Heat Removal System (CHRS) is operated. As part of the response to TQ-EPR-1188 (Ref. 11), EDF and AREVA argue that such effects (which leads to evaporation of around 7% by volume of the IRWST) are also bounded by the conservative source term used for the UK EPR™ calculations presented in the PCSR. They do not however, consider any impact of the PARs, which will be operating throughout this phase, on the re-suspended iodine contained in the evaporated IRWST water.

258 Overall, EDF and AREVA claim that this conservative approach to the in-containment source term bounds any potential influence of PARs on the production of volatile forms of iodine.

4.3.1.3 EDF and AREVA Responses

259 EDF and AREVA provided two main responses to address **GI-UKEPR-RC-01.A3**. Their initial resolution plan included for the production of only a single response, however my assessment of that report indicated that further work was necessary in order to resolve the intent of the GDA Issue Action, as described more fully below. The following brief section describes the chronology and relationships between the various responses to aid clarity; technical assessment follows in subsequent sections.

260 The first main response provided by EDF and AREVA was an IRSN report which provided an analysis of the additional production of volatile iodine due to the recombiners in a French 1300 MW_e PWR for a typical severe accident scenario (Ref. 26). The main shortfalls in this response are that it is not specific to EPR™, which would behave differently, and it does not provide evidence to support (or otherwise) the UK EPR™ safety case claims as described in Section 4.3.1.1. In response I sent EDF and AREVA letter EPR70416R (Ref. 64), which outlined these deficits and asked a number of more detailed queries. EDF and AREVA then responded with (Ref. 27), which attempted to link the original IRSN report (Ref. 26) to the UK EPR™ safety case. However, this response did not completely address my concerns, nor the more detailed queries identified in letter EPR70416R (Ref. 64). Following discussion with EDF and AREVA it was agreed that they would provide more detailed calculations, explicit to UK EPR™, specifically to address the intent of **GI-UKEPR-RC-01.A3**. This resulted in the second main deliverable, Ref. 28.

261 These two main deliverables (Refs 26 and 28) form the basis for the assessment that follows, as they contain the evidence to support the UK EPR™ PCSR claims, although reference to the other deliverables provided by EDF and AREVA is made as necessary.

4.3.1.4 Effects of PARs on Iodine Behaviour

262 The first main response to **GI-UKEPR-RC-01.A3** received from EDF and AREVA (Ref. 26) considers the effects of operating PARs on the behaviour of iodine, particularly any enhanced conversion to more volatile forms. This considers both experimental and modelling results, applying THAI test data to a standard French 1300 MW_e PWR to determine the effects of PAR production of volatile iodine during a single “representative” accident scenario. The THAI tests included several large scale experiments to determine the effects of recombiners on iodine, including several tests with AREVA PARs.

4.3.1.4.1 Conversion Rates

263 The first part of the EDF and AREVA response (Ref. 26) gives details of the relevant THAI experiments. The results of the latest THAI tests are described, particularly in relation to the conversion rate for CsI aerosols into gaseous iodine. This conversion rate is clearly an important input to any subsequent calculation of potential effects.

264 The relevant THAI experiments are described in the EDF and AREVA response (Ref. 26) and the corresponding OECD report (Ref. 65), so are not repeated in detail here. The original THAI data is presented in Ref. 66. It is sufficient to say that these tests are much closer to the environmental conditions expected in UK EPR™ following a typical severe accident and were conducted at large scale (60 m^3 test vessel). Conversion rates of between 1 and 3% were measured during the experiment. These values compare favourably with those predicted when the much simpler bench-scale RECI experimental predictions are extrapolated to the same conditions (i.e. 5%). Based on these results IRSN subsequently chose to use a conversion rate of [redacted]% for their calculations that follow.

265 It is notable however that the THAI tests showed other rates were possible, despite nominally identical conditions. For example a repeat of this test gave an average conversion rate of [redacted]%, with a maximum of [redacted]%.

266 While I am content that the use of THAI experimental data represents a reasonable approach to determine an appropriate conversion rate the use of a single value, measured under one set of conditions, for use in the sensitivity study does put limitations on the usefulness of the response. In addition, while undue pessimism is undesirable, the use of a conversion rate of [redacted]% would appear to be optimistic. The response (Ref. 26) notes that "*… during previous calculations … using a dissociation* [conversion] *rate of* [redacted]*% ... the iodine source term increased by* [redacted]". As described more fully below the calculations presented in the report assume a conversion rate of [redacted]% increasing the release at 24 hours by [redacted]%. This suggests that the increase in effects may be non linear and hence calculations with other conversion rates would be beneficial in understanding the impact and particularly the avoidance of any substantial increase in consequences.

4.3.1.4.2 Impact of Recombiners

267 The second part of the IRSN report (Ref. 26) describes the sensitivity study, based on calculations using the ASTEC code, to estimate the impact of the volatile iodine generated by the dissociation of iodide aerosols on the iodine source term 24h after the start of an accident sequence which releases hydrogen in a French 1300 MW_e PWR equipped with PARs.

268 There are several important assumptions in this study that limit its applicability to UK EPR™ and **GI-UKEPR-RC-01.A3**, specifically:

- The sensitivity analysis uses the ASTEC code, which has not been used previously as part of the EDF and AREVA safety case for UK EPR™. While this may be a well validated and proven code the impact on the results are unclear, for example it is not apparent what iodine chemistry was considered as part of the calculations.
- There is no attempt to rationalise the THAI test conditions with those likely to be experienced in UK EPR™.

- The analysis is based on a French 1300 MW_e PWR. As well as the lower power, there are many important engineering differences in the design compared to UK EPR™, particularly the higher number of PARs, smaller containment volume and lack of CMSS (hence no MCCI) while UK EPR™ has a double containment with a filtered annulus.
- The analysis considers only a single accident sequence which is not detailed in the report. This means that:
    1. The sequence is limited to 24 hours duration to avoid any releases to the environment caused by filtered venting of the containment or MCCI of the basemat, effects which would not occur in UK EPR™.
    2. As described previously for Actions 1 and 2 of this GDA Issue the selection of an appropriate accident scenario is an important pre-requisite. The rates at which the PARs operate in UK EPR™ would be very much dependant upon this, as described for Actions 1 and 2, and hence the masses of iodine converted and available for release. It is not clear if the ASTEC analysis presented in the response is representative for UK EPR™.
    3. There are a number of important phenomenological differences between a severe accident in a French 1300 MW_e PWR and UK EPR™, particularly the lack of MCCI and corium quenching using the iodine laden IRWST water.

269 Notwithstanding the above, the results from the analysis do show that:

- The concentration of elemental iodine produced in the PARs is a function of the concentration of iodine aerosols in the containment over time, the recombiner usage and the rate of conversion in the recombiner. With these factors it should be possible to undertake an analysis of the likely effects in UK EPR™.
- Using a conversion rate of [redacted]% increases the quantity of gaseous iodine released into the containment atmosphere by approximately [redacted]% over the course of the 24 hours considered. This relates to a [redacted]% increase in the quantity of gaseous iodine released to the environment during that period.
- There are some differences in the deposition rates between the sensitivity study and the PCSR calculations. Deposition rates for aerosols are approximately twice as quick in the sensitivity study, but the rates for gaseous species are slower by around 35%. The reasons for these differences are not clear.

4.3.1.4.3 Summary

270 Overall, while the results of the IRSN study are useful in providing an increased level of understanding regarding the potential scale of effects the recombiners could have in UK EPR™, no attempt is made to relate the insights or results of this study to the UK EPR™ safety case. Unfortunately, I do not consider it possible to translate the results presented directly to UK EPR™ a priori, due to the differences highlighted above which means comparisons are not possible with the information as presented. In response to my assessment EDF and AREVA provided a specific UK EPR™ analysis, which I assess below.

4.3.1.5 UK EPR™ Sensitivity Study

4.3.1.5.1 Overview

271 The sensitivity study provided by EDF and AREVA in (Ref. 28) contains analysis of the impact of recombiners on the iodine behaviour in the UK EPR™ containment under a bounding severe accident. This analysis is performed using the latest version of the IODE code, which is a module of the ASTEC code. This particular code is specifically aimed at determining the behaviour of iodine in reactor containments under accident conditions.

272 EDF and AREVA performed this analysis in two stages. The first involved recalculation of the "reference" case presented in the PCSR. This first step was necessary because the detailed iodine chemistry in the IODE code is significantly different to the assumptions used in the PCSR analysis and hence would result in a different baseline to which the effects of PAR operation could be compared. The second stage involves recalculating the "reference" case including the effects of recombiner operation on the iodine behaviour. EDF and AREVA consider conversion rates of [redacted]%. These values encompass the values derived from the THAI tests and have been included to both bound any potential uncertainties derived from experimental factors or phenomenological effects (for example, the potential higher rates of decomposition seen for CdI as opposed to CsI) and to gain further insights into the relationship between the conversion rate and environmental release.

273 EDF and AREVA consider the various physical parameters from EPR™ in their calculations, for example the various volumes, masses and surface areas within the containment. For all the cases considered the main assumptions used are consistent with those from the French method presented in the PCSR, namely;

- 100% core melt.
- 100% release of core iodine inventory to the containment with 95% of the iodine released in aerosol form and 5% in elemental form.
- Aerosol removal from the atmosphere is via natural deposition only (no spray activation), using the same regression function described in the PCSR.

274 EDF and AREVA assume a Mixed-Oxide (MOX) fuel load. MOX is used in France but is outside the scope of GDA although it is nevertheless suitably pessimistic for calculations of this type, in terms of the quantity of iodine available for release to the containment.

275 There are however some important differences, which should be borne in mind when considering the overall results of the study. I consider these more fully below, but these mainly relate to the iodine chemistry considered in the analysis. The overall iodine chemistry considered in the sensitivity study is much more comprehensive, unlike the simple empirical relationships used for the PCSR. For example, unlike the PCSR analysis, the production of organic iodine is calculated in the IODE code on the basis of the various production and removal mechanisms considered. The impact of the silver in the control rods on the liquid phase iodine chemistry is also included.

4.3.1.5.2 Representation of the Recombiner Source Term

276 To calculate the additional source of iodine generated in the recombiners EDF and AREVA apply the assumed conversion rate to the CsI aerosol flow through the recombiners. As described previously, the concentration of CsI is calculated over time, according to the deposition function for aerosols. The amount that flows through the PARs is calculated based on the total gas flow through the PARs. An important assumption is that the outlet gas temperature of the PARs is taken as 300 °C. As

described is Section 4.1.1.5, outlet loads are potentially much higher when the PARs are operating with high throughputs. This low assumed outlet temperature increases the outlet gas density, maximising the CsI throughput of the PARs and hence the amount of iodine produced.

277 The gas flow through the PARs are taken from a previous simulation for both the in and ex-vessel phases. EDF and AREVA select the scenario that maximizes the hydrogen production and hence has a high recombination throughput. The calculations therefore use the "*representative*" SBLOCA scenario as presented in both the PCSR (Ref.16, section 16.2.2.3) and the ex-vessel analysis report from Action 2 (Ref. 25). This is shown in Figure 16 below (from COCOSYS):

[redacted]

Figure 16: Mass release of combustible gases for the SBLOCA scenario from Ref. 28

278 While it may have been possible to select a different accident scenario, which would have resulted in a different recombiner throughput, I am content that this is a reasonable assumption for the present sensitivity calculations. The effects of scenario to scenario variation should be bounded by the results for changing the conversion rate.

279 Importantly, EDF and AREVA recognise that the flow through the PARs calculated using the hydrogen mass flow is not the total gas flow, as described in Para. 106, and assume an "efficiency" of 60% for the PARs (i.e. 60% of the hydrogen that enters the PAR is recombined which means that the total flow is 167% of the flow deduced from the calculated hydrogen flow). This value is consistent with recent experimental data on this effect.

280 As described in Section 4.1.1.7, during the ex-vessel phases some of this hydrogen is actually "hydrogen equivalents" which are a result of EDF and AREVA converting carbon monoxide to hydrogen to simplify their gas distribution and combustion calculations. Data in Ref. 25 suggests that at the end of the period considered (200,000 seconds) [redacted] kg is "hydrogen equivalents", which equates to [redacted] kg of carbon monoxide. As can be seen from Figure 16 above, following RPV failure most of the hydrogen is removed via combustion, with the recombiners operating at a relatively low rate. Additionally this is

around 20,000 seconds into the operation of the PARs (170,000 seconds), when the concentration of aerosols has decreased significantly. While EDF and AREVA have not considered this effect specifically, both of the factors described above would tend to limit the impact of this assumption on the overall results of the sensitivity studies. I am content with this argument for the current GDA Issue Action but would expect a future licensee to confirm this as part of any site specific analysis; hence I consider this to be part of Assessment Finding **AF-UKEPR-RC-68**, detailed later in this section of my report.

281 In addition to the effects of the recombiners, EDF and AREVA also consider a further case which includes combustion. Combustion is predicted to be the dominant combustible gas removal mechanism following RPV failure. For this additional calculation, the hydrogen mass removed by combustion is assumed to instead be removed by recombination resulting in increased recombiner conversion (i.e. the non-combustion case follows the solid blue line in Figure 16 above, while the combustion case uses the dashed blue line). Both mechanisms fundamentally rely on thermal decomposition of the aerosols so by doing this additional calculation EDF and AREVA attempt to demonstrate the potential effects of combustion, despite any differences or uncertainties between the two processes. While this is not strictly part of the GDA Issue Action I am content that EDF and AREVA have considered this and, in the absence of a better understanding, considering conversion in this manner does provide useful information on an effect which would not have been considered otherwise.

282 This approach results in volatile iodine production rates from the recombiners for use in subsequent calculations as illustrated in Figure 17 below, which is for the [redacted]% conversion rate case both with and without combustion. As the conversion rate is simply a multiplier, the results for the other assumed conversion rates show the same release profile but with proportionally higher or lower release rates. Note the different time scale between Figure 17 and 16; zero is taken as the time of first hydrogen release, approximately 148000 seconds on Figure 16.

[redacted]

Figure 17: Iodine production in the recombiners assuming 3% conversion rate, without and with consideration of combustion, from Ref. 28

283 Overall, I am content that this approach is a reasonable basis on which to undertake analysis for the effects of recombiners on iodine in UK EPR™.

4.3.1.5.3 Impact of Recombiners on Containment Iodine Distribution

284 Ultimately it is the effect of the recombiners on the iodine behaviour in containment that will determine the consequences of this interaction. For each calculation EDF and AREVA determine the evolution of the total amounts of iodine in the liquid and gaseous phases as well as that absorbed onto painted surfaces. The analysis also provides information on which particular species are present in each phase over time. These are compared to the results obtained for the "reference" case. A summary of the results from these calculations is shown in Table 6 below, which shows the percentages of the total core iodine inventory which is present in each phase, for both shortly after the initial release and following 24 hours.

	Total Mass of Iodine / % of Core Inventory					
	Liquid Phase		Gaseous Phase		Painted Surfaces	
Case	Shortly after original release	24 hours after the accident	Shortly after original release [from PARs]	24 hours after the accident	Shortly after original release	24 hours after the accident
"Reference" - no recombiner conversion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1.4% recombiner conversion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3% recombiner conversion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3% recombiner conversion with combustion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
6% recombiner conversion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10% recombiner conversion	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 6: Comparison of the partition of iodine between the various phases for the "reference" case and recombiner sensitivity studies in Ref. 28

285 As part of their IODE calculations EDF and AREVA consider detailed iodine chemistry, unlike the analysis presented in the PCSR. These reactions are shown schematically in Figure 18 below. These include various formation and destruction reactions in the gas

and liquid phases (red lines), including radiation and thermal effects, as well as mass transfer between phases (green lines). As described more fully below there are several important reactions that are dominating the subsequent behaviour in this model;

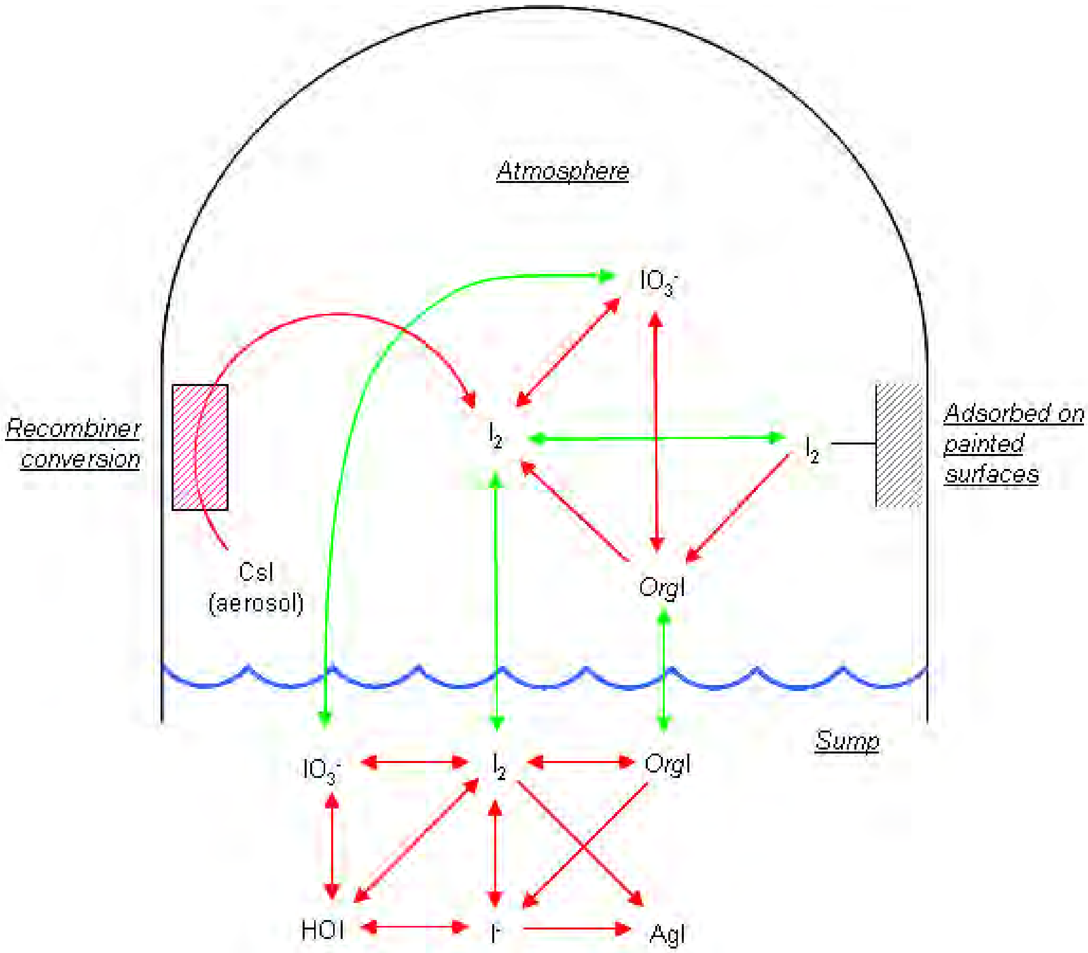

Figure 18: Iodine chemistry considered in the UK EPR™ calculations presented in Ref. 28

286 It is clear that the consideration of detailed iodine chemistry does have a pronounced effect on the results of the simulations, which show that, for all the cases considered:

- The additional source of gaseous iodine is proportional to the conversion rate assumed.
- In the early phases of the accident IO_3^- is the dominant form of iodine in both the liquid and gaseous phases. It is mainly formed from I_2 in the gas phase which absorbs onto painted surfaces and is released as organic iodine before being subsequently destroyed under irradiation producing IO_3^-. This IO_3^- is then transferred into the liquid phase. I_2 produced from the recombiners will directly interact with this process being an additional source for gaseous I_2. This can be seen in Table 6 above, where the percentage of iodine present in both the gaseous phase and on painted surfaces increases with the recombiner conversion rate.
- The other significant reaction is that of silver with iodine producing AgI. This is an efficient sink for iodine, trapping it in a stable involatile form. This reaction becomes

progressively more important as the accident progresses. In the early stages, when the dose rates are high, the equilibrium between the various liquid phase reactions means that IO_3^- formation is favoured but as the dose rate drops more I^- is produced. Provided there is sufficient oxidised silver in the water, which is itself a slow reaction, the I^- produced is trapped. The amount of iodine present as AgI increases from around 12 to 50% of that present within the liquid phase over the course of the two weeks considered in the analysis, with a corresponding drop in IO_3^-. Despite the large amount of iodine trapped, this still consumes only around 5% of the available silver.

- As the water pH is assumed to be 7 throughout the accident (i.e. the NaOH injection has occurred) the conversion of I^- to I_2 in the liquid phase is low. This means that the corresponding mass transfer of I_2 to the gas phase from the liquid is also low, further improving the retention of iodine in the liquid phase and minimising potential environmental releases.
- There is a gradual transfer of activity from the gaseous phase and painted surfaces to the liquid. The simulations show that for all the cases after two weeks more than 99% of the iodine is present in the liquid phase, where it remains due to the combined effects of silver and pH.
- It is also interesting to note that there are significant differences between the results quoted in the IRSN report for a French 1300 MW_e PWR (Ref. 26) and the UK EPR™ analysis. For the French plant assuming a [redacted]% conversion rate increased the gaseous containment iodine by around [redacted]%. The same assumption for UK EPR™ increases the gaseous containment iodine by around [redacted] %. This would suggest that EPR™ is more sensitive to the effect of recombiners, likely due to the increased number of recombiners and other differences in the modelling and supports the need for reactor specific analysis, as has been provided.

287 In general, the basic chemistry included in IODE is consistent with the latest understanding of iodine chemistry in such situations. The main conclusion, that iodine is rapidly transferred and retained in the liquid phase, is reasonable. I was surprised however, by the speed of this process in UK EPR™ and the very small proportions of iodine that were retained in volatile forms in the medium to long term. There are some assumptions used in the analysis which would tend to exacerbate this rapid removal and high retention in the sumps:

- The initial high dose rate assumption would increase the rate of radiolytic oxidation of I_2, producing more IO_3^-. This would lead to less I_2 deposition of surfaces and more rapid transfer of iodine to the sumps.
- The calculations do not appear to consider the deposition onto surfaces of iodine aerosols or iodine species other than I_2. The inclusion of these processes would tend to slow the transfer of iodine to the sump.
- The analysis presented in the PCSR uses a rate of [redacted] hr^{-1} for the absorption of I_2 onto surfaces. The value used for the sensitivity calculation is around 5 times faster. This potentially increases the rate of transfer of iodine to the sump.
- The behaviour is dominated by the gas phase reactions, but these are the least understood and characterised reactions for iodine.

288 I discussed these aspects with EDF and AREVA (Ref. 67), who confirm that they consider the sensitivity calculations to be a “best estimate” of the current understanding in iodine chemistry, as per the SAPs (Ref. 5, especially FA.16 and para. 550). Input

parameters are based upon the latest experimental results, for example the EPICUR experiments, although EDF and AREVA do not consider the sensitivity of their results to these parameters. It would be difficult to try and determine the effect of a single factor in such a complex chemical system. This indicates that there are some uncertainties in the results provided, which are important to consider when comparing the overall results of the sensitivity studies to the PCSR. These relate to iodine chemistry, rather than anything specific to the impact of the recombiners, and are a consequence of using such a complex analysis code. In the context of this GDA Issue action I believe that this position is reasonable at the present stage in the development of the safety case. However, I would expect a fuller consideration of the impact of such uncertainties as part of developing the safety case during the site specific phase, should such an approach be retained. I consider this to be part of Assessment Finding **AF-UKEPR-RC-68**, detailed in the following section of my report.

289 As described previously the amount of iodine produced by the recombiners considers the thermal destruction of CsI. It is evident from the description above that as well as CsI aerosols the majority of gaseous iodine exists as IO_3^-, which would also pass through the recombiners and potentially be converted. There are no reactions in the IODE code to consider this pathway. However, the deposition function for the aerosols means that they remain an order of magnitude higher concentration than IO_3^- making any impact of IO_3^- conversion small.

290 As described in Para. 256, the IRWST water in UK EPR™ will be used to cool the corium transferred to the spreading area, evaporating around 7% by volume of the water. These calculations show that the liquid phase contains around 80-90% of the core iodine inventory during this period. Assuming that the evaporated water contains an equal proportion of iodine means around 6% of the core iodine inventory will be transferred to the containment atmosphere and be available to pass through the recombiners. This is obviously a simplification as there will be partitioning of the iodine dependant upon the precise conditions at the time and the iodine will not be in the CsI form. EDF and AREVA exclude this process from their calculations, which would change the containment iodine distribution and the environmental releases. However, the 6% value described above is much less than the 95% assumed to be in the CsI aerosol form upon initial release, hence I do not expect this phenomenon to make a major contribution to the releases. I would expect a future licensee to confirm this as part of any site specific analysis; hence I consider this to be part of Assessment Finding **AF-UKEPR-RC-68**, detailed in the following section of my report.

4.3.1.5.4 Impact on Environmental Releases

291 In Table 7 below the preliminary source term used in the PCSR is compared to those calculated in the UK EPR™ recombiner sensitivity study detailed in Ref. 28. It is based on the percentage of the core inventory released to the environment for ^{131}I at 70 days compared to either the PCSR (Ref. 16) or the “reference” case from Ref. 28. EDF and AREVA assume that the calculated concentrations for elemental and organic iodine remain constant from 15 to 70 days.

Case	^{131}I Release to the Environment	
	Compared to PCSR	Compared to "Reference" case
"Reference" - no recombiner conversion	[redacted]%	[redacted]%
1.4% recombiner conversion	[redacted]%	[redacted]%
3% recombiner conversion	[redacted]%	[redacted]%
3% recombiner conversion with combustion	[redacted]%	[redacted]%
6% recombiner conversion	[redacted]%	[redacted]%
10% recombiner conversion	[redacted]%	[redacted]%

Table 7: Comparison of ^{131}I releases to the environment based upon the recombiner sensitivity studies in Ref. 28

292 These results shows that:

- Irrespective of the recombiner conversion rate assumed the percentage of core iodine inventory released to the environment is less than the bounding assumptions used in the PCSR.
- The effects of considering a more detailed chemistry are pronounced:
    1. The "reference" case predicts more than two orders of magnitude less environmental release than the PCSR.
    2. Even the highest recombiner conversion rate considered produces an environmental release of less than 10% that considered by the PCSR.
    3. The results above suggest that even a recombiner conversion rate of 100% applied to the "reference" case would not exceed the PCSR source term.
- The scale of impact of the recombiner conversion rate has been demonstrated. This shows that even a modest increase in the amount of volatile iodine generated in recombiners can have a significant effect on the environmental releases, with the lowest conversion rate increasing the environmental releases by nearly a factor of 4 (but still well below the PCSR claims).
- The effect of combustion is rather modest, increasing the environmental releases by 30% compared to the same case without combustion (increasing the in-containment gaseous I_2 by 45%). This is despite a similar mass of hydrogen being removed during the in-vessel and ex-vessel phases and demonstrates that the impact of recombiners is most pronounced very early in the accident, when the aerosol concentration is highest.

293 The reason for the large differences in environmental releases between the PCSR and sensitivity study cases is due to the change in iodine speciation. Table 8 below shows the "long-term" (i.e. after 15 day) containment atmosphere concentrations for elemental, IO_3^- and organic iodine assumed in the calculations of the environmental releases. As the sensitivity analysis uses the same method as the PCSR for determining the aerosol deposition behaviour this indicates that the differences between the sensitivity and PCSR results are due to differences in the other iodine species, particularly over the medium

and long term. It is in these areas where the PCSR makes its most significant assumptions, with long term steady state concentrations of these species (for example, 0.15% organic iodine in the PCSR compared to [redacted]% for the [redacted]% conversion rate sensitivity case).

Iodine Species	"Long-term" containment airborne concentrations / % of Core Inventory		
	PCSR ("French" method)	"Reference" case	10% recombiner conversion case
I_2	[redacted]	[redacted]	[redacted]
IO_3^-	[redacted]	[redacted]	[redacted]
Organic Iodine	[redacted]	[redacted]	[redacted]

Table 8: Comparison of the PCSR and sensitivity study long-term containment airborne concentrations

294 As described earlier, Para. 250, the environmental releases are determined by integrating the airborne activity in containment multiplied by the assumed leak rate to the annulus over time, minus any mitigation before discharge. In all of the calculations elemental iodine and IO_3^- are assumed to be 99.9% retained, while organic iodine is 99% retained (i.e. a factor of 10 lower). Thus, while the PCSR and 10% recombiner conversion case have similar total iodine airborne concentrations in the containment, 10 times more will escape in the PCSR case because it is in the less well retained organic iodine form. In this regard the PCSR assumptions are conservative.

4.3.1.5.5 Summary

295 EDF and AREVA presented a sensitivity study for the effect of recombiners on volatile iodine in UK EPR™. These calculations use the IODE code, which differs from the PCSR by incorporating a detailed treatment of the iodine chemistry. This detailed chemistry changes the form of the iodine in the containment, compared to the assumption in the PCSR, but also decreases the total amounts predicted to be released to the environment.

296 While this treatment of the iodine chemistry represents the current "state of the art", its application does come with the drawback that there is some uncertainty associated with the precise values predicted. However, I am content that the margins between the predicted values and PCSR are such that there is a reasonable basis on which to suggest that margin would still remain even including these uncertainties.

297 The results also show that the impact of recombiners is most pronounced at the early stages of the accident when the recombiners are most active and the aerosol concentrations in containment are highest. Conversely the release behaviour appears to be dominated by the medium to long term behaviour, and the production of persistent volatile forms of iodine. It is in these areas where the PCSR is most conservative.

298 On the basis of the results presented I am content that EDF and AREVA have demonstrated that their claims for the radiological consequence calculations for core melt accidents in UK EPR™ are met, namely only "*limited counter measures*" will be needed

for UK EPR™ in case of a severe accident involving core melt and the PCSR source term is bounding and includes adequate "*margin*" to accommodate any increases in iodine caused by recombiner interactions.

299 EDF and AREVA indicate that they expect the licensee to undertake site specific consequence calculations. I support this approach. I believe that it would be appropriate at this stage to also include consideration of those aspects described above which, while I do not expect to contribute significantly, will impact on the results, namely the treatment of IRWST evaporation and uncertainties in the reactions of iodine. I therefore consider this to be an Assessment Finding, **AF-UKEPR-RC-68**.

> ***AF-UKEPR-RC-68:*** *The licensee shall provide site specific analysis for the radiological consequence of accidents involving core melting, including IRWST evaporation and uncertainties in the reactions of iodine. This Assessment Finding should be completed before fuel is first loaded into the reactor.*
>
> ***Required timescale:*** *Fuel Load.*

4.3.2 PCSR Update

300 EDF and AREVA updated the consolidated Step 4 PCSR (Ref. 16) to account for the deliverables produced and assessment conducted for **GI-UKEPR-RC-01.A3**. This was sent to ONR as a draft version in letter EPR01402 (Ref. 68), which also included a roadmap for the changes. The relevant changes made can be summarised as:

- Inclusion of the results of the sensitivity study on the impact of PAR operation on iodine volatility in containment and addition of the reference in section 3.2.4 in response to GI-UKEPR-RC01.A3. The text has been updated to reflect the additional sensitivity studies and to include reference to Ref. 28.

301 I provided EDF and AREVA with comments on these updates, which they accepted and incorporated into the final version (Ref. 59). I am therefore content that these changes to the PCSR adequately reflect the responses provided to **GI-UKEPR-RC-01.A3**. The overall conclusion drawn by EDF and AREVA on the relevance and impact of the sensitivity study is consistent with my assessment as described above and my conclusions given below.

4.3.3 Summary of the Assessment of the Action 3 Responses

302 In response to this GDA Issue Action, EDF and AREVA provided a number of responses including a study of the impact of recombiners in a French PWR (Ref. 26) and a report providing a sensitivity study for the impact of recombiners in UK EPR™ (Ref. 28). I have assessed these reports and in conclusion I note that:

- The initial responses provided by EDF and AREVA to resolve this GDA Issue Action were lacking in several important areas and it was necessary for them to undertake further work to adequately resolve the intent of this Action. EDF and AREVA responded positively to my concerns and the final response provided contains a sufficient level of detail specific to UK EPR™ to allow my assessment to conclude.
- EDF and AREVA presented a sensitivity study for the effect of recombiners on volatile iodine in UK EPR™. These calculations use the IODE code, which differs from the PCSR by incorporating a detailed treatment of the iodine chemistry.

Despite some uncertainties inherent with the use of such codes, the results of this analysis show that:

1. This detailed chemistry changes the form of the iodine in the containment, compared to the assumptions in the PCSR, but also decreases the total amounts predicted to be released to the environment. Even assuming a pessimistic conversion of 10% of the iodine which passes through the recombiners results in predicted environmental releases less than claimed by the PCSR.
2. The results demonstrate the scale of impact the recombiner conversion rate has on the environmental releases. This shows that even a modest increase in the amount of volatile iodine generated by the recombiners can have a significant effect on the relative environmental releases, with the lowest conversion rate increasing the environmental releases by nearly a factor of 4, although this effect is exaggerated by the very low long term volatile forms of iodine predicted by the calculations.
3. The use of decoupling assumption in the PCSR has been demonstrated to be bounding for the effect of recombiners.

- The update of the PCSR to account for this GDA Issue Action is appropriate.

303 On the basis of the evidence supplied by EDF and AREVA in response to **GI-UKEPR-RC-01.A3**, I am content that an adequate safety case has been made and, in conjunction with the updated PCSR, I am content that this GDA Issue Action can be closed.

4.3.4 Assessment Findings

304 Based upon the assessment of the **GI-UKEPR-RC-01.A3** responses described in Section 4.3 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, by the licensee, during the design, procurement, construction or commissioning phase of the new build project;

> ***AF-UKEPR-RC-68:*** *The licensee shall provide site specific analysis for the radiological consequence of accidents involving core melting, including IRWST evaporation and uncertainties in the reactions of iodine. This Assessment Finding should be completed before the first nuclear operations.*
>
> ***Required timescale:*** *Initial criticality.*

5 ASSESSMENT FINDINGS

5.1 Additional Assessment Findings

305 As a consequence of my assessment for close-out of **GI-UKEPR-RC-01** for the UK EPR™ reactor design, I have identified 13 Assessment Findings that need to be resolved, as appropriate. I conclude that the Assessment Findings listed in Annex 1 should be programmed during the forward programme of this reactor as normal regulatory business.

5.2 Impacted Step 4 Assessment Findings

306 There are no impacted Step 4 Assessment Findings.

307 However, the Assessment Findings raised as part of the close-out of **GI-UKEPR-RC-01** (**AF-UKEPR-RC-56** to **AF-UKEPR-RC-67**) are closely related to **AF-UKEPR-RC-42**, raised as part of the Step 4 Assessment (Ref. 2). All of these Assessment Findings relate to the provision and expectations for site specific analysis of the combustible gas risks in UK EPR™. As such the licensee may wish to combine resolution of these related Assessment Findings.

6 CONCLUSIONS

308 This report presents the findings of the assessment for the close-out of **GI-UKEPR-RC-01** Revision 1 for the EDF and AREVA UK EPR™ reactor, related to the control of combustible gases. The overall conclusions from my assessment, are presented below:

- EDF and AREVA presented analysis which showed the impact of the PARs operating at a reduced efficiency for combustible gas removal. This demonstrated that margin exists in the design to accommodate some degree of degradation in performance by whatever means. Despite some reservations regarding the methodology, I am content this fundamental result is valid and hence am content that Action 1 has been satisfactorily resolved.
- The analysis provided to demonstrate the performance of the CGCS under bounding conditions is adequate for resolution of Action 2 of this GDA Issue. EDF and AREVA provided analysis for the FA3 plant to demonstrate that the generic UK EPR™ PCSR claim, arguments and evidence are valid. In these responses EDF and AREVA logically considered the main risks and conclude that they are successfully avoided or are within the capabilities of the EPR™ design. I have raised a number of Assessment Findings related to these reports where further work is required of a future licensee to complete the safety case. As such, I am content these can be satisfactorily resolved as part of the site specific phase of any UK EPR™ and that the intent of Action 2 has been fulfilled and can therefore be closed.
- The effect of the recombiners on the production of volatile iodine in UK EPR™ were analysed by EDF and AREVA to estimate the impact of any conversion of aerosol forms of iodine to volatile forms during a severe accident. This analysis used information on the recombiner performance derived from the detailed CGCS analysis and a range of assumed iodine conversion rates. A specific analysis code was used, which differs from the PCSR by incorporating a detailed treatment of the iodine chemistry. This detailed chemistry changes the predicted form of the iodine in the containment, compared to the assumptions in the PCSR, but also decreases the total amounts predicted to be released to the environment and even assuming a pessimistic conversion rate for the iodine predicts releases to the environment which are lower than claimed by the PCSR. While there are some inherent uncertainties in this approach, sufficient margin has been demonstrated and the use of pessimistic assumptions in the PCSR has been demonstrated to be bounding for the effect of recombiners. Overall, the claims made in the PCSR have been demonstrated.
- In response to this GDA Issue, EDF and AREVA updated the PCSR. I have reviewed these updates and am content that they accurately reflect the responses to the Issue Actions.

309 Overall, based on my assessment undertaken in accordance with ONR procedures, I consider the responses to be satisfactory and sufficient for closing the GDA Issue. This assessment has resulted in 13 new Assessment Findings which will need to be resolved by a future UK EPR™ licensee on a site specific basis.

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Table 9

Relevant Safety Assessment Principles Considered for Close-out of GI-UKEPR-RC-01 Revision 1

SAP No.	SAP Title	Description
Engineering principles: Key principles		
EKP. 1	Inherent safety	The underpinning safety aim for any nuclear facility should be an inherently safe design, consistent with the operational purposes of the facility.
EKP. 2	Fault tolerance	The sensitivity of the facility to potential faults should be minimised.
EKP. 3	Defence in depth	A nuclear facility should be so designed and operated that defence in depth against potentially significant faults or failures are achieved by the provision of several levels of protection.
EKP. 4	Safety function	The safety function(s) to be delivered within the facility should be identified by a structured analysis.
EKP. 5	Safety measures	Safety measures should be identified to deliver the required safety function(s).
Fault analysis		
FA.15	Fault sequences	Fault sequences beyond the design basis that have the potential to lead to a severe accident should be analysed.
FA. 16	Use of severe accident analysis	The severe accident analysis should be used in the consideration of further risk-reducing measures.
FA. 18	Calculation methods	Calculational methods used for the analyses should adequately represent the physical and chemical processes taking place.
FA. 20	Computer models	Computer models and datasets used in support of the analysis should be developed, maintained and applied in accordance with appropriate quality assurance procedures.
FA. 22	Sensitivity studies	Studies should be carried out to determine the sensitivity of the fault analysis (and the conclusions drawn from it) to the assumptions made, the data used and the methods of calculation.

Table 10

Relevant Technical Assessment Guides Considered for Close-out of GI-UKEPR-RC-01 Revision 1

Reference	Issue	Title	Ref.
T/AST/007	01	Severe accident analysis	37
T/AST/042	01	Validation of computer codes and calculational methods	41
T/AST/051	01	Guidance on the purpose, scope and content of nuclear safety cases	69

Annex 1

GDA Assessment Findings Arising from GDA Close-Out for Reactor Chemistry Issue GI-UKEPR-RC-01 Revision 1

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-56	The licensee shall complete and document, as part of the site specific analysis, a: • Verification and validation of the codes used to support the safety case for combustible gas control, including a comparison of the analysis to relevant good practice guidelines for CFD use. • Review of inter-code comparisons where the analysis procedure calculates the same data in different codes.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-57	The licensee shall demonstrate the adequacy of the CFD codes descretisation as part of the site specific analysis, especially for those phenomena where high spatial or temporal accuracy is required.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-58	The licensee shall include a demonstration of the impacts of allowing unreacted combustible gases to exit the PARs as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-59	The licensee shall demonstrate that the use of a simplified algebraic turbulence model is adequate as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.

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 <u>during</u> the operational phase. For other Assessment Findings, it is the regulators' expectation that the findings are adequately addressed no later than the milestones indicated above.

Annex 1

GDA Assessment Findings Arising from GDA Close-Out for Reactor Chemistry Issue GI-UKEPR-RC-01 Revision 1

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-60	The licensee shall review reasonably practicable design improvements that could be made to UK EPR™ to mitigate against hydrogen accumulation in severe accident conditions within the containment.	This Assessment Finding should be completed before the containment is pressure tested. Required timescale: Containment Pressure test.
AF-UKEPR-RC-61	The licensee shall demonstrate as part of the site specific analysis that the GASFLOW results are adequate to bound the temperature loads predicted during combustion, in terms of the amount of hydrogen burnt.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-62	The licensee shall provide additional evidence to support the claims made on the avoidance of detrimental flame acceleration as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-63	The licensee shall justify the scenario selection for the ex-vessel phases of a severe accident, including consideration of combustion risks at the local scale, as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-64	The licensee shall demonstrate that the assumption that carbon monoxide is treated as hydrogen does not negatively impact on the flammability of the gas mixture as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.

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 <u>during</u> the operational phase. For other Assessment Findings, it is the regulators' expectation that the findings are adequately addressed no later than the milestones indicated above.

Annex 1

GDA Assessment Findings Arising from GDA Close-Out for Reactor Chemistry Issue GI-UKEPR-RC-01 Revision 1

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-65	The licensee shall quantify the temperatures loads from ex-vessel hydrogen combustion as part of the site specific analysis. This should demonstrate the effects of combustion in standing flames on thermal loads.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-66	The licensee shall demonstrate the impact of operation of the containment spray system on the combustible gas risks as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-67	The licensee shall provide a justification for the effects of reduced PAR performance on combustion risks at the local scale as part of the site specific analysis.	This Assessment Finding should be completed before fuel is first loaded into the reactor. Required timescale: Fuel Load.
AF-UKEPR-RC-68	The licensee shall provide site specific analysis for the radiological consequence of accidents involving core melting, including IRWST evaporation and uncertainties in the reactions of iodine.	This Assessment Finding should be completed before the first nuclear operations. Required timescale: Initial criticality.

Note: It is the responsibility of the Licensees / Operators to have adequate arrangements to address the Assessment Findings. Future Licensees / Operators can adopt alternative means to those indicated in the findings which give an equivalent level of safety.

For Assessment Findings relevant to the operational phase of the reactor, the Licensees / Operators must adequately address the findings during the operational phase. For other Assessment Findings, it is the regulators' expectation that the findings are adequately addressed no later than the milestones indicated above.

Annex 2
GDA Issue, GI-UKEPR-RC-01 Revision 1 – Reactor Chemistry – UK EPR™

EDF AND AREVA UK EPR™ GENERIC DESIGN ASSESSMENT
GDA ISSUE
COMBUSTIBLE GAS CONTROL SYSTEMS
GI-UKEPR-RC-01 REVISION 1

<table>
<tr><td colspan="2">Technical Area</td><td colspan="2">REACTOR CHEMISTRY</td></tr>
<tr><td colspan="2">Related Technical Areas</td><td colspan="2">Severe Accident</td></tr>
<tr><td>GDA Issue Reference</td><td>GI-UKEPR-RC-01</td><td>GDA Issue Action Reference</td><td>GI-UKEPR-RC-01.A1</td></tr>
<tr><td>GDA Issue</td><td colspan="3">Impact of Passive Autocatalytic Recombiners during accidents</td></tr>
<tr><td>GDA Issue Action</td><td colspan="3">EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the operation of the UK EPR™ Combustible Gas Control System (CGCS) with reduced performance of the Passive Autocatalytic Recombiners (PARs) .
In the current UK EPR™ safety case the PARs are assumed to work at 100% “efficiency” throughout an accident (i.e. the flow is adjusted so that 100% of the inlet hydrogen is removed). Information has been provided on the derivation of the performance characteristics of individual PAR units. EDF and AREVA claim that their effectiveness is bounded by the current analyses including one analysis with removal of selective complete PARs (6 equipment room PARs and 1 dome recombiner) as a surrogate for reduced PAR efficiency. While this provides a degree of comfort in the CGCS, it does not demonstrate how the system would behave following an overall “efficiency” reduction in all recombiners, as opposed to selective removal of a few entire units.
In addition, it has not been demonstrated that adequate consideration has been given to local flows when modelling the UK EPR™ (i.e. convective flows in the containment acting in the opposite direction to the flow through the PAR). As above, this effect too could result in reduced PAR performance and should be analysed given that this cannot be ruled out.
With agreement from the Regulator this action may be completed by alternative means.</td></tr>
</table>

Annex 2
GDA Issue, GI-UKEPR-RC-01 Revision 1 – Reactor Chemistry – UK EPR™

EDF AND AREVA UK EPR™ GENERIC DESIGN ASSESSMENT
GDA ISSUE
COMBUSTIBLE GAS CONTROL SYSTEMS
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<tr><td>GDA Issue Reference</td><td>GI-UKEPR-RC-01</td><td>GDA Issue Action Reference</td><td>GI-UKEPR-RC-01.A2</td></tr>
<tr><td>GDA Issue Action</td><td colspan="3">EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the performance of the UK EPR™ Combustible Gas Control System (CGCS) in case of a bounding accident scenario.

An important input to the assessment of any accident mitigation system is the source term in terms of the rate and mass of combustible gases released into containment. The CGCS in UK EPR™ will have a limited overall depletion rate based upon the installed equipment (i.e. number and size of PAR units). EDF and AREVA have described the analysis using “representative” and “bounding” scenarios with the latter oxidising around 75% of the available fuel cladding and the former predicting lower levels.

While this provides a degree of comfort that the analysis uses best estimate source terms, a detailed analysis including bounding conditions has to be supplied to demonstrate the adequacy of the system design.

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

Annex 2
GDA Issue, GI-UKEPR-RC-01 Revision 1 – Reactor Chemistry – UK EPR™

EDF AND AREVA UK EPR™ GENERIC DESIGN ASSESSMENT

GDA ISSUE

COMBUSTIBLE GAS CONTROL SYSTEMS

GI-UKEPR-RC-01 REVISION 1

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<tr><td>GDA Issue Reference</td><td>GI-UKEPR-RC-01</td><td>GDA Issue Action Reference</td><td>GI-UKEPR-RC-01.A3</td></tr>
<tr><td>GDA Issue Action</td><td colspan="3">EDF and AREVA to provide a sensitivity analysis, or alternative means agreed by the regulator, to demonstrate the potential impact of operation of the UK EPR™ CGCS on iodine volatility in containment.
With agreement from the Regulator this action may be completed by alternative means.</td></tr>
</table>

Further explanatory / background information on the GDA Issues for this topic area can be found at:	
GI-UKEPR-RC-01 Revision 1	Ref. 8

Annex 3
Overview of the Analysis Codes referenced in this Assessment Report

This appendix briefly presents the computer codes referenced in this assessment report. Further details of the codes used by EDF and AREVA for severe accident events are given in Appendix 16A of the PCSR (Ref. 36).

Code	Description	Validation	Application by EDF and AREVA
MAAP	MAAP (Modular Accident Analysis Program) is used to simulate the response of light water reactor power plants during severe accident sequences, including actions taken as part of accident management. MAAP4 is categorised as an "integral severe accident analysis tool" which means that it integrates a large number of phenomena into a single plant simulation (NSSS + containment + auxiliary building). www.fauske.com/nuclear/maap-modular-accident-analysis-program	MAAP has been benchmarked against a wide range of separate effects experiments and integral experiments, including actual industry experience (TMI-2 in particular).	■ Analysis of primary system response, including the prediction of mass, energy and fission product releases into the containment ■ Analysis of the efficiency of the primary depressurisation
COCOSYS	COCOSYS (COntainment COde SYStem) is a lumped-parameter multi-compartment code developed by GRS for best estimate analyses of the containment behaviour in severe accidents including fission product release to the environment. The code includes models for relevant severe accident processes and phenomena, such as containment thermal-hydraulics, and aerosol and fission product behaviour. These models address both transient processes, which mainly occur early in the accident, and slow processes, which mostly concern the long-term phase of a severe accident. www.grs.de/sites/default/files/fue/COCOSYS	The code has been extensively validated on several experiments (including sensitivity studies): ACE (L6), ACE-RTF (3B), AHMED, BETA (V5.1), BMC (F2, HYJET 4, Gx4, VANAM-M3), BNWL, DEMONA, HDR (E11.4, T31.5, E11.8.1), GKSS (M1), KAEVER, LACE, NUPEC (B-8-3, B-9-4, M7.1), PANDA (BC4, PC1, ISP42), PHEBUS-FP and ThAI.	■ Analysis of containment pressure and temperature ■ Fission product transport in the containment and source term to the environment

Annex 3
Overview of the Analysis Codes referenced in this Assessment Report

Code	Description	Validation	Application by EDF and AREVA
GASFLOW	GASFLOW is a best-estimate finite-volume computer code developed at Los Alamos National Laboratory (LANL) in USA and Forschungszentrum Karlsruhe (FZK) in Germany for predicting the transport of steam/hydrogen/air mixtures as well as the recombination and combustion of hydrogen. http://hycodes.net/gasflow/	The experimental facilities used to validate GASFLOW vary from small shock tubes up to the former large-scale HDR facility (the containment of a decommissioned nuclear power plant) located close to Frankfurt, Germany. Apart from HDR, emphasis in the validation of GASFLOW was laid on the many Battelle experiments, including experiments with combustion and jet injection. Most recently experiments at the Phebus facility (FPT0) and the new ThAI facility are used for validation.	■ Analysis of hydrogen distribution and laminar combustion
COM3D	COM3D is a three-dimensional code for turbulent reactive flow simulation in a complex geometry. COM3D calculates the combustion progress of a pre-defined gas mixture in great detail over a few seconds. Consequently, COM3D must be supplemented by another CFD code such as GASFLOW, which calculates the accident progression and the mixture composition as function of time and space, and thus provides the initial data for COM3D. COM3D has a second-order-accurate compressible Navier-Stokes equation solver coupled to turbulence and chemical kinetics models. http://hycodes.net/com3d/	COM3D had been validated using experiments performed at different scales. The validation of the code has been performed in the framework of the EU HYCOM project, using also some new experiments in the large RUT facility and in smaller facilities, such as TORPEDO and DRIVER all at the Kurchatov Institute, Moscow.	■ Analysis of flame acceleration processes and fast deflagration

Annex 3
Overview of the Analysis Codes referenced in this Assessment Report

Code	Description	Validation	Application by EDF and AREVA
ASTEC	The ASTEC code (Accident Source Term Evaluation Code), jointly developed by IRSN and GRS, aims at simulating an entire Severe Accident sequence in a nuclear water-cooled reactor from the initiating event through the release of radioactive elements out of the containment. www.grs.de/sites/default/files/pdf/Overview_ASTEC.pdf	ASTEC validation is based on a set of French, German and international experiments that cover most aspects of severe accident phenomenology. The validation matrix mainly includes separate or coupled-effect tests that cover most phenomena. It also includes integral applications such as the TMI-2 accident and the integral experiments of the Phebus FPT1 experiment.	■ Analysis of iodine chemistry in containment