Office for Nuclear Regulation
An agency of HSE

Generic Design Assessment – New Civil Reactor Build

Step 4 Reactor Chemistry Assessment of the EDF and AREVA UK EPR™ Reactor

Assessment Report: ONR-GDA-AR-11-024
Revision 0
11 November 2011

.

COPYRIGHT

PREFACE

The Office for Nuclear Regulation (ONR) was created on 1st April 2011 as an Agency of the Health and Safety Executive (HSE). It was formed from HSE's Nuclear Directorate (ND) and has the same role. Any references in this document to the Nuclear Directorate (ND) or the Nuclear Installations Inspectorate (NII) should be taken as references to ONR.

The assessments supporting this report, undertaken as part of our Generic Design Assessment (GDA) process and the submissions made by EDF and AREVA relating to the UK EPR^{TM} reactor design, were established prior to the events at Fukushima, Japan. Therefore, this report makes no reference to Fukushima in any of its findings or conclusions. However, ONR has raised a GDA Issue which requires EDF and AREVA to demonstrate how they will be taking account of the lessons learnt from the events at Fukushima, including those lessons and recommendations that are identified in the ONR Chief Inspector's interim and final reports. The details of this GDA Issue can be found on the Joint Regulators' new build website www.hse.gov.uk/newreactors and in ONR's Step 4 Cross-cutting Topics Assessment of the EDF and AREVA UK EPR^{TM} reactor.

EXECUTIVE SUMMARY

This report presents the findings of the Reactor Chemistry assessment of the UK EPR reactor undertaken as part of Step 4 of the Health and Safety Executive's (HSE) Generic Design Assessment (GDA). The assessment has been carried out on the November 2009 Pre-construction Safety Report (PCSR) and supporting documentation submitted by EDF and AREVA during Step 4.

This assessment has followed a step-wise-approach in a claims-argument-evidence hierarchy. In Step 3 the claims and arguments made by EDF and AREVA were examined.

The scope of the Step 4 assessment was to review the safety aspects of the UK EPR reactor in greater detail, by examining the evidence, supporting arguments and claims made in the safety documentation, building on the assessments already carried out during Step 3, and to make a judgement on the adequacy of the Reactor Chemistry information contained within the PCSR and supporting documentation.

It is seldom possible, or necessary, to assess a safety case in its entirety, therefore sampling is used to limit the areas scrutinised, and to improve the overall efficiency of the assessment process. Sampling is done in a focused, targeted and structured manner with a view to revealing any topic-specific, or generic, weaknesses in the safety case. To identify the sampling for the Reactor Chemistry an assessment plan for Step 4 was set-out in advance.

My assessment has focussed on obtaining further evidence from EDF and AREVA and assessing the chemistry of:

- The EDF and AREVA safety case for the justification, implications and control of primary coolant chemistry during all modes of operation. This included consideration of nuclear reactivity control using boron, the effects of coolant chemistry on the integrity of pressure boundaries, protection of fuel and core components and production, transport and deposition of radioactivity, including its influence on radiological doses to workers and ultimately to wastes.
- Those features of the design, material choices or chemistry controls which reduce radioactivity so far as is reasonably practicable.
- The main secondary circuit systems which control or are influenced by chemistry. This includes consideration of the implications of system design on chemistry choices and the interaction of chemistry with materials and corrosion susceptibility.
- Those engineered systems which allow licensee staff to control, monitor or change the plant chemistry.
- The storage of nuclear fuel within ponds, including the effects of pool chemistry.
- Those systems which mitigate the release of radioactivity to the environment in either the liquid or gaseous form.
- Design basis and beyond design basis accidents, including the production, release and control of hydrogen and fission product nuclides.
- The arrangements for moving the safety case to an operating regime, including the derivation of suitable limits and conditions and the arrangements for specifying plant chemistry.

A number of items have been agreed with EDF and AREVA as being outside the scope of the GDA process and hence have not been included in my assessment. A full list and description of these items can be found in the text of the report.

From my assessment, I have concluded that:

- While the precise values for chemistry related limits and conditions have not been assessed as part of GDA, EDF and AREVA have provided me with sufficient confidence to conclude that a suitable case could be made for UK EPR in this regard. EDF and AREVA have presented their intended operating chemistry for UK EPR, which is similar to many current operating plants with adaptations for the specific design and taking account of operating experience, mainly from the extensive French and German PWR fleets. Notable differences include:
    - (i) Unlike many, but similar to some current PWRs (including in Germany), EDF and AREVA have designed UK EPR to use Enriched Boric Acid (EBA). Boron control is a main safety priority for any PWR. Use of EBA has a number of advantages for chemical safety including a lower volume, higher freezing point and less acidity per equivalence of ^{10}B but requires extra controls on the enrichment. I assessed systems for managing boron, which include a multiplicity of monitoring devices in UK EPR. ND has requested continued work after Step 4 on the diversity of the boron monitoring system, which I will support. It may be desirable to recycle EBA and this may cause some impurities and radioactivity to accumulate in the coolant. I have asked EDF and AREVA to quantify the production and loss of significant components in the coolant in this way. With these exceptions, I am content with the proposed design for boron control in UK EPR for GDA.
    - (ii) EDF and AREVA expect UK EPR to operate with dissolved hydrogen levels in the primary coolant which are at the lower end of current operating experience. This is mainly expected to bring benefits in radiation levels. I remain unconvinced of the evidence to support reducing values to lower levels, but am content that the design of UK EPR is capable of operation at more established concentrations if necessary.
    - (iii) When added to the primary coolant, traces of zinc are claimed to minimise radiation fields within reactors and EDF and AREVA propose zinc addition for UK EPR. I asked for evidence to support this process, and extensive documentation was provided. Apart from an unresolved question related to the distribution of ^{14}C, which I am content is not a safety issue, I conclude that waste generation will be no worse with zinc and radiation should be lower. Thus it appears that zinc addition is justified. So far, EDF and AREVA do not propose to add zinc during commissioning and this will need to be reviewed by the Licensee post GDA.
- I assessed the major chemistry systems which allow the Licensee to control, monitor and change the primary chemistry, including those that are used during accidents. The UK EPR has a number of sophisticated systems for these aspects which are derived from, and often improve on, successful systems which are in operation in PWRs today.
- During Step 3 I noted that the safety case for UK EPR was almost entirely based on experience with previous reactor designs, none of which are directly comparable to UK EPR. Our expectations are that a nuclear safety case is based upon a balance of experience and supporting calculations. Bounding estimates of the radioactive materials such as tritium and cobalt isotopes that would be produced by UK EPR, have been provided by EDF and AREVA based on experience and comparisons with other reactors, primarily in France. These estimates took no account of the size and power of UK EPR which are greater than existing French PWRs. Initially, EDF and AREVA did not consider such figures would be relevant because any predictions would be purely theoretical at this stage. I commissioned independent calculations which showed that UK EPR will, not surprisingly, produce more of the cobalt isotopes than current French PWRs, although this needs to be reconciled with the increased power output of UK EPR. In response, EDF and AREVA are starting to predict levels of tritium and other quantities, which reveal some improvements to their coolant management strategy may be needed. These figures are arriving too late for me to assess and EDF and AREVA

have agreed to provide more calculated data as part of a GDA Issue. These are important additions to the safety case and this process will need to further continue as the UK EPR safety case develops during subsequent plant approval, construction and commissioning stages.

- In addition to the operating chemistry the material choices can have important impacts on the radioactivity and corrosion performance of a PWR. EDF and AREVA have engineered many known ‘problem’ alloys out of the UK EPR design entirely, have reduced many to levels consistent with ALARP and have demonstrated an appropriate level of understanding and control over aspects such as surface finishing and fabrication. Given developments with robotic methods of inspection and in use of zinc, EDF and AREVA see no need to electropolish the steam-generator internals.
- Despite some aspects of the secondary circuit being outside of the scope of the GDA assessment, I have assessed a number of aspects of the design including principal material choices, corrosion threats, chemistry control and tolerance of abnormal chemistry. In general, reasonable arguments have been made by EDF and AREVA in these areas although I have identified a number of Assessment Findings where further work will be required going forward. The main deficiency is that a holistic analysis for the secondary circuit, considering chemistry and material choices, is not yet available, although I am content that there are no fundamental hindrances to safe operation of the plant. It is clear that considerable forethought has been put into the design in a number of areas related to chemistry and the safety case does not present these as well as it could.
- The UK EPR has been designed to prevent accidents and make unplanned releases smaller and less likely. I assessed the chemistry occurring during Steam Generator Tube Rupture (SGTR) events, during accidents which involve generation and release of combustible gases and in the unlikely event of an accident severe enough to melt fuel. These have all been areas of challenge to past reactor designs. In general, while further work will be required by the Licensee in many of these areas the overall EDF and AREVA case for chemistry during accidents in UK EPR was acceptable for GDA. The main exception to this is for the UK EPR system which is used to control and remove combustible gases released into the containment during an accident. This system is based on the use of Passive Autocatalytic Recombiners (PARs) which convert hydrogen to water. These devices are new to the UK for this application although are used extensively in Europe and, being reliant on a chemical process, are potentially susceptible to chemical interferences. EDF and AREVA provided much information on this system during GDA, including details of the modelling and assessment undertaken, which is sophisticated and comprehensive, and this allayed most of my concerns in this area. However, I am not content that an adequate case has yet been made regarding the effects of degraded PAR performance on the plant, performance under bounding accident conditions or when consideration is given to their potential interaction with volatile iodine. I am content that these can be resolved, but expect this to be done before the start of nuclear related construction and I have raised a GDA Issue on this aspect.
- For the extremely unlikely event that the core becomes hot enough to melt fuel, UK EPR provides a core melt stabilisation system. This comprises a melting pit, a fusible plug, a transfer tunnel and a water-cooled spreader. I assessed the chemical performance of individual steps in this system. I assessed the extensive testing and calculation by AREVA, by European research institutions and elsewhere. I concluded that whilst individual steps in this system have been validated, the composite sequence of steps was not demonstrated. However, I am satisfied that its result, in terms of the overall containment goal for large early release, is assured.
- As a result of the GDA assessments, the PCSR for UK EPR has been updated and now includes a sub-chapter dedicated to Reactor Chemistry. This is a valuable addition to the safety case and will provide a basis for further developments of the plant chemistry. EDF and AREVA

have demonstrated that the development of limits, conditions or specifications related to chemistry parameters should be possible for UK EPR. I expect that a ‘chemistry manual’ or similar documentation will be required and produced by the Licensee.

In some areas there has been a lack of detailed information which has limited the extent of my assessment. As a result ND will need additional information to underpin my conclusion and these are identified as Assessment Findings to be carried forward as normal regulatory business. These are listed in Annex 1.

Some of the observations identified within this report are of particular significance and will require resolution before HSE would agree to the commencement of nuclear safety-related construction of a UK EPR reactor in the UK. These are identified in this report as GDA Issues and are listed in Annex 2. In summary these relate to:

GI-UKEPR-RC-01 *– EDF and AREVA need to provide further evidence supporting operation of the combustible gas mitigation system.*

GI-UKEPR-RC-02 *- Demonstration that ex-core radiation levels in UK EPR are minimised so far as is reasonably practicable and can be controlled.*

In addition, there are a number of GDA Issues raised in other assessment areas which need to be satisfactorily resolved before an adequate Reactor Chemistry safety case can be made. These relate to the consolidated GDA safety case (**GI-UKEPR-CC-02**), the boron meters (**GI-UKEPR-FS-01**) and the Steam Generator Tube Rupture (SGTR) safety case (**GI-UKEPR-FS-04**).

Overall, based on the sample undertaken in accordance with ND procedures, I am broadly satisfied that the claims, arguments and evidence laid down within the PCSR and supporting documentation submitted as part of the GDA process present an adequate safety case for the generic UK EPR reactor design. The UK EPR reactor is therefore suitable for construction in the UK, subject to satisfactory progression and resolution of GDA Issues to be addressed during the forward programme for this reactor and assessment of additional information that becomes available as the GDA Design Reference is supplemented with additional details on a site-by-site basis.

LIST OF ABBREVIATIONS

ABP	Low Pressure Feedwater Heater System
ADG	Feedwater Tank
AFNOR	Association Française de NORmalisation (French standards body)
AHP	High Pressure Feedwater Plant and Heater System
AICC	Adiabatic Isochoric Complete Combustion
AISI	American Iron and Steel Institute
ALARP	As Low as Reasonably Practicable (see also SFAIRP)
ASN	Autorité de sûreté nucléaire (Nuclear Safety Authority, France)
ATD	Start-up Condensate and Feedwater Purification Plant
AVS	Annulus Ventilation System [EDF coding system – EVS]
AVT	All Volatile Treatment
BCMS	Boron Concentration Measurement System (in the CVCS)
BDBA	Beyond Design Basis Analysis
BMS	(ND) Business Management System
BOA	Boron Offset Anomaly
BOC	Beginning of Cycle
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium-Uranium reactor
CCWS	Component Cooling Water System [EDF coding system – RRI]
CDS	Coolant Degasification System [EDF coding system – TEP4]
CEA	Commissariat à l'énergie atomique (Research organisation, France)
CEX	Condensate Extraction System
CFD	Computational Fluid Dynamics
CGCS	Combustible Gas Control System [EDF coding system – ETY]
CHRS	Containment Heat Removal System [EDF coding system – EVU]
CILC	Crud-Induced Localised Corrosion
CIPS	Crud-Induced Power Shift
CIV	Containment Isolation Valves
CMF	Change Management Form
CMSS	Core-Melt Stabilisation System
CP	Corrosion Product
CPP	Condensate Polishing Plant
CPS	Coolant Purification System [EDF coding system – TEP2]
CRDM	Control Rod Drive Mechanism [EDF coding system – RGL]

LIST OF ABBREVIATIONS

CREDO	Chemical and Radiochemical EPR Design Optimisation
CRF	Circulating Water System
CSS	Coolant Storage and Supply system [EDF coding system – TEP1]
CSTS	Condensate Storage and Treatment System [EDF coding system – TEP]
CTS	Coolant Treatment System [EDF coding system – TEP3]
CVCS	Chemical and Volume Control System [EDF coding system – RCV]
CVI	Condenser Vacuum System
DBA	Design Basis Analysis
DDT	Deflagration to Detonation Transition
DE	Dose Equivalent
DER	Operational Chilled Water System
DSEAR	Dangerous Substances and Explosive Atmosphere Regulations
EBA	Enriched Boric Acid
EBS	Extra Boration System [EDF coding system – RBS]
EDF	Groupe Electricité de France
EFWS	Emergency Feedwater System [EDF coding system – ASG]
EP	Electropolishing
EPRI	Electric Power Research Institute (US)
ESWS	Essential Service Water System [EDF coding system – SEC]
ETB	Effluent Treatment Building
ExLWDS	Additional Liquid Waste Discharge System [EDF coding system – TER]
FAC	Flow Accelerated Corrosion
FA3	Flamanville 3
FP	Fission Product
FPCS	Fuel Pool Cooling System [EDF coding system – PTR]
FPPS	Fuel Pool Purification System [EDF coding system – PTR]
FW	Feed Water
GDA	Generic Design Assessment
GWPS	Gaseous Waste Processing System [EDF coding system – TEG]
HEPA	High Efficiency Particulate Air
HFT	Hot Functional Testing
HP	High Pressure
HSE	(The) Health and Safety Executive
HVAC	Heating, Ventilation and Air Conditioning
IAEA	The International Atomic Energy Agency

LIST OF ABBREVIATIONS

IASCC	Irradiation-Assisted Stress-Corrosion Cracking
IGA	Inter-granular Attack
IGSCC	Inter-granular Stress Corrosion Cracking
IRSN	L'Institut de Radioprotection et de Sûreté Nucléaire (France)
IRWST	In-Containment Refuelling Water Storage Tank
LB	Large Break
LHSI	Low Head Safety Injection system [EDF coding system – RIS]
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-Site Power
LP	Low Pressure
LRMDS	Control and Discharge of Effluents from nuclear island [EDF coding system – KER]
LTCP	Low-temperature Crack Propagation
LTOP	Low Temperature Overpressure Protection
LWPS	Liquid Waste Processing System [EDF coding system – TEU]
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Program
MCCI	Molten Core-Concrete Interaction
MFWS	Main Feedwater System
MHI	Mitsubishi Heavy Industries
MHSI	Medium Head Safety Injection system [EDF coding system – RIS]
MOX	Mixed Oxide Fuel
MP	Medium Pressure
MSB	Main Steam Bypass system [EDF coding system – GCT]
MSL	Main Steam Lines
MSR	Moisture Separator Reheater [EDF coding system – GSS]
MSSS	Main Steam Supply System [EDF coding system – VVP]
NAB	Nuclear Auxiliaries Building
ND	(HSE) Nuclear Directorate
NI	Nuclear Island
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (US)
NSS	Nuclear Sampling System [EDF coding system – REN]
NVDS	Nuclear Vents and Drains System [EDF coding system – RPE]
OD	Outside Diameter
OECD	Organisation for Economic Cooperation and Development

LIST OF ABBREVIATIONS

OEF	Operator Experience Feedback
ONR	Office for Nuclear Regulation
ORE	Operator Radiation Exposure
OSSA	Operating Strategies for Severe Accidents
OTS	Operating Technical Specifications
PAR	Passive Autocatalytic Recombiner
PASS	Post-Accident Sampling System
PCC	Plant Condition Category
PCER	Pre-Construction Environmental Report
PCSR	Pre-Construction Safety Report
POSR	Pre-Operational Safety Report
PRMS	Plant Radiation Monitoring System [EDF coding system – KRT]
PRT	Pressuriser Relief Tank
PSA	Probabilistic Safety Analysis
PSR	Preliminary Safety Review
PWR	Pressurised Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
PZR	Pressuriser
RBWMS	Reactor Boron and Water Makeup System [EDF coding system – REA]
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System [EDF coding system – RCP]
RES	Steam Generator Secondary Sampling System (part of NSS)
RH	Relative Humidity
RHRS	Residual Heat Removal System [EDF coding system – RRA]
RI	Regulatory Issue
RIA	Regulatory Issue Action
RO	Regulatory Observation
ROA	Regulatory Observation Action
RPV	Reactor Pressure Vessel
SA	Severe Accident (see also BDBA)
SAP	Safety Assessment Principles
SB	Small Break
SCC	Stress Corrosion Cracking
SDA	Nuclear Island Demineralised Water Distribution System
SDM	System Design Manual

LIST OF ABBREVIATIONS

SDS	Seawater Demineralisation System
SED	Nuclear Island Demineralised Water Distribution System
SER	Conventional Island Demineralised Water Distribution System
SFAIRP	So Far as is Reasonably Practicable
SFP	Spent Fuel Pool
SG	Steam Generator
SGBD	Steam-Generator Blowdown
SGBS	Steam Generator Blowdown System [EDF coding system – APG]
SGTR	Steam Generator Tube Rupture
SINCAD	SIlver-INdium-CADmium alloy
SIR	French acronym for Chemical Reagent Injection System in EPR
SIS	Safety Injection System [EDF coding system – RIS]
SIT	Feedwater Sampling System
SML	Master Submission List
SRI	Conventional Island Closed Cooling Water System
SSC	System, Structure or Component
SSER	Safety, Security and Environmental Report
SSS	Start-up and Shutdown Feedwater System [EDF coding system – AAD]
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority, Finland)
TAG	(Nuclear Directorate) Technical Assessment Guide
TQ	Technical Query
TS	Tube Sheet (in Steam Generator)
TSC	Technical Support Contractor
TSP	Steam Generator Tube Support Plate
TT	Thermally Treated alloy (specifically Inconel 600 or 690)
UK	United Kingdom
URD	Utility Requirements Document
US	United States (of America)
USA	United States of America
VCT	Volume Control Tank
VGB	Verenigate Grosskraftwerke Betreiber (Federation of Large Power Station Operators, Germany)
VPU	Steam Line Drain System

TABLE OF CONTENTS

Tables

Figures

Annexes

1 INTRODUCTION

1 This report presents the findings of the Step 4 Reactor Chemistry assessment of the November 2009 UK EPR Pre-construction Safety Report (PCSR) (Ref. 11) and supporting documentation provided by EDF (Groupe Electricité de France) and AREVA under the Health and Safety Executive's (HSE) Generic Design Assessment (GDA) process. The approach taken was to assess the principal submission, i.e. the PCSR and the supporting evidentiary information derived from the Submission Master List (Ref. 175), and then undertake assessment of the relevant supporting documentation on a sampling basis in accordance with the requirements of Nuclear Directorate’s (ND) Business Management System (BMS) procedure AST/001 (Ref. 2). The Safety Assessment Principles (SAPs) (Ref. 4) 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.

2 During the assessment a number of Technical Queries (TQ) and Regulatory Observations (RO) were issued and the responses made by EDF and AREVA assessed. Where relevant, detailed design information from specific projects for this reactor type has been assessed to build confidence and assist in forming a view as to whether the design intent proposed within the GDA process can be realised.

3 A number of items have been agreed with EDF and AREVA as being outside the scope of the GDA process and hence have not been included in this assessment.

1.1 GDA Process

4 In accordance with HSE’s guidance document (Ref. 5), our work on GDA has been conducted in a step-wise approach with the assessment becoming increasingly detailed at each step. Reports of our overall GDA assessment work have been issued at the end of Step 2 and Step 3. Reactor Chemistry assessment began at the beginning of Step 3 and was first reported at the end of that step.

Step 1 The preparatory part of the design assessment process involving discussions between the Requesting Parties (RPs) and the Regulators to agree requirements and how the process would be applied.

Step 2 An overview of the fundamental acceptability of the proposed reactor design concept within the UK regulatory regime to identify any fundamental design aspects or safety shortfalls that could prevent the proposed design from being licensed in the UK.

Step 3 An ND review of the safety aspects of the proposed reactor design to progress from the fundamentals of Step 2 to an analysis of the design, primarily by examination at the system level and by analysis of the RPs’ supporting arguments.

5 This is the report of our work in *Step 4* which was an in-depth ND assessment of the safety case and generic site envelope submitted. This included a detailed examination of the evidence, on a sampling basis, given by the safety analysis presented in the Step 4 PCSR (Ref. 11) and supporting documentation.

2 NUCLEAR DIRECTORATE'S ASSESSMENT STRATEGY FOR REACTOR CHEMISTRY

6 The intended assessment strategy for Step 4 for the Reactor Chemistry topic area was set out in an assessment plan (Ref. 1) that identified the intended scope of the assessment and the standards and criteria that would be applied. This is summarised below:

2.1 Definition of Reactor Chemistry

7 In order to understand the scope of the assessment that was conducted, it is first sensible to consider the definition of Reactor Chemistry that was applied during the assessment such that the boundaries are clearly understood. For the purpose of this assessment Reactor Chemistry was taken to be defined as:

> *the chemistry of the design including the effects of coolant chemistry on reactivity, pressure boundary integrity, fuel and core component integrity, fuel storage in cooling pools, radioactive waste generation and radiological doses to public and workers*

8 Thus, for the purpose of GDA the Reactor Chemistry assessment was principally concerned with five main areas; control of coolant reactivity, protection of the structural materials (specifically related to integrity of the pressure boundaries), maintaining fuel integrity and performance, minimisation of out of core radiation fields and minimisation of releases during accident conditions. The relative influence each of these can have on safety varies depending upon the specific system under assessment; however these main areas were considered throughout.

2.2 Assessment Methodology

9 This report has been prepared in accordance with relevant ND guidance (Refs 2 and 3), which also informs the methodology used, namely a sampling basis, dictated by consideration of risk and hazard significance, in coordination with the other assessment disciplines and the scope defined in the assessment plan (Ref. 1).

10 The Step 4 assessment process consists of examining the evidence to support the claims and arguments in the EDF and AREVA UK EPR PCSR (Ref. 11) and supporting documentation. 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.

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

- Reading the appropriate elements of the RP's GDA submissions.
- Consideration of internal and international standards and guidance.
- Consideration of international experience, operational feedback and expertise.
- Consideration of assessments performed by other regulators, especially their findings.
- Interaction with other relevant technical areas (where appropriate).
- Following the GDA interface arrangements (Ref. 5); raising and issuing of Technical Queries (TQs), Regulatory Observations (ROs) and Regulatory Issues (RIs), as appropriate, followed by assessment of RP responses.

- Holding the necessary technical meetings to progress the identified lines of enquiry.

12 Consistent with the GDA deadlines and to provide ND with information for use in our assessment of Reactor Chemistry in the EDF and AREVA UK EPR, I completed a significant 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 2.3.4 of this report.

2.3 Assessment Approach

13 As identified in Ref. 1, in addition to the Step 4 UK EPR safety case produced at the end of 2009 (Ref. 11), assessment included four principal mechanisms to form a regulatory position on the adequacy of the EDF and AREVA UK EPR safety case during Step 4. These were:

- Assessment of the outputs produced by EDF and AREVA in response to the Regulatory Observations Actions (ROAs) raised at the end of Step 3 and during Step 4
- Assessment of the responses to Technical Queries (TQs) produced during Step 4
- Technical meetings held with the RP throughout Step 4
- Consideration of TSC outputs and reports produced throughout Step 4

14 The overall strategy was to build upon the assessment conducted during Step 3, focussing on the detailed examination of the evidence presented by EDF and AREVA to support the claims and arguments previously identified. For Reactor Chemistry the distinction between claims, arguments and evidence is sometimes somewhat opaque, and the form that evidence can take varies widely; including calculations, assessments and studies, reviews of experience, arguments from first-principles or detailed numerical modelling. As such some degree of overlap between the Step 3 and Step 4 assessments was inevitable and accepted. Nonetheless, the evidence as presented was assessed against the standards and criteria described in Section 2.4.

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

2.3.1 Regulatory Observation Actions

16 The Regulatory Observations (ROs) and associated Actions (ROAs) raised with EDF and AREVA during Step 4 are given in Ref. 9.

17 Three ROs were produced and issued in the Reactor Chemistry area at the end of Step 3, which contained a total of six ROAs. These covered the scope of the PCSR, general radiation levels and the use of zinc in the primary coolant. During Step 4 an additional four actions were raised under these existing ROs.

18 Two further ROs, covering radioactivity in the nuclear island and hydrogen control in the containment during an accident, were issued during Step 4. These observations carried a further five actions.

19 Overall Reactor Chemistry issued five ROs and fifteen ROAs during GDA, in addition to several joint or cross-cutting ROs with other assessment areas.

20 EDF and AREVA did not complete responses to all of the Reactor Chemistry ROAs in time for incorporation into the Step 4 assessment. These gaps have resulted in Assessment Findings or Issues as appropriate, as detailed later in this report.

21 The deliverables provided by EDF and AREVA in response to these actions were assessed by ND during Step 4. Commentary on the individual responses to the ROAs is included in the assessment section later in this report as appropriate. The responses provided by EDF and AREVA to these actions supplied a number of deliverables which contribute significantly to the overall Reactor Chemistry safety case for UK EPR.

2.3.2 Technical Queries

22 A total of 151 Technical Queries (TQs) were raised with EDF and AREVA for the Reactor Chemistry assessment, 137 during Step 4. Refer to Ref. 8.

23 EDF and AREVA completed responses to all of the Reactor Chemistry TQs, however, some were not provided in time for incorporation into the Step 4 assessment. These gaps have resulted in Assessment Findings or Issues as appropriate.

24 The responses provided by EDF and AREVA to the TQs were assessed by ND during Step 4. 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 Reactor Chemistry safety case for UK EPR.

2.3.3 Technical Meetings

25 As part of the Step 4 planning process a series of technical meetings were arranged with EDF and AREVA. These meetings occurred at regular intervals throughout 2010 when most of the Step 4 assessment took place. Approximately 30 days of main technical exchange meetings were undertaken during Step 4, in addition to numerous teleconferences and smaller meetings, as necessary.

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

27 Further meetings were also attended in cross-cutting areas with other assessment areas in GDA; most notably with severe accidents, radwaste and decommissioning and radiation protection.

2.3.4 TSC Outputs

28 As detailed in Section 2.5.4, a number of technical support contracts were placed in technical areas which align with the Step 4 Reactor Chemistry assessment topics. 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 Step 4 assessment of UK EPR undertaken by ND and are an input into the conclusions of this report.

29 Further details of the TSC contracts are provided in Section 2.5.4, and Ref. is made to the most important and relevant TSC contracts in the assessment section of this report, as appropriate.

2.4 Standards and Criteria

30 The following section outlines the relevant standards and criteria that have informed the Reactor Chemistry assessment during Step 4.

2.4.1 Safety Assessment Principles

31 Of all of the standards and criteria that inform the assessment, it is the selection of the relevant Safety Assessment Principles (SAP) (Ref. 4) that plays a key role in determining the scope of assessments in ND. The SAPs considered relevant to the Step 4 assessment are listed in Table 1. These SAPs are focussed on the functions and systems leading to the largest hazards or risk reduction and are similar to those considered throughout the Step 3 assessment.

2.4.2 Other ND Guidance

32 Assessment was conducted to relevant ND internal standards and guidance (Refs 2 and 3 and Table 2).

2.4.3 External Standards and Guidance

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

34 The International Atomic Energy Authority (IAEA) has prepared a standard on Reactor Chemistry (Ref. 21). Although authoritative, wide-reaching and consistent with the assessment conducted for GDA Step 4, this document was only available as a draft issue during the Step 4 assessment, although it has recently been fully issued (Ref. 22), and as such is only suitable as advisory guidance. Similar guidance is also available for the Spent Fuel Pool (Ref. 23), containment systems (Ref. 24) and for defining limits and conditions of operation (Ref. 25) and these were similarly used as advisory during the assessment.

35 During Step 2 of the UK assessment the IAEA conducted a review of the Preliminary Safety Report for EPR and I examined output from the IAEA review (Ref. 26). IAEA considered the Preliminary Safety Review (PSR) did not address the following aspects of the fuel in sufficient detail: swelling, chemical effects, maximum centreline temperature, Fission Product (FP) release. Some of these aspects are discussed in this report in sub-sections covering lithium, hydrogen, crud and accidents.

36 A large number of operating Pressurised Water Reactors (PWRs) worldwide base their chemical specifications on standards and guidance produced by industry bodies like the Electric Power Research Institute (EPRI) (Refs 27 and 28) and the German Federation of Large Power Station Operators (VGB Powertech) (Ref. 29). Some of these documents are authoritative and contain detailed justifications for the recommendations made, whilst other simply list limits and action levels. They are also generally based around operational aspects, which tend to mean the focus is on commercial or other concerns rather than safety explicitly. As such they have been used as advisory guidance.

37 A review of levels defined by the Western European Nuclear Regulators' Association (WENRA) (Ref. 6) found none specific to Reactor Chemistry.

2.5 Assessment Scope

38 Historically, Reactor Chemistry was poorly controlled in early Pressurised Water Reactors (PWRs) which gave rise to a number of safety issues related to structural integrity, fuel damage and high radiation fields as might be expected. Subsequently, recognition of the importance of proper chemical control led to great improvements in each of these areas and modern PWRs would be expected to operate under a regime where due consideration has been given to such problems and controls are available to limit their occurrence.

39 In line with the definition, methodology and approach for the Step 4 Reactor Chemistry assessment, the assessments of Reactor Chemistry concentrated on chemical processes that:

- May cause an uncontrolled variation in core reactivity.
- May threaten the containment of nuclear matter.
- Contribute to operator radiation exposure.
- Generate radioactive waste and discharges.
- Determine source terms for severe accident analysis.

40 Due to the nature of the GDA process, it was not considered feasible or realistic for EDF and AREVA to be able to fully define the chemistry that may be used at this stage as there will also be the need for Licensee input for a specific site. In fact, it was considered beneficial not to compel EDF and AREVA to precisely define every aspect of UK EPR chemistry at this stage due to the likely changes in 'good' practice that may occur between GDA and operation of any reactor. However, the Step 4 assessment was based on what the 'expected' UK EPR chemistry regimes would be (i.e. a baseline case), with further Licensee specific development required during Phase 2 (licensing). The Step 4 assessment also included the provision to identify a range around this 'baseline' such that potential 'cliff edge' effects are avoided.

41 Detailed site specific aspects and commissioning were excluded from the Step 4 chemistry assessment and are to be considered during Phase 2.

42 The following section outlines the scope of the Reactor Chemistry assessment conducted during Step 4 in more detail.

2.5.1 Assessment Topics

43 The Reactor Chemistry assessment topics identified for Step 4 were those which I believed, based upon the assessment conducted during Step 3, held the greatest safety significance and therefore potentially could have the largest impact on the generic design. These were the same to those identified for the Step 3 assessment. These are presented in Table 3, which also includes a brief description of the assessment objective for each identified topic.

44 The original intent was to allow some flexibility in the assessment conducted during Step 4, whilst still meeting the overall objective of undertaking a targeted and proportional assessment of the UK EPR safety case. For instance assessment in the other ND

technical areas, may lead to the need for additional Reactor Chemistry support. Similarly, progress during Step 4 may indicate that some topics require more assessment than others, due to weaknesses or deficiencies in the evidence provided by EDF and AREVA. This original intent was found to be adequate and the originally identified topics were those assessed during Step 4.

45 These were assessed according to the assessment plan (Ref. 1) and according to the approach described in Section 2.3, in order to form an informed position on whether the assessment objective had been met based upon the evidence presented by EDF and AREVA.

2.5.2 Findings from GDA Step 3

46 The Step 3 Reactor Chemistry Assessment Report (Ref. 7) conclusions are given in Table 4.

47 Overall the arguments presented during Step 3 were reasonable; however they were generally at a high level. Much of the information presented was outside the main submission and the PCSR was found to be lacking in a number of key areas in relation to Reactor Chemistry.

48 It is worth noting that none of the other disciplines assessed during Step 3 raised any additional issues related to Reactor Chemistry during their Step 3 assessment work.

2.5.3 Additional Areas for Step 4 Reactor Chemistry Assessment

49 Assessment during Step 4 largely followed up the Step 3 assessment report (Ref. 7). No additional technical areas, outside those examined during Step 3, were assessed during Step 4.

2.5.4 Use of Technical Support Contractors

50 Technical Support Contractors (TSCs) were engaged to assist with the Reactor Chemistry assessment work undertaken during Step 4.

51 In general the TSCs were contracted to undertake detailed technical reviews of EDF and AREVA submissions in discrete technical areas which aligned closely with the ND assessment topics identified for Step 4. In some instances an initial ‘good practice’ review was also undertaken, based upon publically available information, to inform ND and the TSC and to provide a transparent basis for the subsequent RP specific review. The outputs from these reviews are reports summarising the technical review and providing expert conclusions and recommendations. All TSC work was undertaken under close direction and supervision by ND and in line with the overall assessment plan for Step 4 (Ref. 1). Collectively, our TSC generated over 1500 pages of reports, summarising various aspects of the design of UK EPR.

52 While the TSC provide an input into the Step 4 assessment, the regulatory judgment on the adequacy or otherwise of the UK EPR Reactor Chemistry safety case was made exclusively by ND. The TSC outputs were used as an input to this decision making process.

53 The TSC reports are referenced in this report under the relevant assessment section, as appropriate.

54 Visibility of TSC work and feedback on progress and outcomes of TSC work was provided to EDF and AREVA throughout Step 4.

2.5.5 Cross-cutting Topics

55 As a discipline, chemistry is not alone in its potential for impact across reactor designs and hazard types. To cope with these interactions some functions or plant areas had a lead inspector coordinating effort. These topics are by their nature ‘cross-cutting’ and Reactor Chemistry contributed to the following, as detailed throughout the assessment:

- Severe Accidents (incl. core catcher)
- Categorisation and Classification
- Limits and Conditions
- Design Reference
- Definition of Scope
- Boron Dilution
- Smart Instruments
- Source Terms

56 None of these areas impinged significantly on the chemistry assessment planned for Step 4 and the assessment conducted, and described in this report, contributed to the overall ND regulatory position on these topics.

2.5.6 Integration with Other Assessment Topics

57 Reactor Chemistry is an area which interacts with a number of other GDA technical assessment disciplines. Principal amongst these are the radiation protection, structural integrity, fault studies and radwaste and decommissioning areas where chemistry could have a direct impact on consequences and hence safety. For all the disciplines there was an appropriate coordination between technical areas to ensure that the regulatory effort is proportionate and targeted. The Step 4 Assessment Plan (Ref. 1) contains a matrix that captures areas for assessment co-ordination during Step 4 of the GDA process.

2.5.7 Out of Scope Items

58 The following items have been agreed with the RP as being outside the scope of GDA and as such influenced the scope of the Step 4 Reactor Chemistry assessment:

- Use of Mixed Oxide (MO_X) fuel.
- Detailed site specific aspects; which include construction, commissioning and site-specific operational matters such as marine fouling.
- The implications and design provisions for any routine load-following.
- Mid-loop working.
- Aspects of the secondary circuit design, as defined in Section 4.4.

- Conventional chemical hazards; for example the application of the Control of Substances Hazardous to Health (CoSHH) and the Dangerous Substances and Explosive Atmosphere Regulations (DSEAR).

3 EDF AND AREVA'S SAFETY CASE

59 The EDF and AREVA safety case for UK EPR is based around a Pre-Construction Safety Report (PCSR), Pre-Construction Environmental Report (PCER) and supporting documentation, as identified in the Submission Master List (SML) (Ref. 175).

60 The safety case used as the basis of the Step 4 assessments was that submitted during November 2009 (Ref. 11). The PCSR in this submission was not formally updated until the final consolidated GDA submission was produced in March 2011. This PCSR was produced in June 2009 and was the same as that used during Step 3 from a Reactor Chemistry perspective; as such the comments made at the end of the Step 3 assessment remain valid for the Step 4 submission.

61 During Step 4 the safety case for Reactor Chemistry in UK EPR was subject to two significant updates, namely:

- Production of a draft Reactor Chemistry Chapter (February 2011) – In response to my assessment during GDA, EDF and AREVA agreed to produce and incorporate information related to Reactor Chemistry into the PCSR. They presented their plans for the new chemistry chapter in UK EPR during the autumn of 2010. This was incorporated as a sub-chapter to Section 5 of the PCSR, "*Reactor Coolant System and Associated Systems*", with sub-chapters dealing with the primary and secondary circuit water chemistry requirements. This chapter was received in draft in February 2011 (Ref. 103).
- Production of a consolidated PCSR (March 2011) – At the end of Step 4 EDF and AREVA produced a "*consolidated*" PCSR, the purpose of which was to incorporate all the relevant Step 4 assessment into the UK EPR safety case. This included all GDA assessment areas, including Reactor Chemistry. This PCSR was received at the end of March 2011 (Ref. 105).

62 General commentary on the EDF and AREVA safety case for UK EPR is provided in the following sections, with more detailed commentary on specific aspects given in the assessment sections of my report as appropriate; see Section 4. The commentary that follows uses a chronological approach, first describing the Step 4 PCSR, then the draft Reactor Chemistry Chapter and finally the consolidated PCSR.

3.1 Step 4 Submission (November 2009)

63 The following commentary is based on the Step 4 PCSR (November 2009) submission only (Ref. 11). In addition to responses to TQs and ROs, these documents are the basis for the Step 4 assessment. The following presents a high-level overview of the safety case, with more detailed assessment of the safety case presented in the subsequent sections of this report.

64 Subsequent references to the PCSR later in the assessment sections (Section 4 onwards) of my report refer to this revision of the PCSR, unless stated otherwise.

3.1.1 Structure

65 The EDF and AREVA safety case for UK EPR was contained within a PCSR (Ref. 11) which contains claims and some arguments, but very scant evidence with some references out to supporting documents. The UK PCSR was developed from a Preliminary Safety Review (PSR) originally produced for the French Nuclear Safety

Authority, ASN (Autorité de sûreté nucléaire), and does not contain a dedicated section on chemistry. As such the most significant evidence lies in documents outside the PCSR and the most useful information for the Step 4 assessment of Reactor Chemistry has been obtained in response to ROAs and TQs and from discussions with experts in EDF and AREVA.

66 While it was clear that EDF and AREVA have a sound understanding of Reactor Chemistry, and I expect this will eventually translate to safety improvements in UK EPR, it is apparent that the formal presentation of safety claims, arguments and evidence involving chemistry, and for providing an auditable trail identifying responsibilities, was incomplete in the PCSR as presented. The omission of much chemistry related information from the PCSR was a clear failure to meet my expectations for a UK safety case. This was the subject of an ROA during Step 4 (RO-UKEPR-44.A4, Ref. 9) which resulted in development of a specific Reactor Chemistry Chapter to address many of these aspects. This is discussed later in Section 3.2.

67 Since the Step 4 PCSR did not contain a dedicated section on Reactor Chemistry and chemistry interacts with many systems, structures and components throughout the entire plant, precise references to the PCSR are provided within later subsections of this report. Table 5 lists the main sections of the Step 4 PCSR relevant to Reactor Chemistry.

3.1.2 Content

68 As indicated above, the vast majority of Reactor Chemistry content was outside the PCSR, however some general comments can be made on the content of the Step 4 submission:

- The overall claims-argument-evidence structure of the PCSR is weak from a Reactor Chemistry perspective, with much information related to safety during normal operations lacking. Further documentation is required to fully substantiate the ‘evidence’ stage of the assessment. It is apparent that the ‘evidence’ that is currently presented is very much biased towards operational experience with other reactors. This is a valid input to an evidence based argument, but should be balanced with other evidence, such as calculations or modelling, where appropriate. The lack of theoretical or quantitative analyses weakens some arguments, especially where UK EPR differs and this balance will need to be addressed as part of the safety case development.
- EDF and AREVA provided little information on the chemistry of the primary circuit. No evidence was provided in relation to a number of key safety concerns related to the selection of primary circuit chemistry parameters and their interaction with radioactivity, structural integrity and fuel protection. The use of enriched boric acid in UK EPR represents a specific difference in the design where the safety case is lacking in information on how this important material is controlled and monitored.
- The PCSR is significantly lacking in information for a number of secondary circuit systems, some of which are important to the Reactor Chemistry safety assessment. The PCSR also contains very little information on the chemistry associated with many other safety relevant systems in the UK EPR design including:
    i) Component Cooling Water System (CCWS)
    ii) Chemistry requirements associated with the Spent Fuel Pool (SFP) and connected systems, such as the In-containment Refuelling Water Storage Tank (IRWST)
    iii) Safety systems, such as the Extra Boration System (EBS)

- EDF and AREVA have clearly put a lot of effort and development into the design basis and severe accident areas. However, there is a lack of information on how chemistry has been applied specifically to the UK EPR design and a number of the assumptions and modelling approaches taken are somewhat opaque in many instances.
- The As-Low-as-Reasonably-Practicable (ALARP) case presented only considers the major hazards from the plant; no consideration was presented for routine activities which affect operator radiation exposure, waste generation or environmental discharges. This is considered more of a presentational issue with the PCSR, rather than deficiencies in the design, and should be addressed as the safety case is developed.

3.1.3 Summary

69 While sufficient for Step 3, the PCSR was insufficient from a Reactor Chemistry perspective for assessment during Step 4, lacking much of the arguments and evidence necessary for assessment. As such, many of the deficiencies highlighted above were the subject of ROs during Step 4, in order to provide the requisite evidence to conduct the assessment. This evidence was assessed as part of Step 4, and has resulted in the development of a new PCSR sub-chapter which is discussed further in Section 3.2.

3.2 Draft PCSR Reactor Chemistry Chapter (February 2011)

70 The following section describes the draft PCSR Chemistry Chapter submitted in February 2011 (Ref. 103). This chapter is the draft version of that submitted as part of the consolidated GDA submission, see Section 3.3 below.

71 EDF and AREVA submitted an “*outline*” draft of the PCSR Chapter in response to RO-EPR-44.A4 (Ref. 9) in December 2010 (Ref. 104), containing the structure of the proposed chapter with little of the detailed text. I discussed this structure with EDF and AREVA during Step 4.

72 EDF and AREVA claim that the information contained in this draft chapter is based upon the TQ and RO responses and as such should be consistent with the detailed assessment of UK EPR that follows in Section 4 of my report.

3.2.1 Structure

73 The draft Chemistry Chapter is a completely new Section 5.5 of the PCSR. This chapter contains information on the main primary and secondary circuit systems, in separate sections, covering the operating chemistry. It does not cover auxiliary circuit chemistry, accident chemistry or related issues such as operational strategies and construction and commissioning and, under the main Section 5 (Reactor Coolant System and Associated Systems), this would not appear appropriate. Some of these later aspects may be covered in other sections of the overall PCSR, but this cannot be confirmed from the draft PCSR Chemistry Chapter alone. Fundamentally, the addition of this sub-chapter is an immediate and significant improvement in the safety case assessed during Step 4, but this only presents the normal operating chemistry requirements for the plant.

74 Both the sub-sections which deal with the primary and secondary circuit chemistry have a similar content, so the following applies equally to both, unless stated otherwise.

- Initially the ‘claims and arguments’ for the operating chemistry are presented. These claims are relatively high level, such as “*integrity of the first barrier* [fuel cladding]” or “*reduce the radiation fields*”, but do broadly cover the main safety claims I would expect to see for Reactor Chemistry in an operating reactor. The corresponding arguments again are reasonably presented; for example “*integrity of the first barrier* [fuel cladding]” cites minimising fuel crud deposition (via zinc, hydrogen, pH control and limiting impurities) and minimising fuel cladding corrosion (via alloy selection and fuel failure monitoring) as the main arguments for how the chemistry is influencing the claim. As with the overlying claims, the arguments as presented appear reasonable.
- The main bulk of the sub-sections are the ‘evidence’ supporting the initial claims and arguments. In fact, these are actually more detailed arguments, with most of the evidence likely to be found in references. The draft (Ref. 103) contains no specific reference section, but does indicate that a number of the reports provided as part of the GDA ROA responses may be referenced. The level of detail appears reasonable for a PCSR, but the links to references is of obvious importance. This sub-section is also organised in a slightly different way, presenting each of the main parameters (i.e. boron, pH, hydrogen etc.) and then the ‘evidence’ for their impact on whichever of the claims they influence. This is perhaps a more sensible way of presenting the information, rather than trying to link to the claims which would repeat many sections due to the interrelation of many of the chemical parameters. These are also usefully summarised in tabular form. The final version (Ref. 105) does contain the references.
- The final sub-section provides an “*identification and classification*” of the safety significant chemical and radiochemical parameters. This summarises what the expected “*control*” and “*diagnostic*” parameter are for UK EPR, for each of the main areas such as integrity, Operator Radiation Exposure (ORE), wastes etc.

75 A further sub-section provides information on the controls which are expected for chemical parameters in UK EPR, defining the idea of “*control*” and “*diagnostic*” parameters, “*action levels*” and “*expected values*”.

76 The final sub-section tabulates the preliminary primary and secondary parameters. These are essentially the chemistry “*limits and conditions*”, and provides some indication of the values.

3.2.2 Content

77 As for the Step 4 submissions, some general comments can be made on the draft PCSR Chemistry Chapter:

- The overall claims-argument-evidence structure is much improved, presenting a logical and structured description of the plant chemistry influences on safety. At this stage of GDA the level of detail presented appears reasonable, and does not stray into too much technical background or detail. While not presented completely in the draft PCSR, the link to the detailed references will be important. EDF and AREVA need to link to the specific analysis conducted throughout GDA, for example on fuel crud and tritium control, as appropriate. Ref. 105 provided the references after this report was written. Even from the draft, it is clear that the presented information is specific to UK EPR, rather than PWRs in general.
- In terms of the “*scope*” of the chapter (Reactor Coolant System and Associated Systems), the content appears comprehensive and reasonable. Others areas where Reactor Chemistry can influence the plant safety, as described in Section 3.2.1, need to be included in the PCSR as a whole.

- The chapter does not present the safety Classification and Categorisation for the chemistry relevant systems. These were presented outside the chemistry chapter in Subchapter 3.2 of the new PCSR. I was content with the classification and categorisation of the systems on the basis of the content described in Section 3.2.1.
- The chapter presents useful information on chemistry related limits or conditions for the safe operation of the plant. As an overall 'output' from the safety case in the chemistry area, this is summarised in the chapter. While preliminary, and not assessed in detail, the identification and classification of the parameters is an important stage in the development of the safety case, and ultimately plant operating procedures. The structure and content lends itself to understand how these have been derived through the claims-arguments-evidence structure.

3.2.3 Summary

78 Overall, the draft chapter is much improved on the Step 4 submissions and EDF and AREVA should take credit for the significant improvement to the UK EPR safety case for Reactor Chemistry that this represents. While the scope of the chapter does not embody all of the Reactor Chemistry expected throughout the safety case, as presented it makes a reasonable case for the normal operating chemistry of the main primary and secondary circuits.

3.3 Consolidated GDA Submission (March 2011)

79 The following section describes the consolidated PCSR submissions submitted in March 2011 (Ref. 105). This submission includes a new revision to all of the PCSR chapters and includes a number of new sub-chapters, all of which were included by EDF and AREVA in response to the GDA assessment, including the incorporation of the draft PCSR Reactor Chemistry Chapter from February 2011 (Ref. 103), see Section 3.2 above.

80 EDF and AREVA summarised the changes made for the consolidated PCSR in letter EPR00844N (Ref. 188). The consolidated PCSR updates the Step 4 PCSR (November 2009), taking account of:

- Introduction of supplementary technical information arising from responses to Regulator Queries (Technical Queries, Regulatory Observations, Regulatory Issue and Technical Meeting Technical Actions)
- Inclusion of additional Supporting References in the PCSR, for relevant supporting documents transmitted to the Regulators in response to Regulator Queries
- Inclusion of key recommendations from the Design Safety Review Committee and Independent Safety Reviews by EDF and AREVA.
- Consistency with relevant Design Changes
- Minor editorial changes
- Consistency with the updated PCER
- Organisational and procedural changes

81 In addition EDF and AREVA provided a "*Route Map*" which detailed the technical changes made to the consolidated PCSR relative to the previous version of the PCSR submitted in November 2009.

82 As my Step 4 assessment was based on the Step 4 PCSR (November 2009) and TQ/RO responses, the consolidated PCSR should accurately reflect these. As part of my Step 4 assessment I sampled several chapters of the consolidated PCSR to confirm this. This was not a detailed technical review, but was intended to be a factual accuracy and completeness check to confirm or otherwise that the consolidated PCSR accurately reflects the GDA assessment and that the incorporated response information was appropriately reflected.

3.3.1 Structure

83 The overall structure of the consolidated PCSR remains very similar to the Step 4 PCSR, with the notable addition of the Reactor Chemistry Chapter in Sub-section 5.5.

3.3.2 Content

3.3.2.1 Chapter 5.5 – Reactor Chemistry

84 Much of my review of the consolidated PCSR concentrated on the Reactor Chemistry Chapter 5.5. The formal issue of this chapter (Ref. 105) is not significantly different from the draft version submitted in February 2011 (Ref. 103), so the comments made in Section 3.2 above apply. Aside from minor changes to improve language, clarity etc. the only substantive changes of note are:

- Some changes to the presentation of arguments for secondary circuit chemistry. This removes some of the emphasis from Flow Accelerated Corrosion (FAC) and generally appears to improve the case presented for this area, by offering a more balanced approach. The underlying evidence remains that presented during Step 4.
- Some of the Limits and Conditions presented have changed. This will not affect my Step 4 assessment as I did not assess these in detail during GDA (see Section 4.1.3) and these are listed as “*preliminary*”.
- Removal of the section on “*action levels*”. This does not substantially affect the claims-arguments-evidence as presented and does not impact on the Step 4 assessment I have completed, as described in Section 4.

85 I reviewed Chapter 5.5 against the responses to TQs and ROs I asked during Step 4 (see Refs 8 and 9). I was content that EDF and AREVA had adequately included the information from these responses into the chapter and had identified those most relevant for inclusion. The overall content adequately represents the responses I assessed throughout Step 4.

86 The references to Chapter 5.5 of the consolidated PCSR appear appropriate and are mainly RO responses and system manuals. EDF and AREVA did prepare 5 new references for the chapter, none of which were available to ND before the consolidated PCSR was produced; however, these appear to be summaries of various TQ responses received during Step 4. While it has not been possible to review these in detail due to their size, I am content that they do not contain any new information. This is confirmed by EDF and AREVA in letter EPR00841N (Ref. 124) which states that “*These reports do not delineate any new or previously un-submitted information*” and includes an appendix which indicates which TQs have been summarised in the various references.

87 EDF and AREVA also indicate 2 references which have not yet been produced. These appear to be the responses to RO-UKEPR-74.A2 and A3 (Ref. 9), neither of which were

received during Step 4 and are subject of GDA Issue **GI-UKEPR-RC-02**, see Section 4.3.2.7 of my report that follows.

3.3.2.2 Other Relevant Chapters

88 In addition to the Reactor Chemistry Chapter I also reviewed a sample of other chapters, both where EDF and AREVA had indicated that some of my TQ and RO responses had been included and where my assessment had overlapped with the content of these chapters. This mainly involved those chapters related to limits and conditions (18.2) and accidents (16.2 and 16A). The incorporation of responses in these chapters appears reasonable. In general changes to these chapters from those assessed during Step 4 were minimal and have no effect on my assessment that follows. While Chapter 18.2 was updated significantly, this was consistent with the response to RO-UKEPR-55 (Ref. 91), assessed in Section 4.1.3 of my report.

89 As per Section 3.1.2 above, I noted that the Step 4 PCSR (Ref. 11), from November 2009, did not contain information on a number of chemistry relevant systems (such as the SFP and IRWST). I also note that the Reactor Chemistry Chapter only relates to the primary and secondary circuits. The consolidated PCSR does not incorporate any changes in this regard from the Step 4 (November 2009) PCSR. There are a number of Assessment Findings later in my report related to these aspects.

3.3.3 Summary

90 The Step 4 assessment for Reactor Chemistry commenced with consideration of the relevant chapters of the PCSR and supporting references available at that time, and these are referred to as appropriate in this report. As the GDA submission developed during Step 4, in response to my regulatory questions, amendments were made as appropriate to the PCSR and its supporting references. A review has been made of the updates to the GDA submission in my technical topic area and the conclusion of this review is that:

91 The updates to the GDA submission are as expected and contain no new information. The consolidated PCSR (Ref. 105) and its supporting references are therefore acceptable as the reference point for an Interim Design Acceptance Confirmation (IDAC).

3.4 Assessment Findings

92 Based upon the assessment of the UK EPR safety case as described in Section 3 above, I have identified no general Reactor Chemistry Assessment Findings for the UK EPR safety case overview.

3.5 GDA Issues

93 Based upon the assessment of the UK EPR safety case as described in Section 3 above, I have identified no Reactor Chemistry GDA Issues in this area, but there is a cross-cutting GDA Issue concerning the assessment of the PCSR, **GI-UKEPR-CC-02**, see Ref. 197, which requires a satisfactory resolution before an adequate Reactor Chemistry safety case can be made:

> ***GI-UKEPR-CC-02** – Consolidated Final GDA Submission Including Agreed Design Change for the UK EPR – EDF and AREVA to continue to control, maintain and develop the GDA submission documentation, including the SSER, SML and design*

reference document and deliver final consolidated versions of these as the key references to any DAC/SODA ONR or Environment Agency (the joint Regulators) may issue at the end of GDA. These should include the management and acceptance of changes to GDA submission documentation impacted by design changes agreed for inclusion in GDA.

4 GDA STEP 4 NUCLEAR DIRECTORATE ASSESSMENT FOR REACTOR CHEMISTRY

94 The following sections detail the specific assessment undertaken for each of the main technical areas identified for Reactor Chemistry in Step 4.

95 Each section follows the same outline structure:

- Firstly, a summary of the assessment is provided, detailing the work undertaken, external inputs into this assessment (e.g. TSC reports), the principal RP deliverables reviewed and the conclusions of the assessment. As each main technical area may be further divided into sub-topics this first section may contain several sub-sections.
- Secondly, if appropriate, a summary of the Assessment Findings in that area is given.
- Finally, if appropriate, a section summarising the GDA Issues in that area is given.

4.1 Chemistry Standards, Limits and Conditions

4.1.1 Overview

96 Chemical standards are used to define the chemistry around reactor circuits to ensure that the levels of purposeful additions and potentially deleterious impurities are maintained within acceptable limits. The derivation of an acceptable chemical regime is a key step in assuring the safety of reactor operations. A significant percentage of the world’s reactor operators make use of external guidance, such as the EPRI (Refs 27 and 28) or VGB guidelines (Ref. 29), in determining the most appropriate chemical regime.

97 As indicated in Section 2.5, it was not the aim of the assessment to compel EDF and AREVA to devise and detail the exact UK EPR chemistry regimes at this stage of a potential new build project. The focus was instead on understanding how this will be done, building upon the safety case that has been presented during GDA, and how a prospective Licensee would be able to determine the relative importance of the various parameters that would constitute a chemistry standard.

98 Details of the expected chemistry regimes for the various plant systems have been provided in numerous documents supplied in response to TQs and ROAs during Step 4. The assessment of these particular regimes is not discussed under this section, but later in this report under the appropriate sections of the assessment. Notwithstanding the above, the Licensee of a UK EPR will be required to fully define and justify the operating chemistry regimes to be applied in the various plant systems. I consider this to be an Assessment Finding **AF-UKEPR-RC-01**. This finding also relates to other conclusions in this report which highlight the importance of specifying detailed chemistry requirements for fabricators and licensee staff.

99 An important related topic is the derivation and definition of Limits and Conditions. These define the safe operating envelope of the plant, specify the controls that are in place to ensure an unsafe condition is not reached and the actions to be taken if one is approached. For this reason, the EDF and AREVA approach to Reactor Chemistry in this important cross-cutting topic is also discussed in this section.

4.1.2 Assessment – Chemistry Standards

100 During Step 3, the assessment in this area concentrated on exploring the proposed chemical standards for the design, how these were being derived and approved and how the design has been influenced by these standards. Based on the information available to

me at that time it appeared that the mechanism for developing the UK EPR chemistry standards was based around a EDF and AREVA derived approach termed 'Chemical and Radiochemical EPR Design Optimisation' (CREDO). EDF and AREVA claimed that this approach was developed based upon existing EDF and international experience and to take account of the specific differences in the EPR design compared to the latest generation of EDF PWRs. CREDO takes into consideration a number of factors that are directly relevant to the current assessment, namely; nuclear safety, radiological protection, protection of assets (which from a safety point of view I have taken to mean ‘mitigation of damage and failures’), optimisation of effluents and solid wastes production and optimising maintenance requirements.

101 In effect, CREDO is a formalised version of the process that was applied in the UK (and elsewhere) to develop reactor specific standards based on in-house expertise and experience.

102 Overall, at the end of Step 3 I was satisfied that CREDO appeared to be an appropriate methodology for improving the design for chemistry and it was also clear that the CREDO approach had led to design improvements to the original EPR design which have been carried through to Flamanville 3 (FA3) and subsequently UK EPR. However, it was also clear that this approach would not lead directly to chemistry standards for UK EPR, and this aspect was assessed further during Step 4.

103 Similarly, what was not apparent during Step 3 was the link between chemistry standards and the UK EPR safety case for chemistry and this was a key line of enquiry which was explored with EDF and AREVA during Step 4.

104 Chemistry can be a somewhat subjective topic to apply when considering the importance of chemistry parameters to limits, conditions, criteria, levels and so forth. A few chemistry parameters have a direct and immediate impact on reactor safety, and as such would be expected to appear in the top tier of limits and conditions, while rather more have a slower effect on reactor safety, albeit with similar consequences and are often ‘classified’ at a lower level. The treatment of this latter group of chemistry parameters within the safety case is also important as these can often influence other related hazards such as ORE and waste production. Overall, our expectations were for the UK EPR safety case to demonstrate that all safety significant chemistry parameters had been captured and the relative importance of these to plant safety was presented or could be inferred by a potential Licensee from the documentation.

105 A TSC contract (Ref. 32) was let to examine the application of chemistry standards across the nuclear industry and to undertake a technical comparison of the recommendations provided in the various guidelines. The conclusions from this review are consistent with the assessment that follows.

106 TQ-EPR-690 (Ref. 8) queried how chemistry related conclusions from the safety case would be transferred to an operational UK EPR, based upon the responses provided on the CREDO approach. The response provided a general overview of the current EDF approach to developing chemistry standards, based upon the French regulatory system. The approach suggested described the suite of documentation that would define the chemistry of UK EPR and indicated that careful consideration had been given to the ‘classification’ of the various chemistry parameters, with some falling under the top tier “*Operating Technical Specification*” level and other being linked to the other potential hazards such as ORE or environmental releases. Although the response indicated that such decisions are site and Licensee dependant, the approach suggested provided a degree of confidence that the results of such an undertaking would yield a satisfactory link between the safety case and operating documents.

107 As the UK EPR chemistry standards are most likely to be based upon existing EDF standards it is likely that they will follow a similar structure and include "*action zones*" which limit the duration that a given parameter can spend outside of the expected range. As EDF and AREVA make claims that the design of UK EPR will allow equivalent or better control over chemistry parameters compared to existing reactors, TQ-EPR-155 (Ref. 8) was raised to understand if any modifications were anticipated on the historically used 'action zone' boundaries specifically for UK EPR based upon Operator Experience Feedback (OEF, i.e. evidence of learning from experience in defining chemistry standards). EDF and AREVA provided two responses to this TQ, dealing with the primary and secondary chemistry separately.

108 For the primary side data was provided for the four most modern French N4 plants (Chooz 1 and 2 and Civaux 1 and 2) as these are the most representative of likely EPR operations. Current EDF practice is to define three "*Operating Technical Specification*" parameter groups for the primary coolant chemistry; impurities (sodium, chloride and/or fluoride and sulphate), hydrogen and the lithium-boron coordination. Each set has defined 'action zones' which instruct the operators in the management of the plant and remedial actions to be taken:

- Zone 1 (Expected Value) – This zone corresponds to the target value for the parameter to meet the full design intent of the plant.
- Zone 2 (Limit Value) – When a parameter enters Zone 2 from Zone 1, the operator is expected to take corrective action to return to Zone 1. It is recommended to return to Zone 1 as soon as possible, although this need not take priority over other plant operations and no specific time limit is applied.
- Zone 3, 4 and 5 are above the 'normal' operating limits (Zones 1 and 2) defined for each parameter. Specific restorative actions must be taken within defined timescales when in these zones, dependant upon the parameter and zone. When a parameter enters Zone 3, 4 or 5, the operator usually still has the opportunity to carry out actions to return to Zones 1 and 2. Timescales are generally 'days' for Zone 3 and 'hours' for Zone 4. Zone 5 is restricted to 1 hour. Failure to return to normal operations (Zones 1 and 2) in the specified time requires a plant shutdown.

109 The response provides data from the aforementioned N4 plants, which shows very limited excursions above Zone 1 and 2 values, and even then mainly to Zone 3. Information is also provided on the reporting and management arrangements regarding analysis of such out of specification events. While it would be inappropriate to comment on the detailed data presented, the response does demonstrate that such a system may be reasonable and appropriate for a UK EPR. The precise values and timings could be defined at a later stage. Similar data is also presented for the secondary circuit conductivity/sodium values, which supports the above.

4.1.2.1 Summary

110 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of chemistry standards in UK EPR are:

- EDF and AREVA have described a proposed basis for developing chemistry standards for UK EPR, including chemical specifications and associated chemistry documentation.
- Although it is the Licensee who will eventually determine and justify the chemistry standards approach for UK EPR, I am encouraged that the approach suggested

appears a reasonable compromise and should yield acceptable results, notwithstanding the specific comments made later in this report. I note several areas where further work will be required to complete the safety case in this assessment area and have raised Assessment Findings to cover these. I am satisfied these can be resolved post GDA.

111 Overall, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.1.2.2 Assessment Findings

112 Based upon the assessment of chemistry standards in UK EPR described in Section 4.1.2 above, and from other sections of this report, 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-01*** *– The Licensee shall specify the normal operating chemistry regimes for the primary, secondary and auxiliary circuits of UK EPR. The specifications should be comprehensive and incorporate evidence for all modes of operation. The regimes should be consistent with the plant safety case, particularly the limits and conditions required by AF-UKEPR-RC-02. This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Cold Ops.*

4.1.2.3 GDA Issues

113 Based upon the assessment of chemistry standards in UK EPR described in Section 4.1.2 above, I have identified no Reactor Chemistry GDA issues in this area.

4.1.3 Assessment – Limits and Conditions

114 An important input to the development of chemistry standards, and a vital part of any nuclear safety case, is the definition of plant specific limits and conditions. The prime purpose of setting limits and conditions is to prevent operation in unsafe conditions and to limit the consequences of accident conditions should they arise. The safety case should define what these conditions are and how the plant is operated and controlled to maintain within them. From a Reactor Chemistry perspective this should include limits for the operational chemistry.

115 RO-UKEPR-55 (Ref. 9) was issued to EDF and AREVA as a cross-cutting RO requesting evidence of how limits and conditions specific to UK EPR would be developed. The RO specifically made reference to chemistry related parameters and the response provided a section detailing ‘Chemical and Radiochemical Specifications’. Much of the response to this RO (Ref. 91) dealt with aspects which, although related, were not directly within the remit of the Reactor Chemistry area such as plant loading conditions, periodic testing, inspection and maintenance. A summary of my assessment of this response, as applicable to Reactor Chemistry, is provided in the following paragraphs. I also undertook a TSC contract to review the EDF and AREVA response to RO-UKEPR-55, specifically for chemistry (Ref. 33). The conclusions from this review are consistent with the assessment that follows.

116 The response does provide further details of the links between the limits and conditions (referred to as "*Operating Technical Specifications*" (OTS)) and the UK EPR safety case presented for GDA. EDF and AREVA indicate that the responsibility for the definition of precise OTS values, actions and timescales resides with the Licensee, which I agree is a reasonable position for GDA. However, I would also expect EDF and AREVA to be able to identify those which are already included within the safety case at this stage of GDA, even if the various values associated with them are not precisely known at present. It is important that any potential Licensee can identify the importance of chemistry control from the PCSR and supporting documents.

117 In the response EDF and AREVA provide a rationale for the selection of chemistry parameters which are relevant to limits and conditions. This is the same basis presented in the response to TQ-EPR-155 (Ref. 8), building upon the TQ response, and I consider this to be a reasonable position to take at present, albeit at a high level, recognising that this may change for the final plant.

118 Specifically for chemistry, the notion of 'control' and 'diagnostic' parameters is described. The latter provides a means of monitoring plant performance, without limiting operations, while the former are used to control the plant and require a corrective action if an associated limit is breached. This type of approach is almost universally applied in PWR chemistry and is very similar to that proposed in both the EPRI (Refs 27 and 28) and VGB guidelines (Ref. 29).

119 A number of chemistry and radiochemistry parameters are identified in the response to RO-UKEPR-55 as being relevant to plant safety, including the primary, secondary and safety systems. It is apparent that the list of parameters presented does not represent all the chemistry requirements for operating a UK EPR. This indicates that EDF and AREVA expect a number of these to be classified as 'lower tier' limits, perhaps residing in operating manuals or specifications. Of those presented, notably absent are any limits on secondary circuit feedwater oxygen or Component Cooling Water System pH control, amongst others. According to the criteria suggested by EDF and AREVA, these would both be implicated in "*integrity of barriers in the medium to long term*". These are specific examples of the generic shortfall described below.

120 In response to my questions, EDF and AREVA provided further information (in Refs 158, 159 and 92). These supporting documents provided details of the expected approach on limits and conditions for the FA3 EPR. In general, the parameters suggested align with the approach taken by EDF in France, as reported by my TSC review in this area (Ref. 33) and the final selection of chemistry parameters for control of UK EPR will take place later in the project, by the Licensee. It is notable that no overall justification was provided on which parameters were included or otherwise, but again EDF and AREVA state that this aspect will be provided later in the project.

121 While the response is 'preliminary' in terms of the final approach that may be taken in an operating UK EPR, as indicated in Section 3.2.2, my expectation for GDA was an identification of all relevant safety parameters would be provided. I do not believe this is a fundamental deficiency in the UK EPR safety case, and can be rectified as the project progresses and the plant chemistry becomes finalised. As limits and conditions require a complete understanding of the plant chemistry regimes in all operating modes, some of which are still being developed for UK EPR, this can be satisfactorily addressed at a later stage. Post GDA, the Licensee of any UK EPR should detail all limits and conditions for UK EPR, including full justification for the actions and timings. I consider this to be an Assessment Finding **AF-UKEPR-RC-02**.

122 An important point made in the response to RO-UKEPR-55 is that; *“depending upon the approach adopted in developing OTS, the radiation and chemistry limits may either feature in the OTS, chemical specifications and radiochemical specifications…, or only in the chemical and radiochemical specifications”*. While I accept that this decision is in the hands of the Licensee, ND expectations would be that an appropriate balance be struck on ‘classification’ of the relevant chemistry parameters depending upon their importance to safety. As described above, this can be a subjective area, but based on the information available at present I believe that a number of chemistry parameters should be part of the highest level plant limits and conditions, with many more at the level just below this. The justification for the final approach taken by the Licensee would be required post GDA. This is part of Assessment Finding **AF-UKEPR-RC-02**.

123 The draft PCSR Chemistry Chapter (Ref. 103), described in Section 3.2, contains information on the expected limits and conditions in UK EPR. The description given there is consistent with the assessment described above. Further information on some of the preliminary UK EPR limits and conditions is described in Section 4.2.10 of my report in terms of the holistic approach to primary circuit chemistry.

124 During construction and commissioning of any UK EPR, a detailed chemistry document, containing the basis and description of the chemistry requirements for the various Systems, Structures or Components (SSCs) through all phases of operation, for example, purity, cleanliness or material compatibility, will be necessary. TQ-EPR-1349 (Ref. 8) was raised to understand the EDF and AREVA expectations for when and what form such documentation would take for UK EPR. The response indicated that EDF and AREVA expect several documents to be produced, dealing with site chemistry and cleanliness requirements during erection and initial operations. While reasonable, a wider range of information will be needed. Chemical specifications are essential for all phases from component fabrication onwards and also include the preventative exclusion of foreign materials, reagent purity, guides to operating make-up and purification systems and expected surveillance and cleanliness during fabrication, commissioning and in normal operations. Such guides and specifications would make the chemistry in the various systems transparent to all involved and any problems should be avoided. Production of this type of documentation should be pursued at a later stage and I consider this to be an Assessment Finding **AF-UKEPR-RC-03**.

4.1.3.1 Summary

125 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of limits and conditions in UK EPR are:

- EDF and AREVA have described a proposed basis for developing chemistry related limits and conditions for UK EPR, including the ‘preliminary’ identification of some of the parameters which are expected to be included.
- The approach suggested appears to consider the main chemistry parameters I would consider needed in chemistry related limits and conditions and I am encouraged that the approach suggested appears a reasonable compromise and should yield acceptable results, notwithstanding the specific comments made above. I note several areas where further work will be required to complete the safety case in this assessment area and have raised Assessment Findings to cover these. I am satisfied these can be resolved post GDA.
- The specification of a normal operating regime, which is finding **AF-UKEPR-RC-01**, clearly relates to the definition of the controls which bound it. The finding below

expects the Licensee to specify in the safety case all chemistry limits and conditions, including radiochemistry parameters that have an impact on safety, identifying the timescales over which corrective action would be needed.

126 Overall, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.1.3.2 Assessment Findings

127 Based upon the assessment of chemistry standards in UK EPR described in Section 4.1.3 above, and in other sections of this report, 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-02*** *– The Licensee shall specify in the safety case all chemistry limits and conditions, including radiochemistry parameters, that have an impact on safety including ORE, wastes, combustion hazards, maintenance and testing. Limits and conditions for all modes of operation should be stated. The justification and classification for the limits should be made clear. Where appropriate, the nature and timescale of any corrective action should be justified. This Assessment Finding should be completed before the first stages of commissioning are undertaken and such limits or conditions may be needed. Target milestone – Cold Ops.*
>
> ***AF-UKEPR-RC-03*** *– The Licensee shall specify detailed chemistry related requirements for all phases of construction and commissioning through to normal operations. This Assessment Finding will be staged throughout the new build project, but should begin with the production of a plan for developing appropriate documentation. The main stages will include delivery to site of major equipment (such as the Reactor Pressure Vessel, RPV) and subsequent commissioning. Requirements should be set before delivery to site of major equipment. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

4.1.3.3 GDA Issues

128 Based upon the assessment of chemistry standards in UK EPR described in Section 4.1.3 above, I have identified no Reactor Chemistry GDA Issues in this area. There is a cross-cutting issue that contains an action requiring the specification of operating limits and conditions for UK EPR; **GI-UKEPR-CC-02**, see Section 3.5 of this report.

4.2 Primary Circuit

4.2.1 Overview

129 The principal system in the primary circuit is the Reactor Coolant System (RCS). The UK EPR RCS is described in detail in the PCSR (Ref. 11, Section 5). The UK EPR RCS configuration is a conventional four-loop design, developed from both the latest French (N4) and German (‘Konvoi’) designs. The Reactor Pressure Vessel (RPV) contains the fuel and reactor core, through which the reactor coolant is pumped and heated. The reactor coolant flows through each of the four loops before returning to the core, cooler after the transfer of heat to the secondary coolant via the Steam Generators (SGs). Each loop comprises a hot leg pipe, SG, Reactor Coolant Pump (RCP) and cold leg pipe. A

pressuriser (PZR) is connected to one hot leg via the surge line and to two cold legs by the spray lines. This arrangement is shown below, including the connections to the main support systems (Ref. 11):

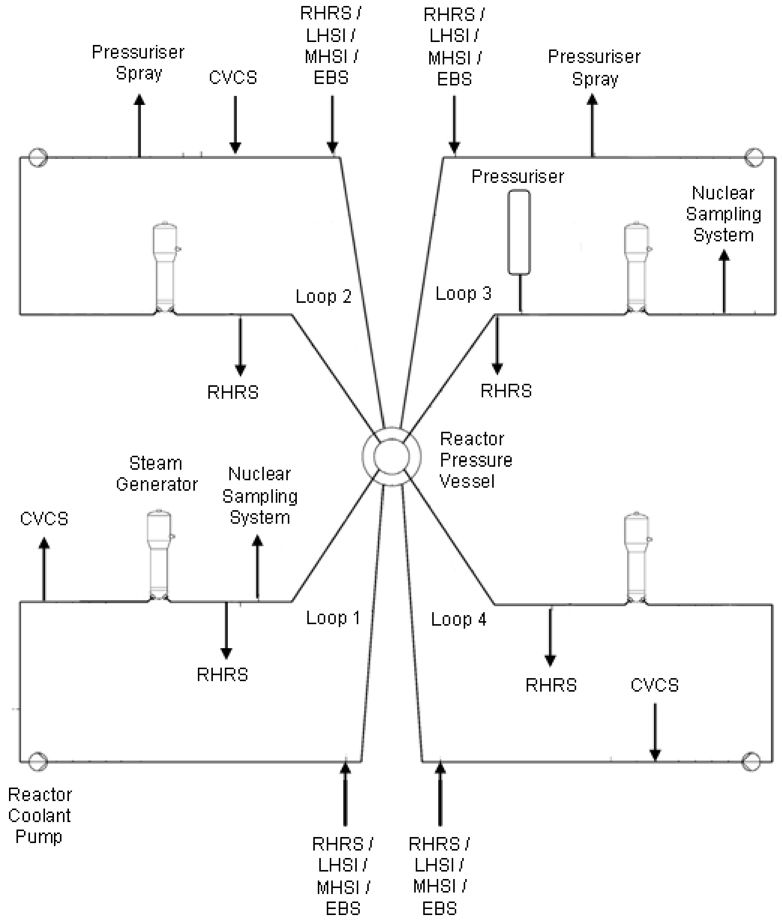


Figure 1: UK EPR Reactor Coolant System

130 Many of the main components used in the UK EPR RCS have been used in previous French and German designed PWRs, with adaptations for the specific design of EPR. Section 1.3 of the PCSR (Ref. 11) provides a comparison of UK EPR to similar reactors. New features of the EPR and relevant to this assessment include the:

- Relatively large volume to core power ratios for the RPV, PZR and SGs, which is claimed as a safety feature.
- Higher steam pressures in the SGs to increase efficiency.
- Addition of a core-melt stabilisation system.

131 The control of the primary coolant chemistry plays a key part in the normal operation of any Light Water Reactor (LWR). It contains the soluble boron, as part of nuclear reactivity control, and its interaction with the metallic structural materials can result in undesirable corrosion. In extreme cases, corrosion may challenge the integrity of components of the reactor. The coolant and the minute quantities of corrosion products it carries are made radioactive by their passage through the core. Dissolved solids may deposit on the heat transfer surfaces of the fuel rods, accelerating their corrosion and absorbing boron in

extreme cases. Chemicals are deliberately added to the coolant to control these effects and some impurities can be very damaging; thus the control of primary coolant chemistry must achieve a balance between all of these effects and much effort during operations is concerned with ensuring that the coolant chemistry remains within required ranges.

132 The primary coolant chemistry in UK EPR, as with every commercial PWR, is dominated by the requirement to add soluble boron for nuclear control purposes. Boric acid is present throughout most of the operating cycle and a number of key faults relate to the loss or dilution of boron. The boron is particularly needed at the start of the cycle and during shutdowns. Unchecked, the use of boric acid acidifies the coolant, resulting in increased corrosion, so lithium hydroxide is added to adjust the pH to alkaline, mitigating these effects. However lithium itself can adversely affect the fuel cladding if too much is used and produces radioactive tritium. The water itself is subject to radiolysis as it passes through the radiation field in the core producing reactive oxidising species, so hydrogen is dissolved in the coolant to avoid formation of these species. As with a number of current operating PWRs, EDF and AREVA proposes to add soluble zinc to the coolant in UK EPR to minimise plant radiation levels.

133 As stated in Section 2.5, the aim of the assessment was to assess the ‘expected’ chemistry regimes for UK EPR, rather than a ‘final’ specification that may be applied. Throughout Step 4 EDF and AREVA provided details of the expected chemistry regime to be applied to the primary, secondary and a number of auxiliary circuits in UK EPR. In response (Ref. 172 and 51) to RO-UKEPR-44.A1 (Ref. 9), EDF and AREVA proposed the following primary circuit chemistry for UK EPR, which is the basis for the assessments that follow:

- A constant $pH_{300°C}$ as early as possible in the fuel cycle, with a target value of $pH_{300°C} = 7.2$. A maximum lithium concentration of [redacted] mg kg^{-1} at Beginning of Cycle (BOC) in combination with the use of Enriched Boric Acid (EBA) make this possible.
- A minimum hydrogen concentration of 17 cm^3 kg^{-1} (STP), assessed in Section 4.2.7 (note that cm^3 kg^{-1} referred to here, and subsequently in this report, refers to cm^3 of hydrogen gas per kg of coolant at Standard Temperature and Pressure (STP) conditions of 0 °C and 100 kPa)
- Limitation of impurities to avoid localised RCS and fuel materials corrosion
- Add zinc acetate to achieve 10 ± 5 μg kg^{-1} zinc, assessed in Section 4.2.6.

134 In addition to the coolant chemistry, the design of the reactor, choice of materials and their finishes determine the ease with which corrosion and its consequences can be controlled. With the proper selection of materials, finishes and adequate passivation, threats to structural integrity from normal chemistry are limited. The limited corrosion that does occur is nevertheless responsible for much of the radioactivity outside the core during shutdowns. Whilst some radioactivity in the coolant is unavoidable (for example, ^{16}N), much can be controlled and even reduced by careful management of coolant chemistry and design choices such as material selection and the design of the Chemical and Volume Control System (CVCS). In addition to the RCS and CVCS, other systems on which the primary coolant could have an effect in normal operation include the Safety Injection System / Residual Heat Removal System (SIS/RHRS) and In-containment Refuelling Water Storage Tank (IRWST) and these in turn can affect successful cooling. The largest surface area of any single metal is the alloy from which the SGs heat transfer tubes are constructed. The second largest surface is the cladding of the fuel and this barrier retains more than 99% of the radioactivity in the reactor. Only a small proportion of the material that corrodes in a modern PWR comes from the Steam Generators or the

fuel cladding. As a result, the steels which make up smaller areas in the remainder of the circuit are becoming increasingly important.

135 In UK EPR, a number of other systems are connected to the RCS, which support chemical control, sampling and safety functions of the primary circuit, including specifically for the UK EPR:

- The Safety Injection System / Residual Heat Removal System (SIS / RHRS)
- The Accumulators
- The Extra Borating System (EBS)
- The Chemical and Volume Control System (CVCS)
- The Nuclear Sampling System (NSS)

136 The overall arrangement of the primary circuit in UK EPR is shown in the figure below, from Ref. 174.

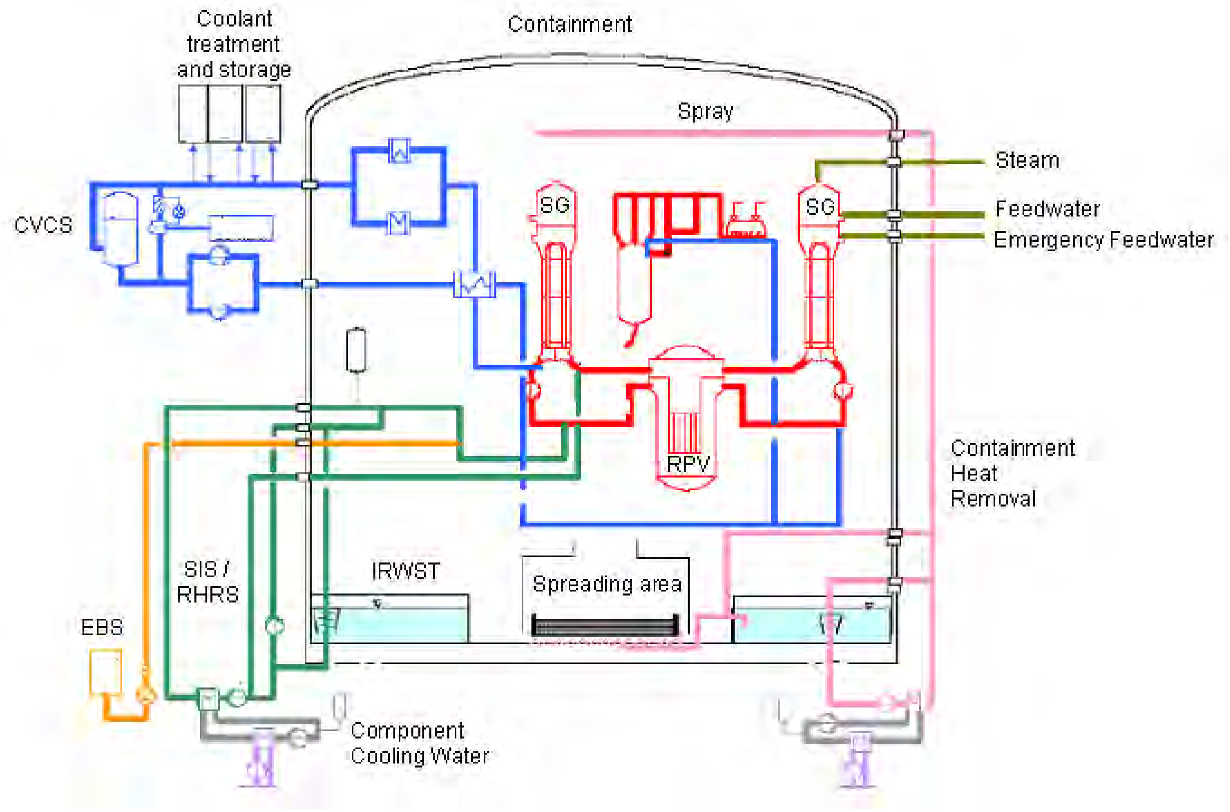


Figure 2: UK EPR Primary Circuit and Connected Systems

137 The main systems that control the coolant chemistry are the Chemical Volume control System (CVCS, Section 4.2.2) supported by the Nuclear Sampling System (NSS, Section 4.2.9) and the water make-up systems (Section 4.4.2.1.9), all of which are assessed in this report. While the functions of the safety systems are assessed elsewhere (mainly, Ref. 58) their impacts on plant chemistry are assessed in this report.

138 Overall, the assessment of primary circuit chemistry during GDA has sampled a number of interrelated areas namely; control of coolant chemistry, protection of the structural materials (specifically related to integrity of the pressure boundaries), maintaining fuel

integrity and performance and minimisation of out of core radiation fields. The approach was to identify the current EDF and AREVA approach and expectations for primary circuit chemistry in UK EPR, to determine whether or not the chemistry supports plant safety. The areas sampled were:

- Chemical Control
- The influence of Materials and Chemistry on Radioactivity
- Material Integrity and Corrosion Control
- Fuel Integrity
- Zinc Addition
- Hydrogen Addition
- Control of Safety System Chemistry
- Sampling Systems
- Holistic Approach to Normal Operating Chemistry
- Start-up and Shutdown Chemistry
- Hot Functional Testing

139 Each of these is discussed in detail in the following sections.

4.2.2 Assessment – Chemical Control

140 This section assesses the capability of the chemical control systems for supporting the chemical requirements of the plant; namely, a demonstration that the system performance and reliability requirements of the plant are substantiated by the detailed engineering design. As stated previously, the main system which controls the primary coolant chemistry in UK EPR is the CVCS, and this section focuses on this system during normal plant power operations; transient conditions such as start-up and shutdown are considered elsewhere (Section 4.2.11), as is the use of the CVCS to support refuelling operations (Section 4.3).

141 Assessment of the CVCS in UK EPR was started during Step 3 and significant further assessment was undertaken on this important system during Step 4, which included commissioning specific TSC support in this area (Ref. 150). During Step 3, I was broadly satisfied with the overall claims and arguments presented, noting several features and potential improvements the design offered over existing comparable systems. However, I recognised that the system was complex and further work would be needed in Step 4 covering:

- The letdown coolant flow is high (like the ‘Konvoi’ stations) and filtration is taken as the principal step for reducing the radioactivity carried by the coolant, thus placing higher demands on filters and their control systems.
- The extent of reliance on boron monitoring is greater in UK EPR.
- Splitting and diverting the coolant flow through a number of optional processes, including ion-exchange and make-up or recovery of water, boron and lithium, injection of hydrogen, zinc dosing and degassing increases the system sophistication and consequently the potential for some faults.

- Most of the letdown coolant flow bypasses the CVCS Volume Control Tank (VCT), which is smaller than those in comparable reactors and is covered with nitrogen, as opposed to hydrogen.
- Hydrogen addition is performed in a dedicated ‘hydrogenation station’ which adds hydrogen to the flowing coolant stream, as opposed to the more common cover gas approach.
- Recycling boron may lead to the build-up of contaminants or activity in the coolant and an accumulation of radioactivity in the recycling plant.
- Material choices for CVCS valves and other components in contact with the coolant, potentially including Stellite^{TM}, require clarification and justification.
- The linear velocity of coolant through the ion exchange beds in UK EPR may be high.

142 Although EDF and AREVA claim that the UK EPR has been designed to permit load following, which would put further demands on the CVCS, ND did not assess this feature in GDA. Load-following is out of scope of GDA.

4.2.2.1 CVCS Overview

143 As in most PWRs, the CVCS for UK EPR (Ref. 11, Section 9.3.2) is mostly outside the containment building and its principal components operate at ambient temperatures and pressures. Coolant flows in and out of the CVCS through separate letdown and make-up lines via one regenerative heat-exchanger and a series of isolating valves. The CVCS also provides coolant to the pressuriser, main Reactor Coolant Pump (RCP) seals and various other cooling and safety reservoirs. It is a large and sophisticated system, comprising three ion-exchange beds, several filters, a gassifier and degassifiers, a volume control tank (VCT) and has multiple connections to separate storage, recovery and waste-treatment systems. The CVCS in UK EPR supports a very high coolant flowrate and consequently possesses anti-dilution features for boron

144 The CVCS in UK EPR is described in the PCSR (Ref. 11, Section 9.3.2) and in the System Design Manual (SDM) (Ref. 167). The functions provided by the CVCS are closely linked to two further systems:

- Coolant Purification, Degasification, Storage and Treatment System (CSTS). The CSTS is described in the PCSR (Ref. 11, Section 9.3.3) and associated SDM (Ref. 113).
- Reactor Boron and Water Make-up System (RBWMS). The RBWMS is described in the PCSR (Ref. 11, Section 9.3.4) and associated SDM (Ref. 114).

145 While EDF and AREVA distinguish between the CVCS, CSTS and RBWMS, the functions provided by the CVCS are dependant on the CSTS and RBWMS; hence for the purposes of the assessment that follows I have taken these systems to collectively comprise the CVCS in UK EPR.

146 The CVCS has a central role supplying coolant to many parts of the reactor and the coolant it supplies must always a) contain enough boron to control the nuclear chain-reaction, b) be conditioned to minimise corrosion and c) treated to control radioactivity so far as is reasonably practicable. However in UK EPR the CVCS as a whole is not safety classified and there are only a small number of important safety functions claimed. There are safety classifications (in Ref. 20) applicable to a few of the CVCS components, several having a C3 classification; for instance, the pressuriser spray line has A1 classification along part of its length, to prevent leakage but not to provide a spray,

whereas the charging pumps themselves are C3. The safety functions were presented in Section 9.2 of the PCSR (Ref. 11) and may be summarised as:

- Reactivity control by adjusting the boron concentration in the primary circuit coolant to respond to power changes and fuel burn-up, in all modes of operation
- To prevent / mitigate boron dilution accidents
- Assist provision of coolant in small Loss of Coolant Accident (LOCA)
- Ensure leak-tightness of the main coolant pump seals, even if letdown from the main circuit is unavailable
- Control chemistry (lithium, hydrogen, silica etc.) to limit corrosion
- Provide auxiliary spray water to the pressuriser
- Help prevent overfill of the steam-generators
- Maintain the coolant pressure boundary
- Ensure containment isolation in an accident

147 These are repeated in the system functional specification for the CVCS (Ref. 167) and augmented by two additional safety functions:

- Control the volume of water in the core when the Residual Heat Removal System (RHRS) is in use.
- Supplement the boron supplied by the Safety Injection System (SIS) in a total loss of feedwater; however this is not credited in the fault analysis which assumes boron is supplied by the Extra Boration System.

148 The CVCS performs the following operational functions (amongst others) which were also considered in this assessment:

- Continuous control of the RCS water inventory during all normal plant operating conditions utilising the charging and letdown flow path.
- Adjusting of the RCS boron concentration as required for power variation control, plant start-up or shutdown, or core burn-up compensation through the addition of boron and/or demineralised water.
- Cooling and purifying water into the RCP seals to ensure cooling and leak tightness and return of any seal leakage.
- Provide primary coolant chemical control by interfacing with the coolant pH control, purification, treatment, degasification and storage systems (CSTS and RBWMS).
- Control the concentration and the nature of dissolved gases in the RCS by maintaining the required hydrogen concentration in the charging flow and degasifying the reactor coolant, when required.

149 The following figure provides the schematic design for the CVCS (from Ref. 160):

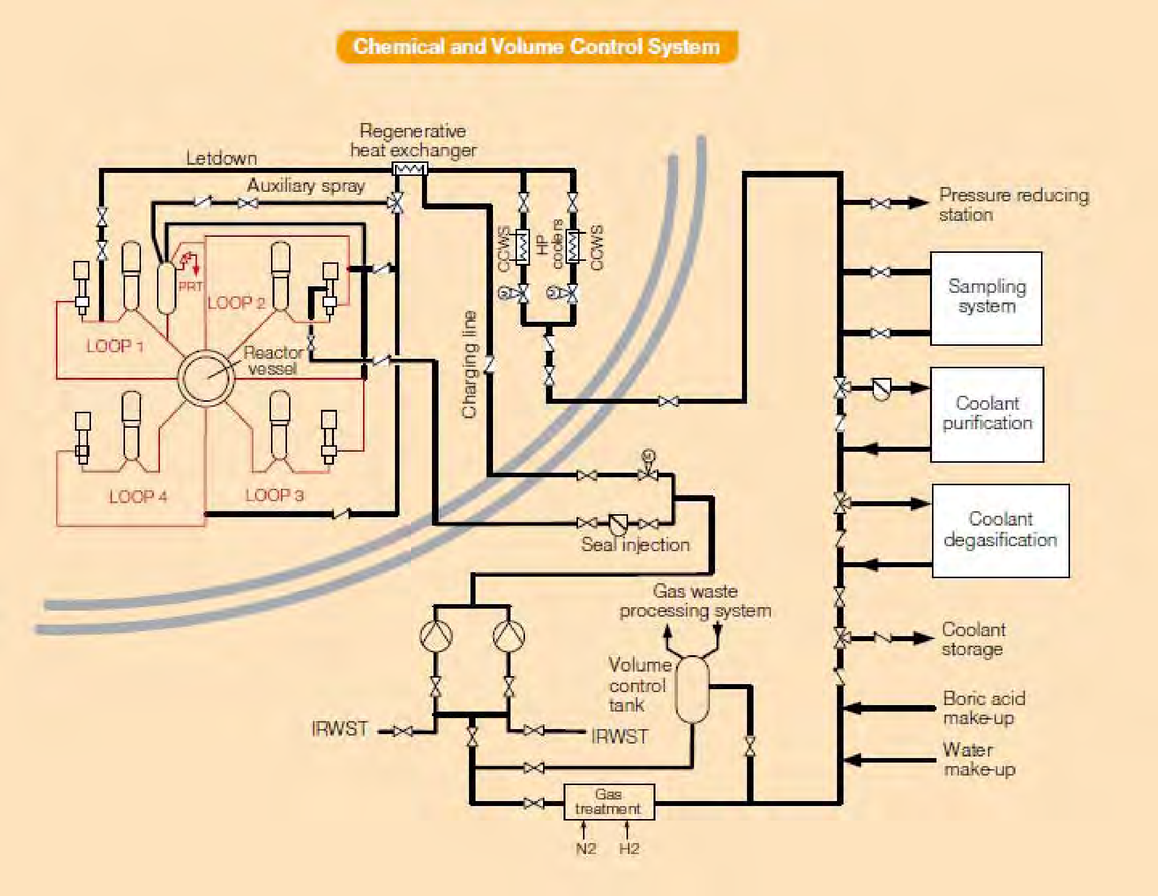


Figure 3: UK EPR Chemical and Volume Control System

150 The CVCS is the interface between the high pressure RCS and the low pressure systems outside containment. The CVCS provides a flow path for the continuous letdown and charging of RCS water and maintains the RCS water inventory at the desired level via the Pressuriser (PZR) level control system and provides auxiliary spray for PZR cool down. The system is normally in continuous operation during all modes of plant operation from normal power operation to cold shutdown. The specific functions these systems have in shutdowns and start-ups are covered in a separate section of this report (Section 4.2.11).

151 In normal operations, coolant flows in and out of the CVCS through separate letdown and make-up lines via one regenerative heat-exchanger, one of two parallel let-down heat exchangers (cooled by the Component Cooling System (CCWS)) and pressure reducing station. These components are inside the containment boundary. The let down line is taken from the RCS hot leg on loop 1, while the return line feeds both the Loop 2 and 4 cold legs. The CVCS also provides a small portion of the return flow to provide coolant to the RCP seals on all four loops. The cooled and depressurised coolant which enters the CVCS is subject to a number of optional processes whilst inside the CVCS, via connections to associated systems, mainly the NSS, CSTS and RBWMS; these include sampling, purification, degasification and storage. Those processes that operate continuously during normal operations include:

- A high proportion of the coolant that enters the CVCS passes through the purification sub-system, comprising two parallel coolant filters, three ion-exchange beds and a resin trap (Ref. 167). The normal flow path will be through one filter followed by one mixed resin ion-exchange bed. The first two ion-exchange beds are parallel duplicate beds, while the third is intended to be used mainly during shutdowns for corrosion product removal. The filters are duplicates providing back-up capability. Treated coolant is returned back to the main CVCS flow. The purification sub-system is located in the Nuclear Auxiliary building.

- The letdown flow passes to the two parallel high pressure charging pumps. In doing so it passes through the hydrogenation system, which includes the Volume Control Tank (VCT) and system for adding dissolved hydrogen to the coolant. Only a small portion of the coolant passes to the VCT, with most passing to the pumps via the hydrogen addition system.
- Other additions can also be made to the coolant before it is returned to the RCS. Continuous additions will include hydrogen and zinc (acetate). Other additions, such as boric acid, lithium (hydroxide), hydrazine or hydrogen peroxide, can be added as required. The systems which do this are described in more detail and assessed in later sections of this report.

152 Once purified, chemically conditioned and pressurised by the charging pumps the return coolant flow is split, with the majority of the flow passing back to the RCS via the cold leg make-up connections. On request, this flow can be diverted automatically into the pressuriser auxiliary spray. The bulk flow exiting the charging pumps is subject to boron measurement by the boron meter system. This aspect is assessed further in Section 4.2.2.2.1 of this report. A smaller flow is permanently diverted to the RCP seals. Before reaching the RCPs this flow passes through one of two parallel seal flow filters. Inside containment the seal flow line is split to provide flow to all four RCPs. The return flow from the RCP seals similarly combine to a single return line which is filtered by a further seal flow filter before returning to the CVCS, normally to the VCT.

153 The systems to which the CVCS is connected in UK EPR include the:

- Reactor Boron and Water Makeup System (RBWMS) for recycling boric acid. (Ref. 11, Section 9.3.4). The RBWMS consist of three separate sub-systems which supply, mix and store boric acid and demineralised water for the Safety Injection System (SIS), accumulators, IRWST, RCS and the spent fuel pools and accepts water recycled from the CSTS.
- Coolant Storage and Treatment System (CSTS) for storing, cleaning and degasifying coolant for reuse or disposal. The CSTS comprises four separate sub-systems; the coolant storage and supply system (CSS), the coolant treatment system (CTS),the coolant degassification system (CDS) and the coolant purification system (CPS). The CPS is provided to limit the accumulation of impurities and activity in the RBWMS. A full description of each of these sub-systems can be found in the UK EPR PCSR (Ref. 11, Section 9.3.3) and is not repeated here.
- Normal Residual Heat Removal System (RHRS) for cooling in shutdown.
- The In-containment Reactor Water Storage Tank (IRWST) also provides coolant to the CVCS for use in certain faults.
- Pressuriser auxiliary spray, for use in cool-down and start-up.
- Main Coolant Pumps (MCP), to keep the pump bearings cooled and sealed.

154 Each of these systems can be connected or by-passed by operator or the control computers. The relationship that the CVCS has with some of these systems will be described in more detail below.

155 EDF and AREVA propose the use of isotopically enriched (in ^{10}B) boric acid for UK EPR. This would, by necessity, also be dissolved in all stocks of emergency coolant and pond waters. The enrichment and concentrations used will depend on the fuel management and pH profile eventually specified for the UK EPR. The boron enrichment is defined by the characteristics of the fuel. The sub-criticality criterion at cold shutdown and minimum pH define the amount and form of boron actually needed. EDF and AREVA have specified bounding upper values for the enrichment and concentration of the boron as part of GDA. The boric acid storage tanks in UK EPR, particularly the Extra Boration Tank (EBS) and IRWST are too small to permit the use of natural boric acid with modern uranium fuel. This has several consequences on the primary circuit chemistry of UK EPR, and the CVCS design as described later in this section and later in my assessment.

156 In addition to the findings from Step 3, in Step 4 I assessed the manner in which the design of CVCS in UK EPR had been changed from that of its progenitor, the CVCS in the German Konvoi reactors. TQ-EPR-905 (Ref. 8) was raised to identify these features, the rationale behind the changes and any implications in terms of the distributions of silica, ^{14}C, zinc and boron between different parts of the reactor. The reply provided by EDF and AREVA included three principal changes which I assessed:

- The provision of coolant filters upstream of the ion-exchange beds and absent in Konvoi, which is discussed in the sub-section on filtration (Section 4.2.2.3.2).
- The emergency seal water supply is taken from the IRWST, instead of the boron make-up system in Konvoi.
- The use of a class A1 (F1A in France) on-line boron metering system for the anti-dilution protection function (Section 4.2.2.2.1).

157 My assessment of each of these changes is also presented below. The other four changes quoted in TQ-EPR-905 (Ref. 8) were made for mechanical reasons and were therefore not considered further in my assessment. I also note the following specific features apparent from the response to TQ-EPR-905 (Ref. 8):

- The ratio of the CVCS flow to the total coolant flow is a significant factor determining the overall efficiency of the coolant purification and treatment systems. For instance, an adjustment to the concentration of an additive takes a finite time to reach all of the coolant. UK EPR is no different from any other PWR in this respect, and may in fact be better due to the relatively large CVCS flow rates. I took account of such effects in my assessment.
- Flowrates through the CVCS will be very high in UK EPR. This has implications for the analysis of Steam Generator Tube Rupture (SGTR) faults which are discussed in Section 4.6.2. It also has implications for boron dilution, which is discussed in Section 4.2.2.2.1.

158 TQ-EPR-717, 772 and 1140 (Ref. 8) were raised to request a number of documents which described the CVCS. Some of these refer to Flamanville Unit 3 (FA3), the French EPR currently under construction which is also the reference plant for UK EPR, see TQ-EPR-908 (Ref. 8).

4.2.2.2 Chemical Additions

159 The following section describes the assessment of the capabilities of the UK EPR CVCS to provide the chemical additions necessary to control the primary coolant chemistry. This section does not assess the implications associated with the concentrations of any particular species added, which are assessed later in this report.

4.2.2.2.1 Boron

160 Boron is dissolved in the primary coolant to regulate rates of nuclear reaction at power and as a backup to the shutdown control-rods at other times. The more boron that is dissolved in the coolant the less nuclear reaction can take place, but there is a limit at high concentration above which further boron becomes unreliable as a means of control. Stocks of coolant for use in emergencies, shutdowns and the Spent Fuel Pool are held with a sufficiently high boron concentration to completely suppress nuclear chain reaction, and these are routinely checked and occasionally adjusted by the station chemists. At power, the concentration of boron in the circulating primary coolant is modified on a daily or weekly basis to compensate for variations in the fissile content of the fuel and contraction of the coolant in a shutdown.

161 The precise enrichment of the boron required and its concentration at any one time are determined by nuclear physics. Safety regulators normally demand at least two methods of preventing unintentional nuclear reaction and the operators of any PWR must have rigorous control over the boron in use, as it is often one of the two controls employed (the other usually being control rods). Exercising this control is a normal activity for all PWR operators.

162 In Step 3, my assessment covered two separate aspects of boron addition; a) the increase in boron needed mid-cycle when burnable poisons are used and b) the effect of boron on the pH of the primary coolant. I was satisfied that a) use of burnable poisons would not require an unsuitably high concentration of boron mid-cycle and b) use of Enriched Boric Acid (EBA) would permit a stable operating pH at a high-enough level to minimise effects from corrosion. During Step 4 I raised a number of further queries with EDF and AREVA on boron control in UK EPR, particularly related to the capabilities of the CVCS to deliver and control boron and the hazards posed by homogeneous boron dilutions, where the boron concentration is slowly diminished rather than rapidly removed entirely (heterogeneous dilution). The latter of these faults is assessed elsewhere (Ref. 58).

Boron Addition

163 Details of boron control in UK EPR were provided in the response (Ref. 172) to RO-UK EPR-44.A1 (Ref. 9), which asked for a justification of primary coolant chemistry in UK EPR.

164 In addition to boron changes to maintain the correct pH, if power changes take place and the new power level is maintained for a long period, the boron concentration may need to be adjusted to offset xenon effects and ensure an adequate shutdown margin. In either case this entails injection of borated or demineralised water from the RBWMS, via the CVCS. The RBWMS injects boron (or water) after the coolant purification demineralisers and before the VCT.

165 EDF and AREVA have designed UK EPR to operate using Enriched Boric Acid (EBA). This has benefits for many other aspects of reactor operations, but potentially complicates the management of boron and means that UK EPR is equipped with a means of recycling the boric acid discharged from the plant so as to reduce losses of the valuable EBA. Essentially this involves distilling the waste boric acid to recover a concentrated boric acid solution and create (almost) boron free water which can be disposed using the radioactive waste treatment systems. This operation is part of the CSTS and is discussed later in Section 4.5.1. The implications for this type of control

arrangement on radioactivity (Section 4.2.2.3.3), refuelling activities (Section 4.2.3.3.3) and boron dilution events (this Section) are discussed in my report.

166 The main components of the RBWMS are a boric acid mixing tank and two parallel boric acid storage tanks, plus associated pumps, filters and connections to served and feed systems. The RBWMS is made from stainless steel. The boric acid tanks are maintained above 20 °C by the plant ventilation systems to avoid boron crystallisation. Headspaces in the tanks are connected to the Gaseous Waste Processing System (GWPS, see Section 4.5.1). Stocks in the RBWMS would be sampled and analysed prior to use in any system.

167 The boric acid mixing tank is used to prepare a solution of 4 wt. % boric acid (7000 mg kg^{-1}), of the correct enrichment, by dissolving granular boric acid in heated demineralised water at elevated temperature (around 50 °C). This mixing tank is used to feed the two boric acid storage tanks and the EBS tanks directly. Other systems are fed with boric acid diluted with demineralised water. This process will be used to feed the plant at the first start-up, but much less during normal operations, only that required to make-up for losses as the plant is intended to operate on a ‘closed cycle’ for boron.

168 The boric acid storage tanks contain the entire mass of boron required for normal operation of the plant. The amount of 4 wt. % boric acid in these tanks varies throughout the cycle, from nearly full at the end of a cycle to their lowest point at the start of cycle when the RCS is at the cold shutdown concentration. During operation boric acid concentrate is recovered from the CSTS evaporator to gradually refill the tanks. The boric acid is fed to the CVCS from these tanks.

169 Purely from the perspective of delivering a solution of boric acid to the primary circuit of UK EPR these arrangements appear reasonable, however it is notable that the controls and processes required to achieve the level of control of boron anticipated for UK EPR are complex and will require detailed operating procedures and controls to be developed and applied by the Licensee. I see no reason why these are not possible for UK EPR.

Control of Boron Enrichment

170 The use of EBA requires additional controls on the boron usage in UK EPR; in addition to the overall concentration of boric acid used, the enrichment must be strictly controlled to ensure there is no inadvertent reduction in the ^{10}B content. Such a process happens throughout the fuel cycle by the poisoning effect of the boron. In other reactors which do not recycle the boric acid this effect is not seen as the boron is continuously refreshed with ‘new’ natural (around 20% ^{10}B) boric acid.

171 I queried several points related to the use of EBA in TQ-EPR-1235 (Ref. 8). EDF and AREVA provided details on how the enrichment will be controlled and changed throughout a cycle when using EBA. These responses were based upon the FA3 analysis so are not directly applicable to UK EPR, but do suggest that such effects are controllable in UK EPR. For example, the FA3 analysis shows that the RCS enrichment drops by several percent during a fuel cycle. I understand that the isotopic enrichment of the boron will be increased back to the required level by the addition of a small amount of nearly 100% EBA, thus increasing the overall enrichment. I was content with the EDF and AREVA responses in this regard. EDF and AREVA indicate that detailed arrangements will be provided by the Licensee, which is a reasonable position.

172 The response to TQ-EPR-1235 (Ref. 8) provides a description of the risk analysis approach for EBA usage in the FA3 EPR. While a high level description, this appears to consider the main impacts I would expect to see in such an analysis. EDF and AREVA

confirmed that an exhaustive analysis has been carried out in order to determine the boron management. The Response to TQ-EPR-1235 (Ref. 8) states that this analysis for FA3 was based upon:

- *Justification for the use of EBA*
- *Identification of the required control parameters*
- *Identification of the different scenarios having an impact on boron depletion and uncertainties:*
  - *Fuel management conditions*
  - *Stretch out periods and intermediate shutdowns*
  - *Margins associated with enrichment strategy*
  - *Boron measurement uncertainties*
  - *Isotopic impurity of boric acid provided by suppliers*
  - *Boron solution preparations differences due to the volumes and mass measurements by NPP* [Nuclear Power Plant] *chemistry staff laboratories*

The individual margins lead to an estimation of a global and conservative uncertainty inherent in the boron enrichment. Identification of operator actions was based on the global uncertainty calculation and:

- *Criteria applied to perform the boron make-up, including the method of preparation and injection of high enriched boron*
- *On-line monitoring in RCS/RHRS/CVCS*
- *Grab sampling at other times and locations:*
  - *after filling and homogenisation of EBA preparation tank*
  - *RBWMS boron after recycling before CVCS connection*
  - *IRWST*
  - *EBS tank*
  - *SIS accumulator*
  - *Spent Fuel Pool*

All of these elements have been used to define an overall strategy of EBA monitoring and EBA enrichment for FA3 EPR including the safety considerations and the human factors. EDF and AREVA will provide several tools and procedures to the UK licensee including conversions, quantifiable depletion simulations, and corrective actions (make-up, enrichment process, etc.). These simulations are also performed for UK-EPR taking into account the different scenarios (shutdowns, stretch-out, and fuel management). EDF and AREVA will provide the overall EBA strategy to the UK licensee as an operational procedure.”

173 By doing this work for FA3, this means that EDF and AREVA have effectively already identified the requirements and scope for an EBA strategy in the UK. I am content with their approach and consider that such an analysis, fully justifying the EBA strategy to be applied by a Licensee for UK EPR will be required once UK specific details are available on fuel management and chemistry. This analysis should also consider other factors necessary to ensure the correct control of EBA, including:

- Physical control of enriched boron stocks and control over any natural boron on the site
- Availability of a suitable analytical technique for enrichment measurements
- Implementation of a boron dosing and metering plan
- The application of zinc treatment

I consider this to be an Assessment Finding **AF-UKEPR-RC-04**.

174 The implications of EBA on boron dilution are assessed below.

Boron Dilution

175 In this section I describe my assessment in Step 4 of certain faults involving boron. This assessment was supported by a TSC review, Ref. 150. My assessment included several aspects of boron control, certain CVCS faults, the anti-dilution protection in the CVCS and specifically the design and operation of the boron meters intended to prevent boron dilution.

176 There are two general types of boron dilution fault:

- Heterogeneous dilution - in which a sudden slug of un-borated water, from an internal or external, is swept into the core.
- Homogeneous dilution - in which the boron concentration gradually reduces until the control rods cannot cope.

177 The heterogeneous dilution was assessed by the Fault Studies Inspector in ND (Ref. 58). My assessment in Step 4 considered chemical and process perturbations that might cause homogeneous dilution, and how these would be detected and stopped. Homogeneous dilution events tend to be slow and are challenging because they allow all of the coolant to reach the threshold value, at which point the anti-dilution protection system is required to act promptly. The protection system must take account of the deliberate adjustments in the boron concentration, which take place regularly in any PWR.

178 Using EBA has several advantages but introduces the possibility of enrichment-loss through the accidental use of natural boron. Before describing some of the faults and protection methods, I outline the normal method of boron control and protection in the design of UK EPR.

179 In normal dilution mode, the RBWMS supplies EBA at a concentration just lower than the main coolant concentration and at a nominal flowrate of 1 t hr^{-1}, via the CVCS. At the same time, the CVCS bleeds the more concentrated coolant to the CSTS. This can be done automatically or in a manual mode. Towards the end of a cycle or in stretch-out (a period of reduced-power operation beyond the normal end of a cycle), the volumes of coolant needed for dilution may be larger than the ability of the CSTS to cope. In this case the licensee may choose to use one of the ion-exchange beds to absorb EBA from the coolant. Ion-exchange resins would be checked before use to prevent isotopic dilution of the EBA in the primary coolant. The loss of EBA through the inappropriate use of ion-exchange beds was considered by EDF and AREVA as a heterogeneous dilution fault, despite it being slow acting, so is not considered here.

180 As stated above, the CVCS in UK EPR can feed coolant more quickly into the core than many operating PWRs, such that the potential dilution rate is higher. To counter this

effect EDF and AREVA have specified a fast-acting automated detection and shut-off system to provide anti-dilution protection, which requires some processing by digital logic. The dedicated boron metering system, classified at the highest A1 (F1A in France) safety category, is fitted in the CVCS return flow after the High Pressure (HP) charging pumps. The Boron Concentration Measurement System (BCMS) consists of four measurements of ^{10}B in the returning coolant based upon attenuation of neutrons from a self contained source. The measurement process is entirely external to the coolant pipe, the following figure provides a schematic view of the boron meter from TQ-EPR-1146 (Ref. 8):

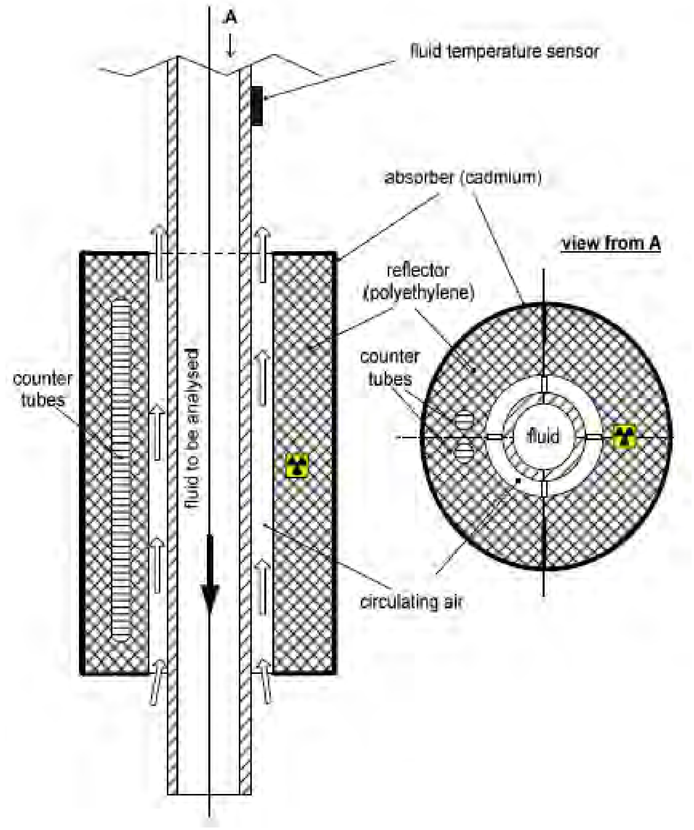


Figure 4: UK EPR CVCS Boron Metering System

181 I raised a number of TQs covering various aspects of boron control and discussed dilution faults and anti-dilution protection with EDF and AREVA during several of our meetings in 2010. I raised one action under RO-UKEPR-44 (Ref. 9); Action 6 covered the specification for the boron meters and its diversity. Actions A1 and A4 under the same RO-UKEPR-44 (Ref. 9) requested further information and justification for the control of boron in addition to other requirements for a chemistry topic report and PCSR chapter, all of which contain further information on boron controls. In total I raised eleven TQs on boron faults and their prevention (TQ-EPR-96, 131, 904 and 1142 to 1149). This relatively large number of queries reflects the number of connections to the CVCS, the need to maintain flow to the main pump seals and finally the complexity of the boron meters. The following paragraphs consider un-isolable dilutions caused by the CVCS, then subsequent paragraphs outline isolable dilutions.

182 The CVCS High Pressure Cooler is downstream of the BCMS and a breakage in this heat exchanger might cause in-leakage of un-borated water into the CVCS. An un-isolable dilution from this cause would only be possible in shutdown (mode 6) with the reactor

depressurised. With the reactor pressurised, the net flow of coolant would be outwards and the fault would be a LOCA. TQ-EPR-1144 (Ref. 8) concerned the safety systems that do protect the dilution fault in shutdown and the time needed for a response. The first line of defence would be the neutron monitors in the core with alarms in the control room, which should prompt the operator to find and isolate the dilution. If the dilution continued to the point that re-criticality might occur, the Extra Boration System (EBS) would activate automatically to provide additional boron.

183 The PCSR (Ref. 11) claims the EBS can cope with all dilution flowrates but really it is designed to cope with leaks. Estimations by my TSC (Ref. 150) suggest that the CVCS running a maximum flowrate can just out-run the EBS. Achieving such a rapid rate of dilution would need at least two other faults to occur with no operator response after 30 minutes, so I consider this to be highly unlikely.

184 My assessment gave me confidence that un-isolable dilution from the CVCS would not challenge the reactor and that the anti-dilution system outside of the CVCS would protect against un-isolable dilutions which might originate within the CVCS. Regular laboratory analysis should provide back-up and confidence tests for these systems.

185 Sources of water in the CVCS, other than a leaking High-Pressure Cooler, can be isolated near to their origin. The first line of anti-dilution protection for these sources comprises the CVCS instrumentation and the containment isolation valves. In the event of a dilution, the containment isolation valves are closed and a number of other valves and adjustments are made, depending on the operating mode of the reactor. Even when the CVCS is isolated, seal-water flow to the main cooling pumps must be maintained.

186 A number of TQs were raised, covering the various instruments and computations made to control the valves that isolate and realign coolant flow:

- TQ-EPR-1142 (Ref. 8); Response time of the valve shut-off terminating a dilution source. This response gave me confidence that the actuation system was capable of operating in a timely manner.
- TQ-EPR-1143 (Ref. 8); Existence of anti-dilution protection in all plant states. This response assured me that anti-dilution protection was available in all plant states.
- TQ-EPR-1145 (Ref. 8); Clarified the re-routing of primary coolant that would occur if a dilution were detected modes 1 – 4 (cold standby with RCP running). The main coolant pump seals would be supplied with EBA from the IRWST and the balancing main coolant bleed would be dumped whilst other CVCS bleeds and feeds would be isolated, see Section 4.2.2.4.1.
- TQ-EPR-1146 (Ref. 8); Provided further clarification of the interconnection of the IRWST and the CVCS and method used by the computers for calculating the expected boron level.

187 If a dilution occurred during refuelling, the main coolant pumps would not be running and the RHRS system would be providing coolant flow. In this case there would be additional isolations of the RHRS connection to the CVCS, the low-pressure reducing station and the volume control tank and coolant returning from the seals would be dumped to radwaste.

188 In order to achieve the isolation, it is first necessary to detect the dilution of coolant leaving the CVCS. Because the boron concentration might be varying deliberately, the expected concentration must be calculated and compared with the actual rate of change. The primary instrumentation provided to do this are the BCMS. Corrections are made to the measured concentration using readings from the CVCS flowrate and temperature

monitors. All the calculations are performed by computers. The computers, software and voting logic which actuate the isolation system are not Reactor Chemistry aspects and were assessed with all other smart logic, in the ND assessment of Control and Instrumentation, Ref. 20.

189 TQ-EPR-904, 1148 (Ref. 8) and RO-UKEPR-44.A6 (Ref. 9) were raised to obtain detailed technical descriptions of the boron meters in the CVCS. In addition to the BCMS there is also a boron meter on-line in the sampling system. There are a number of such devices in use in PWRs worldwide, but almost none have an A1 (F1A in France) safety classification.

190 TQ-EPR-1146 and 1149 (Ref. 8) also clarified the calculation methods and ranges of error and uncertainty involved in calculating the expected boron level and the determination of set-points for the boron metering and control system. The cumulative effect of measurement and calculation uncertainties would result in actuation of the protection slightly later than necessary in fast transients and prematurely in a slow transient (Ref. 150) but these effects should be small.

191 By measuring ^{10}B, these systems will protect against losses of enrichment of the EBA, such as an accidental feed of natural boron. Much effort has been put into the design of the boron metering system and there is clearly a lot of redundancy in the four detectors, with the system designed to cope with operation on a reduced number of detectors for limited periods.

192 During discussions with several staff at EDF and AREVA, it became clear that these were sophisticated systems and, quite apart from the Control and Instrumentation aspects, operational controls would be needed to prevent externally created (mainly '*user common mode*' type) errors, see SAP EDR3. Along with other colleagues in ND, I questioned whether the meters were diverse enough to achieve A1 reliability and this has become the subject of a Fault Studies lead cross-cutting GDA Issue, **GI-UKEPR-FS-01**, see Ref. 58, which I will support as appropriate to ensure an adequate resolution of the Reactor Chemistry aspects.

193 The CVCS in-line boron meters are claimed in the UK EPR fault analysis as a means of protection. However, the boron meters in the sampling system are the ones quoted in the Chemistry PCSR Chapter (Ref. 103), where the in-line CVCS meters are not mentioned. This is inconsistent and I find that the Licensee should clearly identify the boron metering system used for safety to identify procedures that assure common-mode calibration errors do not arise. I consider this to be an Assessment Finding, **AF-UKEPR-RC-05,** which applies to all boron meters which rely in neutron absorption.

4.2.2.2.2 Lithium

194 Most PWR have safety limits and action levels associated with the primary coolant pH. In order to limit corrosion within the RCS, lithium hydroxide is added to the boric acid in the primary circuit to produce an alkaline pH. As the boron concentration changes through the cycle, so must the lithium concentration. Similarly Lithium is produced during a cycle from the boron neutron absorption reaction. The addition of the correct quantity of lithium has an overall beneficial effect in terms of corrosion and radiation, but adding the wrong amount can negate these benefits. Having too much or too little lithium (or the wrong isotope of lithium) can impact on a number of systems. The specification for lithium concentration is assessed in several sections of my report that follow and summarised in Section 4.2.10 (Holistic Approach).

195 In UK EPR, lithium would be highly enriched in ^{7}Li. This avoids ^{6}Li which is a main source of tritium in the reactor, see Section 4.2.3.3.3. Enriched lithium will be recovered from the coolant by the stand-by mixed-bed ion exchange unit in the CVCS, avoiding de-lithiation on the operating bed which is already fully pre-lithiated. The presence of the correct isotope should be confirmed by laboratory measurement before use.

196 The arrangements for injecting lithium in UK EPR are described in the CVCS SDM (Ref. 167). Additions will be made to the common header before the HP charging pumps using an automatic system based on on-line lithium measurements taken in the Nuclear Sampling System (NSS), see Section 4.2.3.3.3. EDF and AREVA provided details of lithium controls in the response to RO-EPR-44.A1 (Ref. 172). The automatic system to be used for injecting lithium in UK EPR is described in Ref. 167, a prototype of the device has been in use at the EDF Tricastin 2 plant for several cycles, with positive results. The system is primarily aimed at control lithium during load-follow operations when boron, and hence lithium, must be frequently changed. This system includes:

- A total conductivity measurement to estimate the lithium concentration.
- A control computer, to calculate and automate the injection based on acquired data.
- An electromechanical assembly which injects lithium hydroxide via the CVCS.

197 Automatic lithium hydroxide injection is activated when either:

- The difference between the measurement / reference [target] value exceeds 0.05 mg kg^{-1},
- Considerable water movements (due to dilution, for example) lead to a significant reduction of the lithium hydroxide concentration in the primary system.

198 In TQ-EPR-1235 (Ref. 8), I asked what provisions were made in UK EPR to prevent the automatic system from dosing too much (or too little) lithium. In reply EDF and AREVA confirmed the existence of automatic alarms and controls that should control the lithium concentration normally. In the event of a more significant failure of the automatic system, manual sampling and cross-checks would still be possible. Operation with lithium between [redacted] and 5 mg kg^{-1} would only be permitted for 24 hours. If lithium increased above 5 mg kg^{-1}, the reactor would be shut down. I was content that these arrangements do not pose additional risks over more conventional ‘manual’ dosing arrangements.

199 I note that the lithium addition line is separate from the zinc addition line, so that zinc will not be precipitated before it enters the main circuit.

200 Overall, I was satisfied with the design of the system proposed for lithium injection and control in UK EPR.

4.2.2.2.3 Hydrogen

201 In normal operation of any PWR, hydrogen is dosed into the primary coolant in small quantities to a) suppress oxidising species production in the core and b) help prevent cracking of high nickel alloys and c) maintain iodine in a non-volatile form. Section 4.2.7 assesses the need for, and concentrations of hydrogen used in the coolant.

202 The hydrogen addition system in UK EPR was also reviewed by my TSCs (Ref. 138 and 150), their conclusions are consistent with the assessment that follows.

203 In any PWR there are losses of hydrogen by various processes so that dosing must be carried out (semi) continuously. These losses are; radiolytic reactions, diffusion through the SG tubes, boiling of the coolant and deliberate operation of degasification equipment.

In most PWRs, hydrogen is added by pressurising the ullage of the VCT with hydrogen gas. The hydrogen concentration in the coolant is thus controlled by Henry's law, which is a simple and reliable method. However, if this were attempted in UK EPR, there would be between 5 and 15 m^3 of hydrogen gas in the VCT and the low flow through the VCT would need a proportionally higher hydrogen concentration in the cover gas, or higher operating pressure. Both of these factors would result in a significant risk of deflagration if the VCT leaked or if there was ingress of air.

204 As such the VCT will not be used in this way in UK EPR; the design includes a dedicated "*hydrogenation station*" as part of the CVCS. This comprises an injection jet pump followed by a mixing element. TQ-EPR-865 and 1269 (Ref. 8) were raised to obtain further information on the hydrogenation station design and the following figure shows the hydrogenator in relation to the VCT and the main letdown-charging line in CVCS:

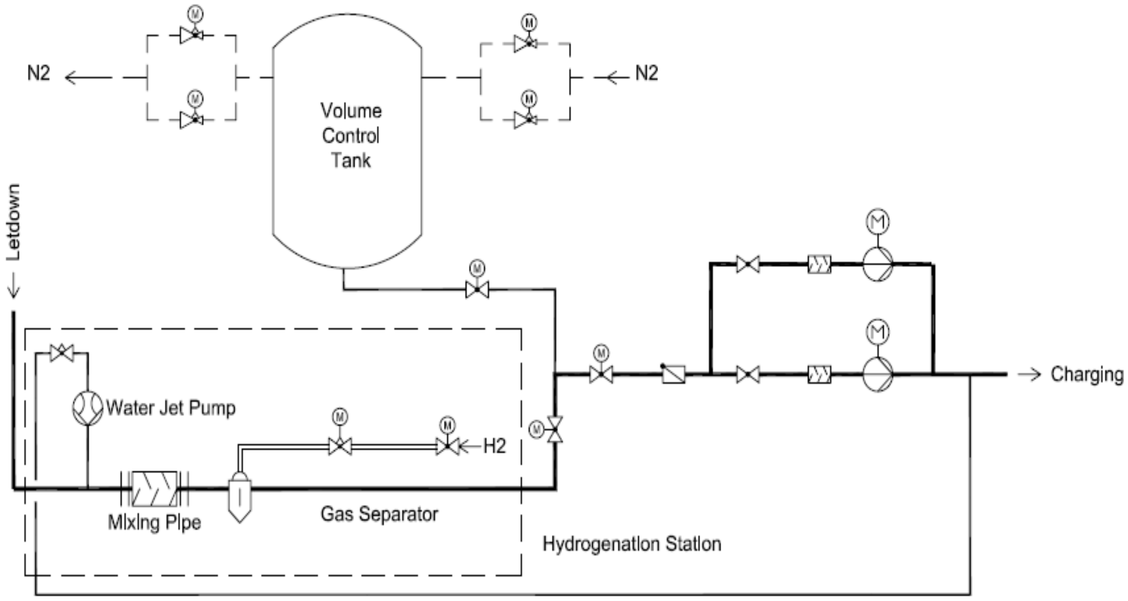


Figure 5: UK EPR Hydrogen Addition System

205 A small flow of coolant is taken from downstream of the HP charging pumps and used to mix with hydrogen gas in a water jet pump. The outlet from this pump, which contains coolant with both dissolved and un-dissolved hydrogen bubbles, is mixed with the main coolant flow before passing through a mixing pipe to further solubilise the hydrogen. The flow enters a gas separator where un-dissolved hydrogen is removed, and along additional hydrogen gas, returned to the water jet pump for re-mixing. The coolant which now contains only soluble hydrogen passes to the HP charging pumps, after mixing with the VCT outlet flow.

206 In this system the dissolved hydrogen concentration in the coolant is controlled by varying the hydrogen partial pressure in the hydrogen addition station. Since the head-space of the jet pump and the separator vessel will primarily contain hydrogen, the partial pressure will be set by the VCT head-space nitrogen over-pressure, which is controlled by injection of nitrogen and purged to GWPS.

207 In their reply to TQ-EPR-865 (Ref. 8), EDF and AREVA confirmed the design of the hydrogenation station is closely based on the design of similar systems in eight operating

German Konvoi stations, which has operated successfully for several years. A further two German stations are back-fitting this system. Graphs of the performance of the German hydrogenation system were provided to ND, which showed steady control in the long term. Short term variations are expected to be slow acting due to the low rates of loss expected.

208 By adopting such a system, the quantity of hydrogen gas in the hydrogenation station of UK EPR would be around 0.045 m^3 at 2.7 bar abs, greatly reducing the flammability risk compared to the alternative of using the VCT for hydrogenation. The presence of nitrogen in the cover-gas of the VCT may produce some ammonia by radiolysis. Ammonia production by such routes should be quantified as part of **AF-UKEPR-RC-01**.

209 I assess target concentrations for hydrogen dosing in Section 4.2.7 of this report. Since expert opinions differ on the optimum hydrogen concentration for controlling stress-corrosion cracking, some believing they should be increased to above 50 $cm^3\ kg^{-1}$ and others that they should be reduced, it is important that UK EPR should be able to provide whatever level of hydrogen dosing will be expected in the future within these likely bands. I asked EDF and AREVA what the maximum hydrogen concentration achievable in UK EPR would be. They replied that the maximum dissolved hydrogen level would be limited by the VCT pressure to 60 $cm^3\ kg^{-1}$. The minimum hydrogen concentration recommended for radiolysis control is 10 $cm^3\ kg^{-1}$. In UK EPR this minimum concentration still corresponds to a VCT pressure more than double the cavitation pressure of the HP charging pumps. It is clear from this that UK EPR can provide hydrogen at any concentration in the likely expected range.

210 In TQ-EPR-1269 (Ref. 8) I asked if the mixing element of the hydrogenation system might also remove radioactive gases out of coolant. I was satisfied with the reply from EDF and AREVA, that even if this was the case any gases from the mixing element would normally be recycled to the coolant and the hydrogenation station is not vented, except for maintenance. This may put further requirements on the CDS and pressuriser vents to degasify the coolant in operation.

211 In TQ-EPR-1235 (Ref. 8) I asked how much coolant boiling would deplete hydrogen in solution. EDF and AREVA replied that boiling up to 5% would deplete dissolved hydrogen by a maximum of 20%.

212 I concluded that the hydrogenation station would be capable of replenishing hydrogen losses by various processes and is a satisfactory alternative to the use of the VCT.

4.2.2.2.4 Zinc

213 EDF and AREVA propose to add zinc to the primary coolant of UK EPR, in the form of zinc acetate solution. The effects of zinc addition are assessed further in Section 4.2.6. The zinc addition system consists of a zinc injection tank and injection pump plus associated valves and controls necessary. Zinc acetate, at the required concentration is prepared manually in the tank and injected at a low constant flow rate to the CVCS pipework at the HP charging pump header where it mixes (but not mechanically) with the CVCS flow. The zinc flow will be set manually (between 0.01 and 10 $cm^3\ min^{-1}$) based on operating conditions in the CVCS. Operational procedures to control and check concentrations and flowrates will be specified in a later phase.

214 This is a simple system, similar to many that have been retro-fitted to operating plants. EDF and AREVA have verbally confirmed that the maximum pump flowrate will be very small, so it is not a realistic dilution source although it should appear on the schedule of potential dilution sources. It could however, over-pressurise the reactor at certain times

and should be included in Low Temperature Overpressure Protection (LTOP) arrangements. The zinc addition line is distant from the lithium make-up, in accordance with recommended guidelines (Ref. 187) to avoid immediate precipitation as the hydroxide, Section 4.2.6.1.1.

215 Overall, I am content that the zinc addition system in UK EPR is adequate. The addition of an engineered means of addition is a positive step.

4.2.2.2.5 Other Chemicals

216 Other chemicals may need to be added to the RCS on occasion, mainly during transients such as start-up and shutdown. The main of these will be hydrogen peroxide (shutdown) and hydrazine (start-up and shut-down). These additions are assessed further in Section 4.2.9.

217 In UK EPR these are added from pre-purchased sealed containers with quick connect couplings containing the requisite solution. A three-way valve connects these to an injection pump capable of adding up to 0.2 m^3 hr^{-1} to the CVCS, into the HP charging pump header.

4.2.2.3 Coolant Purification Systems

218 The following section describes the assessment of the UK EPR CVCS chemical purification systems. The coolant letdown from the main circuit in UK EPR is subject to chemical purification by filtration and degasification in CVCS and its associated systems. There are a number of resin beds in the CVCS and CSTS for chemical purification by ion-exchange and each has a slightly different role. These differences were clarified through TQ-EPR-1141 (Ref. 8), discussed below. Significantly, there is an evaporator in the CSTS to concentrate and recycle the EBA, which as well as being the primary means of ‘purifying’ the coolant for boron, will concentrate some solutes whilst removing others, which is assessed in Section 4.2.2.3.3.

219 The entire CVCS purification chain can also be used to purify water from the spent fuel pool.

220 The CVCS will be the main outlet for liquid and gaseous radioactive wastes created elsewhere in the reactor. Other than spent fuel itself, the main solid radwaste products of the CVCS in UK EPR, i.e. the ones containing the bulk of the radioactivity, will be spent ion-exchange resins and the main coolant filters. The quantities of resin produced will be determined by factors relating to corrosion in the rest of the reactor, which are discussed in Section 4.2.3.

221 Arrangements for sampling, to monitor the system performance, are described in Section 4.2.9, while operations under start-up and shutdown conditions, when much of the demand on the CVCS purification systems is at its highest, is described in Section 4.2.11. EDF and AREVA presented an overview of the principal chemical functions of the CVCS in FA3 in Ref. 102.

4.2.2.3.1 Ion Exchange

222 There are number of ion-exchange vessels in the CVCS, supported by similar vessels in the CSTS, provided to purify the coolant chemically. These beds are intended to remove soluble species from the coolant, including radioactivity and impurities. The main vessels are those within the CVCS itself. The vessels are located within the Nuclear Auxiliary

building, so are accessible during normal operations, and the system includes the facilities for flushing and removing spent beds to radwaste; spent resins will be fluidised with water then discharged by hydraulic transfer, Ref. 167. This type of practice is now standard at many stations to reduce operator radiation exposure.

223 The SDM for the CVCS (Ref. 167) provides much information on the various configurations for the CVCS under different operating modes. The following diagram (PCSR Section 9.3.2, Ref. 11) shows the arrangement of the main ion exchange and filtration systems for primary coolant, while operating under 'normal' conditions:

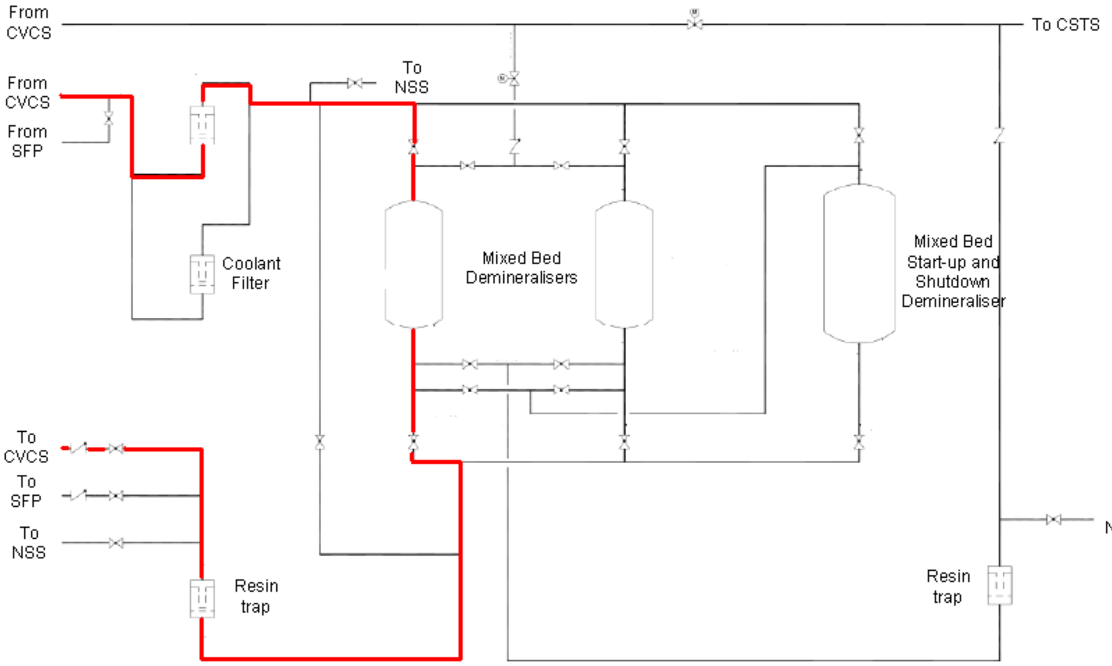


Figure 6: UK EPR Coolant Purification Sub-system

224 Currently there are three ion-exchange vessels in the CVCS, arranged in such a way that the first two beds are parallel and the third in series. The first two beds contain 2 m^3 resin, while the third is slightly larger at 2.2 m^3. The beds are:

- Two '*normal*' demineraliser vessels, with one intended for use during a full cycle. EDF and AREVA expect the operating bed to be in the $^7Li^+$ / BO_3^- form, while the standby bed will be in the H^+ / BO_3 form. This arrangement avoids de-boration and allows recovery of ^7Li, by using the stand-by bed to remove lithium and swapping the full with the empty bed once exhausted. This will remove a high proportion, but not all radioactive species passing through it. This type of arrangement is standard for many plants which have the capabilities to operate in this manner and has benefits in reducing radwastes.
- One additional '*shutdown and start-up*' demineraliser vessel which is normally reserved for additional purification during shutdown or start-up but additionally claimed for end-of-cycle de-boration.

225 EDF and AREVA state that the current intention is to use the third vessel for end of cycle de-boration, in Ref. 167, but this may be inconsistent with its expected use in shutdown and start-up, see Section 4.2.11. For example, if the resin is loaded with lithium because

of de-boration, it would be less effective for removing corrosion products in a shutdown. Conversely, if it is used to remove corrosion products, it will be less effective for de-boration. Due to the sizing of the beds these effects may not be significant. This would have been one of the main reasons why the further third vessel was added by AREVA (Areva modifications CS50, CS244 and CS394). Ref. 172 suggests the third vessel should be loaded with anion-exchange resin for efficient de-boration. This is an example of where the precise operational details for the system are unknown at present; however the design can be seen to offer multiple possibilities and a degree of redundancy and diversity. Robust controls over the operation of the beds can be specified by the Licensee at a later phase, when the precise operating strategy is known.

226 The letdown flow to the CVCS is cooled, partly because ion exchange beds are generally sensitive to temperatures above 60 °C. The beds in UK EPR would normally be run at less than 50 °C, which is common for many plants. Operation at this temperature will result in some reduction in resin capacity over time, but as this is common practice will be accounted for in the design by additional margins.

227 EDF and AREVA are aware that new lithium beds must be equilibrated with borated coolant and the coolant discharged before use. This is to ensure that the new bed does not excessively reduce the coolant boron level, a fault classed as heterogeneous dilution in their analysis, see Section 4.2.2.2.1 above.

228 EDF and AREVA have not specified the precise resin types and loading patterns for use in UK EPR. There is plenty of time for them to do this and there should be flexibility in the design to respond to plant operating characteristics. Nevertheless, I raised TQ-EPR-903 and 909 (Ref. 8) to understand the factors determining the efficiency and lifetimes of the resins.

229 In TQ-EPR-909 (Ref. 8), I queried the capacities of the beds and resin lifetimes. EDF and AREVA replied that the decontamination factors will be regularly evaluated and a decrease in this parameter below expected values (100 for some species) will trigger further investigation and appropriate corrective action. Resins will be replaced once they are used up, as measured by low fission product separation factors, ageing or high differential pressure. The TQ response said there were currently no criteria on dose-rates. I am content that EDF and AREVA have done enough to identify resin-change criteria for GDA. The target normal separation factor will be identified later.

230 The response to TQ-EPR-909 also provided information on separation efficiencies of individual elements. Resins have some ability to remove cobalt, caesium and zinc and may remove sulphate and chloride but cannot remove species such as silica, hence the importance of avoiding fibreglass filters or other sources of silica contamination (Refs 102 and 148).

231 Quoting recommendations for the EDF fleet, Ref. 169 recommends that resin beds be replaced every 5 to 7 years, irrespective of usage. The resin beds in UK EPR will be quite large and may well have capacity to last this long. However, in this time they will be subject to various forms of physical and chemical degradation from attack by peroxide, hydrazine, ammonia and radiolysis. In responding to TQ-EPR-903 (Ref. 8), EDF and AREVA agreed that chemical effects would decrease the efficiency of the resins but only quantified the effect for ammonia. Such effects would not be immediate and should be detected as part of normal monitoring of the system performance.

232 Ion-exchange resins and the filters which precede them will be the most radioactive and significant types of solid radwaste produced by the CVCS. I have not seen a detailed and realistic assessment of resin use in different modes, or a comparison of different loading and management patterns. I accept the calculation presented for ammonia is reasonable

but a realistic assessment would include allowances for other aging effects such as poisoning and radiolysis. This will be needed to ensure that waste generation will be effectively controlled. This is because the large size of the resin beds may lead to them being discharged before they are consumed, increasing the volume of solid radwaste per Becquerel.

233 Overall the main CVCS purification ion-exchange system does not include any novel features over existing PWRs and potentially improves on them by including larger, higher capacity vessels. The precise arrangements for usage and change of these beds still need to be specified, but I am content this can be done later, as the fundamental design appears adequate.

234 Additional ion-exchange material is included in the CSTS. This is part of the Coolant Purification System (CPS) sub-system of the CSTS and consists of a single H^+/OH^- form mixed bed. It is used to remove lithium, caesium and other isotopes not initially removed by the CVCS purification demineralisers, as well as ionic and colloidal impurities to avoid an accumulation in the Coolant Treatment System (CTS) (a sub-system of the CSTS) and an eventual re-introduction of these impurities into the RCS. Further discussion on how this vessel fits into the overall boron recycle system in UK EPR is given below, but purely as an ion exchange purification system it appears reasonable and should further reduce the potential for accumulation of impurities and unwanted material in the primary coolant.

4.2.2.3.2 Filtration

235 There are three pairs of filters in the CVCS which are used to remove activated corrosion products and protect against resin ingress to the RCS; upstream and downstream of the main CVCS resin beds and on the seal water inlet and return lines. They are arranged in parallel pairs for duty and standby. Filters in a water-reactor generally fulfil two purposes; they help to control the build-up of solid corrosion products in the coolant and they can also prevent damage caused by any larger particles.

236 Glass-fibre filters should not be used in a water reactor, because of the small quantity of silica which dissolves from the glass into the coolant. The silica could then deposit on fuel, increasing the surface temperature and hence fuel cladding failure probability.

237 In TQ-EPR-906 (Ref. 8), I requested information on these filters. The French standard for filter mesh is defined differently to the UK. In their response, EDF and AREVA said their precise throughputs would be specific to the filter manufacturer but did provide some information on changing the filters.

238 The primary function of the filters downstream of the resin beds is not to remove corrosion products but to prevent resin beads from being flushed from their beds into the main circuit. The escape of small quantities of resin would lead to a build-up of sulphur compounds in the coolant, which are known to increase cracking and other corrosion problems. Ref. 168 quotes an absolute filtration rating of 99.8% at 10 μm, which I consider adequate for this duty. Ref. 168 also notes that "*glass fibre is not recommended*", which is a positive step but not as restrictive as may be necessary.

239 UK EPR differs from the progenitor Konvoi CVCS design in having filters upstream of the resin beds. These are the main filters for removing crud from the primary coolant. Ref. 168 specifies an absolute filtration rating of 99.8% at 1 μm. Coarser filters may be necessary during commissioning and the 1 μm specification may only be achievable some time later. The specification of the filter in use should be reviewed by the Licensee as operational data become available and adjusted to achieve satisfactory filtration, but

this is normal practice in PWRs. Along with the ion-exchange resins, these filters are expected to be the most radioactive and significant source of solid radwaste from CVCS. A sophisticated shielded and automated machine will be used to change them, minimising ORE. Cartridges are used for all these filters, simplifying handling. Refs 167 and 168 describe techniques to minimise operator dose when changing filters.

240 Filters upstream of the resin beds offer the additional advantage of ensuring a physical barrier to the gross escape of resin. An incident at Fessenheim in 2004 (Ref. 170) proved how significant such a release could be, although that release occurred through a safety valve which relieved back into the primary circuit. Because the incident challenged safety systems at Fessenheim, EDF and AREVA took account of the experience when designing UK EPR.

241 The design presented for UK EPR is clearly appropriate for detaining particulates as early as possible and preventing their transfer to locations of potential harm. Mechanical handling will reduce doses to operators changing the main high-radiation media. I am content with the location and generic design of filters used in UK EPR.

242 The usage data provided by EDF and AREVA in TQ-EPR-906 describes the criteria for changing the filters and does not identify how often they actually would be changed. The frequency of filter change will be very dependent on the filter mesh size and the performance of the plant in terms of generation of suspended solids in the coolant. I note that Refs 168 and 169 are inconsistent in their specification of mesh size for these filters. Clearer specifications will be needed before inactive commissioning. EDF and AREVA have said that filter specifications would not be reviewed but the specification of the main filter is optimistic and should be reviewed by the Licensee during commissioning and thereafter. I consider this to be an Assessment Finding **AF-UKEPR-RC-06**.

243 Overall, I consider the design of the fixed filtration equipment to be suitable and sufficient for the CVCS of UK EPR. Since various types of filter media exist and media are disposable items, I am satisfied that the specifications for filter media are reasonable at this stage, and I have identified a finding covering more detailed specifications. The arrangements for filter change are sophisticated and it appears significant effort has been invested in this regard by EDF and AREVA which should have benefits for ORE and radwaste.

4.2.2.3.3 Evaporation

244 EDF and AREVA wish to recover the EBA used to control reactivity in the core, for economic reasons. Because of its cost, most EBA in use would be recycled, with very little make up during operations – only that which is required to compensate for leakage or isotopic depletion. To do this, discharged coolant will undergo evaporation as part of the CSTS where EBA will be recovered from the evaporator concentrate and returned to the RCS as part of the RBWMS. The CSTS is a complex system, providing a number of functions. EDF and AREVA split the CSTS into four separate sub-systems:

- Coolant Storage and Supply System (CSS)
- Coolant Purification System (CPS)
- Coolant Treatment System (CTS)
- Coolant Degasification System (CDS)

245 The CSS consists of six storage tanks which are used to hold water (either fresh or produced in the evaporator) or discharged coolant. The CPS consists of the ion exchange

vessel described in Section 4.2.2.3.1, used to further purify the discharged coolant before treatment in the CTS. The CDS (CSTS-4) is used to degasify the primary coolant, and is assessed in Section 4.2.3.3.4, below. The CTS contains the evaporator part of the CSTS and is used for:

- Separation of reactor coolant, which is discharged during normal operation of the plant and which is temporarily stored by the CSS, into a concentrated boric acid solution (4 wt. %) (concentrates) and demineralised water (distillates), for further reuse in the primary circuit.
- Degassing (via CSTS-6) of the distillates prior to either their reuse in the primary circuit and degassing of demineralised make-up water.

246 The CSTS SDM (Ref. 113) provides detailed information on the intended operation of the CSTS, so is not repeated here. The SDM states that the main operating mode will be "*evaporation without degasification and with coolant recycling*" and this arrangement is shown below. Note however that this may not actually be the most frequent operating mode, as this recycles the water from the evaporator as well as the EBA and has implications for tritium controls in the plant; see Sections 4.5.1, 4.2.11 and 4.3.2.3. This arrangement is shown in the following figure.

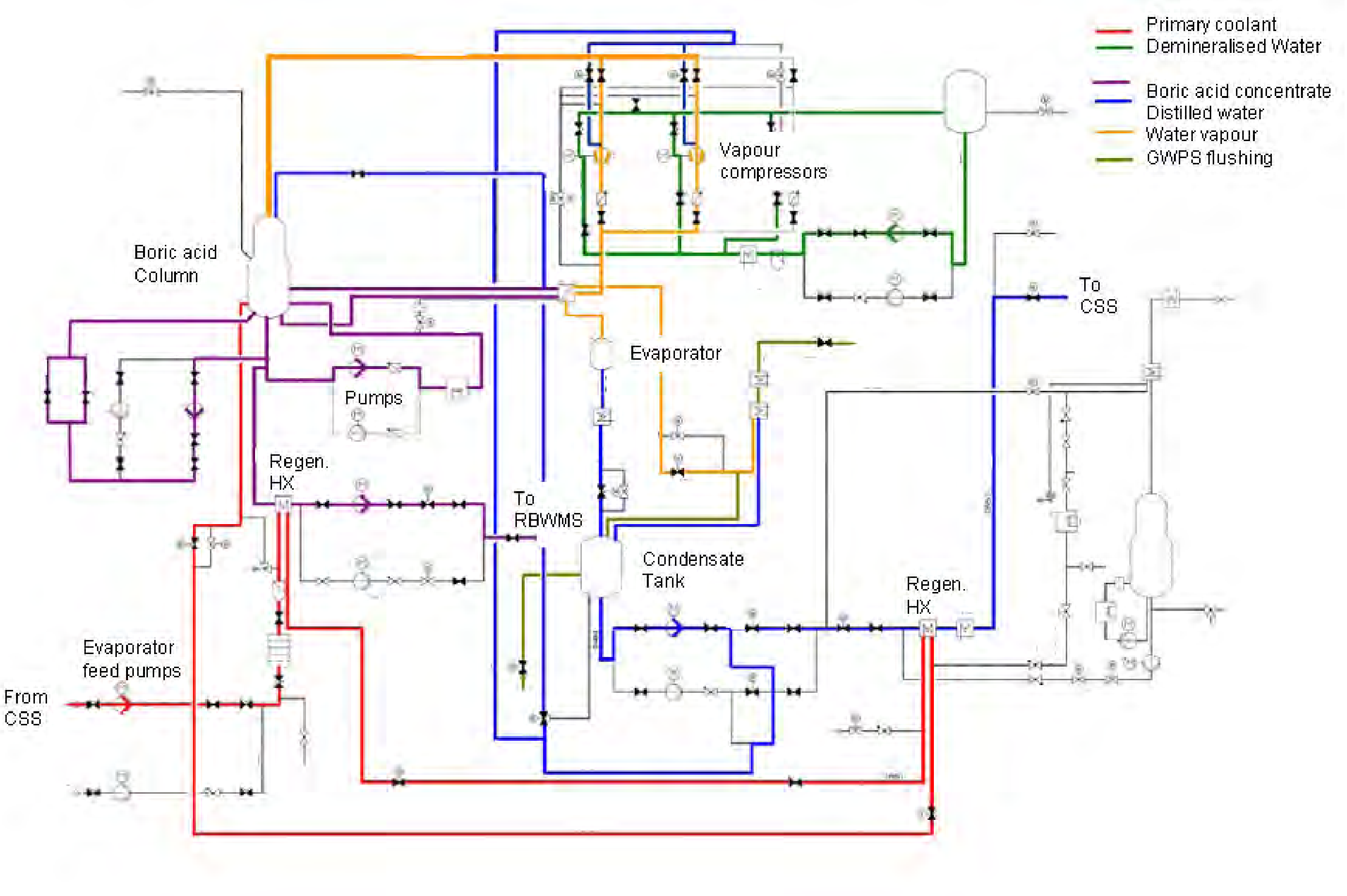


Figure 7: UK EPR Coolant Storage and Treatment System (operating with evaporation without degasification and with coolant recycling)

247 In this arrangement, coolant stored in the CSS is passed through several stages of pre-heating by regenerative heat exchangers before entering the boric acid column. In this column the coolant is separated into steam and boric acid by evaporative heating. The separated boric acid solution at 4 wt. % is sent to RBWMS via one boric acid delivery pump. The steam produced is extracted and compressed by 2 of the 3 vapour compressors for condensing on the shell side of the evaporator thus bringing the heat of evaporation back into the process. The condensed water, the distillate, is collected in the condensate collector, cooled down by the evaporator and let into the condensate tank. The distillate is sent by one of the condensate pumps (after cooling down to 50°C) back into the CSS for storage. A small flow of demineralised water is routed via the three-way valve back into the boric acid column for filling the bubble trays.

248 While the detailed engineering may be different in UK EPR, the process of evaporation to recycle boric acid is well known and used in many PWRs. As such the consequences of such operations are known and can be controlled. The main drawback with such processes is the unintentional accumulation of other non-volatile species in the boric acid concentrate over time, such as radioactivity, lithium, zinc or impurities such as silica. The addition of the further ion exchange bed in the CPS before evaporation should minimise these effects in UK EPR (see Ref. 102, TQ-EPR-910, Ref. 8 and Section 4.3.2.2 of this report). This will also help to control ORE in the region of the evaporator.

249 Originally, EDF and AREVA thought the water distillates could also be recycled when required. I recognised this would have implications for the tritium build-up in the plant. Through RO-EPR-74.A1 (Ref. 9), I asked EDF and AREVA to justify levels of tritium in the Nuclear Island (NI) systems, such as the RCS, SFP and IRWST. In response to this RO, EDF provided a translation of the guidelines used by the rest of their fleet (Ref. 34). Since UK EPR has different power and tritium production rates, I requested assessments for tritium calculated specifically for UK EPR. EDF and AREVA responded with Refs 106 and 107, which are assessed in Section 4.2.11.4 of my report. As a result of these discussions, EDF and AREVA now propose to dispose of most distillate from this evaporator, see TQ-EPR-835 (Ref. 8). The coolant will be further cleaned and tested in the liquid radwaste system, as assessed in Section 4.5.1, before discharge in accordance with environmental discharge limits. I did not assess the potential for recycle of ammonia as the bulk of the distillate will not be re-used.

250 Because the purification systems are not effective at removing impurities such as silica or fluoride, there is no substitute for a high-purity demineralised water feed system, as has been provided for UK EPR, see Section 4.4.2.1.9. However, irrespective of this some level of impurities could accumulate within the evaporated boric acid. EDF and AREVA provided some information on this in their response to TQ-EPR-1042 (Ref. 8) and EDF states that there has never been a difficulty meeting the fluoride specification in their fleet of N4 reactors. However, as this is dependant on the site specific strategy, the licensee should show the effect of EBA recycle on impurities such as fluoride and silica, which are not removed by the standard ion-exchange units in UK EPR, as part of their EBA strategy for the plant. This is part of **AF-UKEPR-RC-04**.

4.2.2.3.4 Degasification

251 Gaseous species can accumulate within the primary coolant of any PWR from a number of sources including purposeful additions (hydrogen), adventitious impurities (for example oxygen or nitrogen) or from the fission or activation processes (for example xenon or krypton isotopes from fuel leakage or helium from the soluble boron). These are all

relatively small volumes, whereas large rapid intrusions, for example that might affect safety system performance, are not considered as part of Reactor Chemistry.

252 UK EPR differs from other PWRs because most of the CVCS coolant flow by-passes the Volume Control Tank (VCT). The coolant that does enter the VCT is maintained under a nitrogen atmosphere hence may also pick up further dissolved nitrogen before mixing with the main return flow. This would leave radioactive and non-radioactive gases to circulate in the coolant and accumulate in the pressuriser. To prevent accumulation to hazardous levels, these gases should be monitored and removed periodically.

253 To prevent activity releases in a shutdown and to prevent flammable gas mixtures forming, the design of UK EPR includes an engineered degassing facility called the Coolant Degasification System (CDS), part of the CSTS. The CDS will be operated just before shutdowns and start-ups and can be operated at other times for adjustment. The gases removed by the degassifier are usually passed to the Gaseous Waste Processing System GWPS. Since operation of the CDS may introduce more gas than GWPS can handle during start-up, the extracted gas can be sent to the Nuclear Auxiliary Building (NAB) ventilation system instead. Start-ups and shutdowns are assessed in Section 4.2.11.

254 The reactor coolant, coming from the RCS via the CVCS, enters the degasifier column above the top plate (bubble tray) with a temperature of approximately 50°C and descends under counter current flow conditions through the rising vapour. The gaseous and liquid phases are intimately mixed while passing the bubble trays. To allow the coolant to boil the degasser is maintained at a sub-atmospheric pressure of 0.125 bar. Under these conditions, most of the gases dissolved (> 99%) in the coolant are released and extracted from the column to the GWPS (normally). The degasified coolant is pumped back to the CVCS using the degasifier extraction pump. The degasifier can also be used as part of the CSTS for preparing degasified demineralised water for use in the CVCS. The design of the CDS makes provision for the condensation of the moisture inevitably created.

255 When CDS is operated at power, most of the hydrogen that is deliberately added to the coolant will be lost, so the downstream hydrogen injection system would be used to replenish dissolved hydrogen to the set level, see Section 4.2.2.3.

256 Any remaining permanent gases that do accumulate in the pressuriser would be removed by a vent line in a controlled manner, see TQ-EPR-158 (Ref. 8). Whilst most of the ^{14}C will be removed to gaseous waste by these methods, there is a paucity of data on the fraction that remains within the coolant. This is not a problem with degasification and is discussed further in the sections on zinc (Section 4.2.6) and radioactivity (Section 4.2.3).

257 I have examined these design features and find them a satisfactory alternative to use of the VCT to provide degasification in UK EPR. The volume control tank in UK EPR will have a greatly reduced role compared to other PWRs. Although the flow though the VCT will be lower, the pressure in the VCT will still control the concentrations of gases in the coolant. I was satisfied that the new arrangements for the control of radioactive and flammable gases in the primary coolant would be adequate.

4.2.2.4 Other Aspects

258 In addition to the purification and treatment of coolant, my assessment of the CVCS covered a number of other aspects. These included the provision of seal water, the operation of valves and corrosion. These additional assessment areas are summarised below.

4.2.2.4.1 RCP Seal Water Supply

259 As is common in PWRs the main RCPs in UK EPR have a seal system which prevents leakage of active primary coolant. The UK EPR is no different in this respect and the CVCS provides the seal water for these seals. Ref. 167 describes the provision of water to the number 1 seal on the main cooling pumps as one of the "*operating missions*" of the CVCS.

260 The injected water is taken from the CVCS injection line in normal operation and passed through one of two filters arranged in parallel (both filters are not used simultaneously). Used seal water returns to the VCT. If there were a dilution fault and the CVCS were isolated, the provision of seal water in UK EPR is unlike the arrangement in Konvoi reactors. Water for the seals is supplied from the IRWST in UK EPR, unlike the Konvoi reactors which maintain the seal coolant from Extra Boration System (EBS). If the CVCS is isolated in UK EPR, the seal water would be supplied from the IRWST and the return sent to radwaste.

261 The upstream (main) filters, the resin beds and downstream filters would probably be used almost continuously, but the coolant flow can be diverted to avoid them. Because the coolant does not always pass through the main filters, particles might reach and damage the coolant pump seals, so filters are provided on the seal water feed to prevent this. This was one of the main systems affected by the resin leak at Fessenheim in 2004 (Ref. 170).

262 Filters are provided on the seal water return to prevent material from pump bearing wear (typically high cobalt) from being recycled to the RCS. Refs 168 and 169 are inconsistent in their specification of mesh size for these filters, and this is a subject of Assessment Finding **AF-UKEPR-RC-06.**

263 Usually, the seal water filters only see water that has already been filtered. Therefore I expect the usage and radioactivity of the seal filters to be low. I am content that adequate provision has been made for the supply of seal water in UK EPR.

4.2.2.4.2 CVCS Materials

264 The internal surface area of the CVCS in UK EPR forms a small but potentially significant fraction of the total metal area exposed to coolant in the reactor. There are a number of components in the CVCS made from different alloys including motors, valves and some joints with seals. The amount of cobalt and presence of any silver or antimony in these materials could impact radioactivity in the reactor if released to the coolant and activated in the core. This might arise due to corrosion, wear or maintenance activities. Activated material might then deposit elsewhere in the reactor, as hot-spots in ponds, or return to the CVCS for treatment as waste, also becoming a source of radiation to workers during shutdown.

265 I have considered the CVCS as a particular source of material for the generation of inadvertent radioactivity in Section 4.2.3 of my report. Overall, EDF and AREVA have gone to great lengths to consider improved materials for most applications in the CVCS, see Section 4.2.3.

4.2.2.4.3 Prevention of Leakage

266 The CVCS in UK EPR performs a number of different roles in preventing leakage, which are given the high A1 and A2 (or F1A and F1B in France) classifications. The CVCS in UK EPR features the isolation and containment valves I would expect to see for such

duties. There are two unusual features which illustrate the complexity of this function, both requirements not to overfill the reactor with coolant:

- Should a leak develop in the SG, primary coolant would flow into the secondary side of the SG and the secondary side may begin to fill with radioactive primary coolant. There is a signalling system to shut off the CVCS and prevent liquid coolant flowing out of the secondary relief valves. The Reactor Chemistry aspects of such events are assessed in Section 4.6.2 of my report.
- High-pressure charging pumps should not be operated when the primary circuit is water solid. This hazard is similar in UK EPR to any other PWR and the plant features Low Temperature Overpressure Protection (LTOP) for such instances. See Section 4.2.11 on start-up and shutdown operations and the assessment of start-up in Ref. 116.

4.2.2.4.4 Valves

267 The CVCS in UK EPR contains a greater number of valves, pumps and vessels than earlier generations of PWRs. In my assessment I looked for valve failures that might create a particular hazard and identified two groups of valves whose failure might be considered as safety challenges:

- Two valves and one check-valve in series, which supply the pressuriser with an auxiliary spray have a significant role in controlling the reactor.
- In the main CVCS flow path, there are ten motorised valves, three check-valves, one manual valve and three three-way valves in series. If any one of these were to stick closed, all CVCS flow would stop.

268 It is foreseeable that one of these valves could stick closed, in which case there could be an impact on the plant. Considering each of these carefully in terms of their overall safety impact, I concluded that other installed safety systems (SIS, IRWST etc) would be sufficient to protect the reactor should this unlikely event happen. Therefore I was content that the design and categorisation of these valves in UK EPR was adequate.

269 Section 2.5.3 of the CVCS SDM (Ref. 167) identifies the key functions that require periodic testing but does not identify specific valves. I have not seen operational experience for some of these valves. Operational experience of these valves in conditions representative of UK EPR operating conditions should be established and a mechanism put in place to guide maintenance staff where new components will require extra monitoring. It would be normal practice for the licensee to monitor the performance of all new types of hardware until their performance and reliability have been well established. The number of components in UK EPR increases the need for clear operating instructions and displays. Overall, I consider the CVCS hardware in UK EPR to be sophisticated and flexible rather than complex or unreliable in this regard.

4.2.2.4.5 CVCS as a Source of Coolant for Other Systems

270 The CVCS in any PWR performs a number of functions to purify and treat reactor coolant for ancillary systems outside the RCS. For instance, when the reactor is opened for refuelling, there is a significant exchange of cooling water and radioactive contamination between the primary circuit, Spent Fuel Pool (SFP) and In-Reactor Water Storage Tank (IRWST). In addition the CVCS is the source of concentrated boric acid for use in safety supplies, as assessed in Section 4.2.8.

271 EDF and AREVA described the design features and operating modes of the UK EPR CVCS for clean-up of the IRWST and SFP and details are provided in the CVCS SDM (Ref. 167). Whilst I was generally content with the flexibility of the design, two questions arose:

- How much radioactive material did EDF and AREVA *expect* to be transferred to the Spent Fuel Pool (SFP) and how could it be kept as low as reasonably practicable.
- How does UK EPR control and adjust boron in these and a number of other vessels.

272 My assessment of the former is addressed in Section 4.3 of this report. To address the latter, I raised TQ-EPR-1235 (Ref. 8) asking EDF and AREVA to outline the actions required to maintain the proper boron enrichment in all of the tanks and vessels in UK EPR. This is as described in Section 4.2.2.2.1.

4.2.2.5 Summary

273 My assessment has focussed on its prime safety functions and areas that were new to the design. I have assessed the CVCS in UK EPR as a radwaste processing system, as a source of treated coolant and as a homogeneous dilution source. Based upon the evidence presented during GDA, the main conclusions I draw for the CVCS assessment are:

- Overall, I consider the CVCS hardware provides sophisticated and flexible facilities for the treatment of coolant in UK EPR. The bulk of the design for the CVCS is closely based on existing German plant that has run safely for many years. The number of features that the CVCS has will increase the need for clear operating instructions and displays.
- The CVCS in any PWR has a finite capability to clean up the coolant and does not substitute for a high-purity feedwater system. The CVCS in UK EPR is no exception.
- The CVCS in UK EPR has a high coolant flowrate which creates more demand for a strong dilution protection function. EDF and AREVA have engineered a highly redundant system to protect against boron dilution faults, which is the subject of a Fault Studies GDA Issue, **GI-UKEPR-FS-01**, see Ref. 58. In other respects the CVCS provides suitable and comprehensive facilities for the control of boron. I note the use of EBA proposed for UK EPR and consider that EDF and AREVA have clearly considered implications for its application thoroughly. I have raised a finding related to this.
- EDF and AREVA have proposed changes to the ‘normal’ means of adding lithium and hydrogen to the primary coolant. These are based upon proven techniques applied at existing PWRs. The zinc addition system is a simple process, similar to many currently in use. I have assessed novel features in the design for the injection and removal of gases and consider them a suitable alternative to the use of the VCT for this purpose. I am content with the proposed arrangements for chemical dosing in the CVCS of UK EPR.
- I am content that the systems in the CVCS have been designed to process radwaste safely and effectively. The number of filters and resins for the purification of coolants is comprehensive and their usage criteria appear reasonable. However, the CVCS resins may have to be discharged before they are fully loaded, thereby increasing the volume of solid radwaste from UK EPR in proportion to its radioactivity. The increase in volume would however be small, at one or two cubic metres per year.

- Several points identified in my assessment should be covered by documentation being provided to the licensee. For instance:
  - i) Part of the process of achieving adequate control will include the quantification of the normal operating chemistry for UK EPR and the specification of controls. These are the subjects of findings elsewhere in this report.
  - ii) EDF and AREVA are developing documentation specifying purity and cleanliness for components and processes from shop fabrication onwards.
- A number of components in the new reactor would need monitoring until their performance and reliability have been well established. The performance of components made with materials which differ from previous designs should be reviewed as data becomes available.

274 I judge that the claims, arguments and evidence as presented for the CVCS appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.2.6 Assessment Findings

275 Based upon the assessment of the CVCS in UK EPR described in Section 4.2.2 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-04*** *– The Licensee shall generate a detailed risk analysis, fully justifying the boron strategy to be applied. This should include commissioning, the fuel management and chemistry requirements, necessary control actions and effects from evaporation on radioactivity and impurity accumulation. This Assessment Finding should be completed before fuel is loaded into the reactor and boron is required for reactivity control. Target Milestone – Fuel on-site.*
>
> ***AF-UKEPR-RC-05*** *– The Licensee shall clearly identify the boron metering system used for safety and specify procedures that ensure common-mode calibration errors do not arise. This Assessment Finding should be completed before the first fuel is brought onto site to ensure rigorous control of borated coolant used for reactivity control. Target milestone - Fuel on-site.*
>
> ***AF-UKEPR-RC-06*** *– The licensee shall implement appropriate control over the specifications for filters and other consumables with nuclear applications. The specifications should include purity and cleanliness requirements and take account of minor inconsistencies noted in this assessment regarding filter and resin aging and replacement and consider conversion of French specifications for materials and consumables to UK specifications. This Assessment Finding should be completed before the first use of such consumables on site. Target milestone - Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

4.2.2.7 GDA Issues

276 Based upon the assessment of the CVCS in UK EPR described in Section 4.2.2 above, I support the following GDA issue on boron control, originally raised by Fault Studies, which requires resolution before I can be satisfied from a Reactor Chemistry perspective:

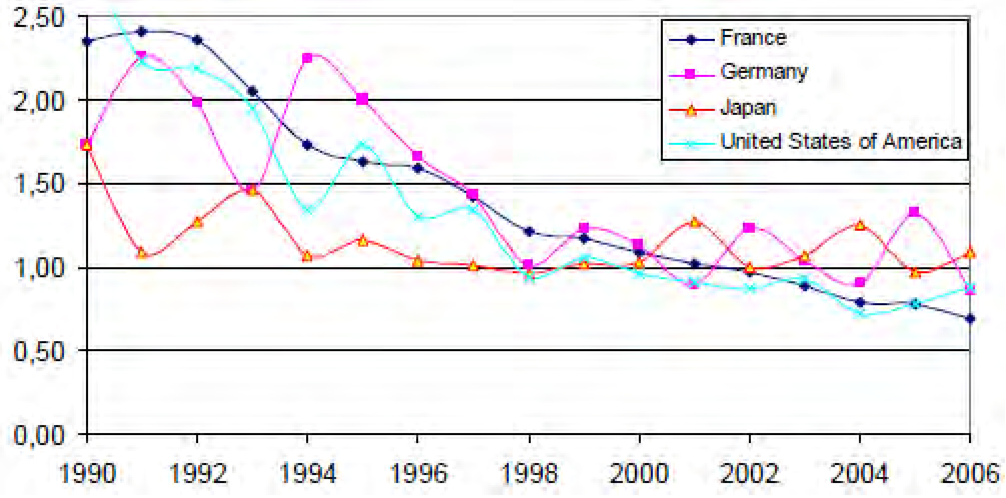
> ***GI-UKEPR-FS-01*** *– Heterogeneous Boron Dilution Safety Case – A safety case for heterogeneous boron dilution events is required. Both external dilution events and intrinsic dilution mechanisms from certain accident situations need to be addressed.*

4.2.3 Assessment – Material, Chemistry and Radioactivity

277 Radioactivity carried by the primary coolant of a PWR is a principal source of ORE and routine radioactive wastes as well as a potential source term in accidents. Roughly 90% of the ORE in a PWR can arise from activated corrosion products, and the major source of this is fuel crud. Unlike many other source terms in a PWR (core radiation, ^{16}N, spent fuel etc.), the operator of a PWR can influence the amount of crud produced. As well as activation of corrosion products, other sources of radioactivity arise from activation of the coolant additives or impurities and releases of fission products from the fuel cladding, either through diffusion or more directly, but unlikely, in the case of cladding defects.

278 From a Reactor Chemistry perspective an important characteristic of the primary circuit systems are the materials which are in contact with the primary coolant. Corrosion causes metallic corrosion products to be carried by the coolant into the core, where they may become activated in the radiation field. The selection of materials in contact with the coolant is a primary factor that determines the susceptibility of the reactor to the production of activated corrosion products. In a PWR, essentially all of the activated corrosion products within the plant are produced by the activation of material released either via general corrosion or wear of the RCS materials in contact with the coolant. Reactor Chemistry has a direct influence on the extent of general corrosion; in addition it can influence the redistribution of released material around the RCS and connected systems, depending on factors such as solubility or speciation.

279 Historically there has been a great variation in levels of radioactivity generated by different PWRs. The figures below illustrate average world-wide annual worker doses (in man.Sv) per PWR in different countries (Ref. 195). While it is difficult to directly compare results of this nature, due to factors such as plant design, number of plants and cycle history, these graphs do exemplify the general trend towards lower ORE seen in recent years for PWRs:



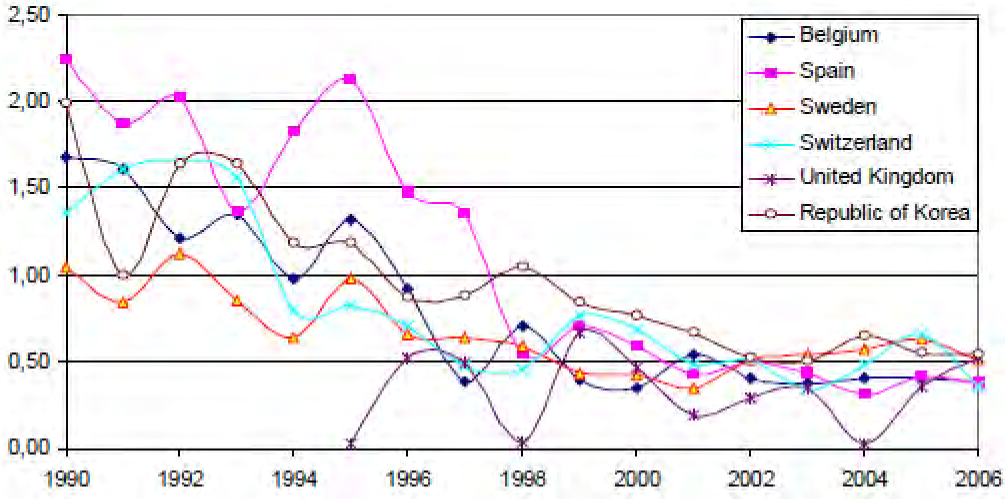


Figure 8: Evolution of Average PWR Collective Radiation Exposure by Country

280 One of the main reason for the wide variability is the interaction of the materials of these reactors with the chemistry of the coolant. General corrosion, even if slight, results in the passage of non-radioactive cobalt and nickel through the core to be activated to the intensely radioactive isotopes ^{58}Co and ^{60}Co, which are the main sources even in the best controlled plants. The nickel and cobalt dissolves in the coolant, agglomerates as fine particulate, or deposits out on the fuel. The more corrosion product residing in the core at any one time, the more radioactivity is produced. There are therefore four main ways of avoiding this form of radiation build-up:

- Choice of materials to minimise the release of elements such as cobalt and nickel into the coolant.
- Modifying the chemistry to reduce corrosion, by controlling a large number of parameters including pH, levels of zinc and oxygen.
- Using the CVCS clean-up system to try and remove as many of the precursors and radioactive products as possible.
- Maintain high purity specification make-up sources and avoid adventitious impurities.

281 The influence of material choices in UK EPR on chemistry, and vice versa, was an area for assessment during Step 4. The overall assessment objective was to determine whether or not primary circuit radioactivity had been reduced So Far as is Reasonably Practicable (SFAIRP) in UK EPR, based upon both the chemistry and material choices. The following sections describe my assessment of primary circuit chemistry and materials on radioactivity in UK EPR. An outline of some of the activities undertaken by AREVA to reduce radioactivity in EPR is presented in Ref. 190.

4.2.3.1 Overview

282 Decreasing personnel doses and controlling radwastes were important objectives for EDF and AREVA in the design of UK EPR and Section 2.1 of Chapter 12.4 of the PCSR (Ref. 11) presented their claims for GDA that this goal had been achieved. The evidence which supported this was based on the best performance of the French fleet. Since this appeared to take little account of the specifics of the UK EPR design, I raised RO-UKEPR-46 (Ref. 9) asking EDF and AREVA to justify that materials and chemistry

specified for UK EPR would achieve the low levels of radioactivity claimed, based on both the material (Action 1) and chemistry (Action 2) choices.

283 Their replies (Refs 13 and 161) outlined the main material choices and the chemistry needed to minimise the concentration of corrosion products in the coolant and minimise their deposition on fuel cladding and limit accumulation on out-of-core surfaces. This would be achieved by controlling the pH and dissolved hydrogen at a steady value throughout the cycle, avoiding oxidising conditions at temperature, and preventing the ingress of impurities such as chloride, which are known to cause corrosion. The information supplied in the RO responses was later supplemented by TQs requesting a full material schedule and further fabrication details intended to control corrosion, as well as information on calculations performed in TQ-EPR-864 (Ref. 8). In reply to TQ-EPR-864, EDF and AREVA said no modelling of the corrosion product source term was undertaken for UK EPR, although the PACTOLE code had been used for the calculation of pH profiles. Therefore, I commissioned TSC support to undertake modelling of the corrosion product source term in the UK-EPR (Ref. 133). I also commissioned TSC support to review the materials of construction of UK EPR and chemistry of the primary circuit (Ref. 149). The assessment that follows is consistent with this TSC review. The information in these responses is summarised below.

284 Information on the basis for the UK EPR radiation analysis is provided in the following documents:

- Source term overview: Use of source term in the different GDA areas (Ref. 176) , plus associated references.
- Source term: Primary Source Term of the EPR Reactor (Ref. 60).

285 There were a number of parallel ROs and TQs raised in GDA on other aspects of radioactivity in UK EPR:

- I raised RO-UKEPR-74 (Ref. 9), asking EDF and AREVA to quantify and justify levels of radioactivity leaving the primary circuit and entering other systems in the Nuclear Island (NI), including the Spent Fuel Pool and IRWST, mainly as a result of refuelling activities. Some responses to this RO were received during the writing of this report and others were not. Those received are assessed further in Sections 4.5.1, 4.2.11 and 4.3.2.3 of my report. EDF and AREVA have agreed to complete this work under GDA Issue **GI-UKEPR-RC-02**.
- RO-UKEPR-73 (Ref. 9) was raised as a joint RO with Radiation Protection, Radwaste and Decommissioning and the Environment Agency. This RO sought assurance that the whole of the source term was applied consistently to the estimations of doses and radwaste. The total source term for dose prediction includes some radiation sources over which the licensee has little control but in a well-designed reactor these may be one tenth of the radiation from corrosion-product sources described in this section. These responses are assessed further in Sections 4.6.2.2 and 4.5.11

286 A number of other areas of the assessment are relevant to radioactivity:

- EDF and AREVA wish to add zinc to the coolant to further reduce out-of-core fields. This would be new to the UK and the addition of zinc is discussed in Section 4.2.6.
- To prevent oxidising conditions, hydrogen is added to the coolant and this is assessed in Section 4.2.7.

- My assessment also included tritium and ^{14}C, which are not major contributors to occupational dose but are accumulated and discharged in radwaste of various types. These are covered in Sections 4.2.3.3.3 and 4.2.3.3.4 of my report.
- Most of the other radioactive fission products and actinides generated in UK EPR will stay in the fuel. My assessment of the chemistry relating to the fuel concentrated on preventing major releases by maintaining fuel integrity. Generally, chemistry that minimises crud build-up on fuel helps to maintain fuel integrity (limiting defects induced by cladding corrosion) as well as reduce the activation of corrosion products.
- The fission products and actinides generated from tramp uranium or which escape from defective fuel elements are captured by waste-treatment systems, described in Section 4.5.1 of this report.
- My assessment of the radioactive source term (mainly iodine) in accidents is presented in Section 4.6.

287 EDF and AREVA have provided assurances that in normal operation, fission products will be minor contributors to Operator Radiation Exposure. The following sections describe my assessment of the bulk materials in the reactor, use of cobalt, other elements and nuclides and my assessment of the chemistry, with initial results from the simulations that I commissioned. I have coordinated with both the Radiation Protection and Radwaste and Decommissioning inspectors in this important area throughout Step 4.

4.2.3.2 Materials

288 EDF and AREVA identified the significant nuclides that may be produced from the RCS materials in UK EPR in Ref. 176:

Nuclide	Origin	Reaction(s)	Approximate half life	Main gamma energies / KeV
^{58}Co	Nickel alloys (Inconel 690) and Stainless steels	$^{58}Ni\ (n,p) \rightarrow {}^{58}Co$ $^{59}Co\ (n,2n) \rightarrow {}^{58}Co$ $^{55}Mn\ (\alpha,n) \rightarrow {}^{58}Co$	71 days	511 (30%) 811 (99%)
^{60}Co	Stellite™, impurities of other metallic materials	$^{59}Co\ (n,\gamma) \rightarrow {}^{60}Co$ $^{58}Ni\ (n,\gamma) \rightarrow {}^{58}Co \rightarrow {}^{59}Co \rightarrow {}^{60}Co$	5.3 years	1173 (100%) 1333 (100%)
^{54}Mn	All the metallic materials	$^{54}Fe\ (n,p) \rightarrow {}^{54}Mn$	312 days	5 (23%) 835 (100%)
^{59}Fe	All the metallic materials	$^{58}Fe\ (n,\gamma) \rightarrow {}^{59}Fe$	45 days	1100 (57%) 1300 (43%)
^{110m}Ag	Neutron absorbers Ag-In-Cd in control rods, some silver coated seals	$^{109}Ag\ (n,\gamma) \rightarrow {}^{110m}Ag$	250 days	658 (94%) 885 (73%)
^{122}Sb	Pump bearings, Secondary neutron sources	$^{121}Sb\ (n,\gamma) \rightarrow {}^{122}Sb$	2.7 days	567 (71%)
^{124}Sb		$^{123}Sb\ (n,\gamma) \rightarrow {}^{124}Sb$	60 days	603 (98%) 1691 (48%)
^{125}Sb		$^{124}Sb\ (n,\gamma) \rightarrow {}^{125}Sb$	2.8 years	400 670

Nuclide	Origin	Reaction(s)	Approximate half life	Main gamma energies / KeV
^{51}Cr	All the metallic materials	^{50}Cr (n,γ) $\rightarrow$ ^{51}Cr	28 days	5 (20%) 320 (10%)

Table 6: Significant Radionuclides Produced from RCS Materials

289 The amount of corrosion that affects radiation production is very small and often invisible to the naked eye. Nevertheless, the exchange of material that occurs in general corrosion over several thousand square metres can create, indirectly, quantities of cobalt and other nuclides which are significant for radioprotection. There are three main sources of activated cobalt:

- Corrosion products from components made from cobalt or high cobalt alloy
- Corrosion of steels and alloys which contain traces of cobalt
- Corrosion of nickel alloys with subsequent activation of the released nickel

290 General corrosion is greatest at the beginning of a reactor's life, and should fall by a large factor over 4 – 8 cycles of operation (Ref. 148). This process is known as passivation and the target for a good reactor is to achieve a high factor of improvement in the least number of cycles. This does not diminish the need for careful chemistry control, which is a vital part of this process.

291 I raised RO-UKEPR-46.A1 (Ref. 9) requesting justification from EDF and AREVA that the materials in UK EPR had been selected so as to reduce levels of radioactivity So Far As Is Reasonably Practicable (SFAIRP). In Ref. 133, they outlined the selection of bulk materials, cobalt alloys and other materials for UK EPR. Many components would be made entirely from stainless or nickel-based alloys that resist corrosion. Ferritic alloys are used where greater strength is required, but have lower corrosion resistance. Stainless alloys are therefore also used to clad the ferritic alloys. Almost all the wetted surfaces would be made from stainless or Inconel, except the fuel and small areas where special materials are needed. In UK EPR, the SG tubing would be made from Inconel 690, a nickel-based alloy.

292 The surface area of each alloy is an important factor. Low-cobalt alloys with a very small surface should make little contribution to activity build-up. Stellites^{TM} and large surfaces like the SGs, will have a bigger effect. In TQ-EPR-1236 (Ref. 8), I asked EDF and AREVA which surfaces they thought were the most important. They replied that steam-generators provide 88% of the surface of the reactor (excluding fuel) and expect them to contribute 10 – 20% of the ^{60}Co activity. I requested further evidence of wetted material surface areas in TQ-EPR-900 (Ref. 8), for the hard-surfaces and claddings in TQ-EPR-1190 (Ref. 8) and for weld details in TQ-EPR-1194 (Ref. 8). The following table (from TQ-EPR-900 (Ref. 8)) lists the wetted surface areas of the principal alloys.

Alloy	Total Wetted Surface Area / m^2	Typical locations
Inconels		
Inconel 690 [redacted]	[redacted]	SG tubes

Alloy	**Total Wetted Surface Area / m^2**	**Typical locations**
Inconel 52 [redacted]	[redacted]	SG tube sheet cladding
Inconel 718 (aged)	[redacted]	Fuel grids and springs
Stainless steels		
[redacted]	[redacted]	Fuel nozzles
[redacted]	[redacted]	Fuel anti-debris filters
[redacted]	[redacted]	RPV cladding
[redacted]	[redacted]	Core internals
[redacted]	[redacted]	Core support plates
[redacted]	[redacted]	RCP
[redacted]	[redacted]	CVCS piping and tanks, RCP
[redacted]	[redacted]	RCP internals
[redacted]	[redacted]	RCP coils
[redacted]	[redacted]	RCS loop piping
[redacted]	[redacted]	CVCS heat exchanger tubes
High Cobalt alloys		
Stellite^{TM}	[redacted]	RPV internal, Control Rod Drive Mechanism (CRDM) and RCP
Zircaloys		
M5®	[redacted]	Fuel cladding

Table 7: Wetted Surface Areas of the Principal Alloys Used in the UK EPR Primary Circuit

293 Generally, French grades of stainless steel were specified for much of the CVCS. It was necessary to convert the French grades to their AISI (American Iron and Steel Institute) equivalents for our assessment. It appears that most of the RPV wetted parts and internal assemblies will be constructed of grades 308L, 304L and 304LN stainless steels. Other primary circuit pipework (hot leg, cold leg, crossover leg etc.) are essentially constructed from grade 304 and grade 304LN stainless steels. In addition, the lower and upper support plates comprise Association Française de Normalisation (AFNOR) grades with chromium and nickel levels comparable with 304LN. My assessment of these material choices appears in the following sections, apart from the fuel cladding which is discussed in Section 4.2.5.

4.2.3.2.1 Bulk materials

294 In a typical western PWR, successful reductions in ^{60}Co will leave proportionally more ^{58}Co because it is more difficult to replace Inconel than Stellite^{TM} in reactors. Alloy 800 is not an Inconel and could be a replacement, but its different thermal properties would have a significant effect on the reactor design. The Inconel alloys used in most PWRs, especially for SG tubing, contain a significant proportion of nickel. As the SG tubes make

up a high percentage of the RCS internal surface area, any slight corrosion of such a large area will result in some nickel transferring to the core of the reactor. Nickel does not absorb neutrons as much as cobalt, but moderate absorption does produce a radioactive product ^{58}Co with a 71 day half-live.

295 To minimise corrosion, Inconel alloys contain chromium which is meant to form a corrosion resistant layer. Unfortunately, the chromium level in the Inconel 600 used in earlier PWRs was insufficient to prevent chromium-free regions developing at grain boundaries during thermal treatment. The Inconel 690 specified for UK EPR has much higher chromium content which helps to stabilise the grain boundaries. Steam-generator tubing, tube divider plates and some radial supports and nozzles in the reactor head will be made of Inconel 690.

296 A number of other radioisotopes are produced by activation of corrosion products from the structural steel materials, including ^{59}Fe and ^{51}Cr. These materials are required to preserve the integrity of the pressure boundary and cannot be replaced. As such emphasis is based on controlling the corrosion rate of these materials by chemistry optimisation and material treatments.

297 Radiation fields in modern PWRs are low, partly as a result of the use of Inconel 690 (Ref. 136). However, material selection is not the whole story because there have been some reactors with Inconel 690 which passivated slowly or did not passivate at all. The main reason for this seems to relate to the finishing treatments applied to metal components by their manufacturers, and to the commissioning carried out. Passivation prior to nuclear operations, Hot Functional Testing (HFT), is assessed in Section 4.2.12 of this report.

298 EDF and AREVA have specified austenitic stainless steel for the main pipework, which is normal practice for a PWR (Ref. 13). This material is resistant to general corrosion and erosion by primary coolant. It has been difficult to get clear unambiguous definitions of the materials in UK EPR at times; but after several exchanges, I consider their selection of bulk materials to be broadly sound. Remaining gaps in information presented relate to minor components, such as bearings, seals and valve components, all of which have been sources of elements of concern in the past. It is not appropriate that these (or their surface finishes) should be specified at this stage of the project and I conclude that the licensee will need to finalise the precise schedule of materials for UK EPR. I consider this to be an Assessment Finding **AF-UKEPR-RC-07**.

299 As the SG tubes make such an important difference to the radiation behaviour of a given plant, I selected the SG tube fabrication process for my assessment sample during Step 4. EDF and AREVA presented and described their processes for tubing manufacture in Ref. 119. My assessment of these follows.

Conditioning, Manufacturing and Surface Finishing

300 The surface treatment of alloys used to construct UK EPR will also have an effect on corrosion rates and activity pickup. Most surface treatments are intended to modify stresses or help with Non-Destructive Testing (NDT), but by making the surface smoother, some improve general corrosion or activity pick-up (Ref. 148). The surface finish should be inspected so that sub-standard material can be rejected or repaired. This is especially important with claddings that are built up by repetitive welding methods.

301 I commissioned TSC support to review surface finishing and conditioning, both in general and for UK EPR specifically (Refs 134 and 117).

302 EDF and AREVA provided some information on the SG tube manufacturing processes for UK EPR in the response to RO-UKEPR-46.A1 (Refs 9 and 13). This information demonstrated the importance of SG tube alloy manufacture on subsequent corrosion releases, particularly the time taken to 'passivate' the new surfaces. EDF and AREVA quote OEF from plants with Inconel 690 SG tubing to demonstrate the diminishment in the ^{58}Co release peak during shutdowns; this is taken as a measure of the rate of release during the cycle. General information was also provided on the improvements in manufacturing in the last 20 to 30 years which have much reduced the release rates from SG tubing. Improvements cited include heat treatment processes, surface finishing, degreasing and pilgering steps. EDF provided information on the improvement in corrosion performance in steam-generator tubing as manufacturers developed surface finishes over time in Ref. 191. This contained the following graph of the peak in ^{58}Co production at forced oxygenation in their N4 reactors following SG replacement with Inconel 690:

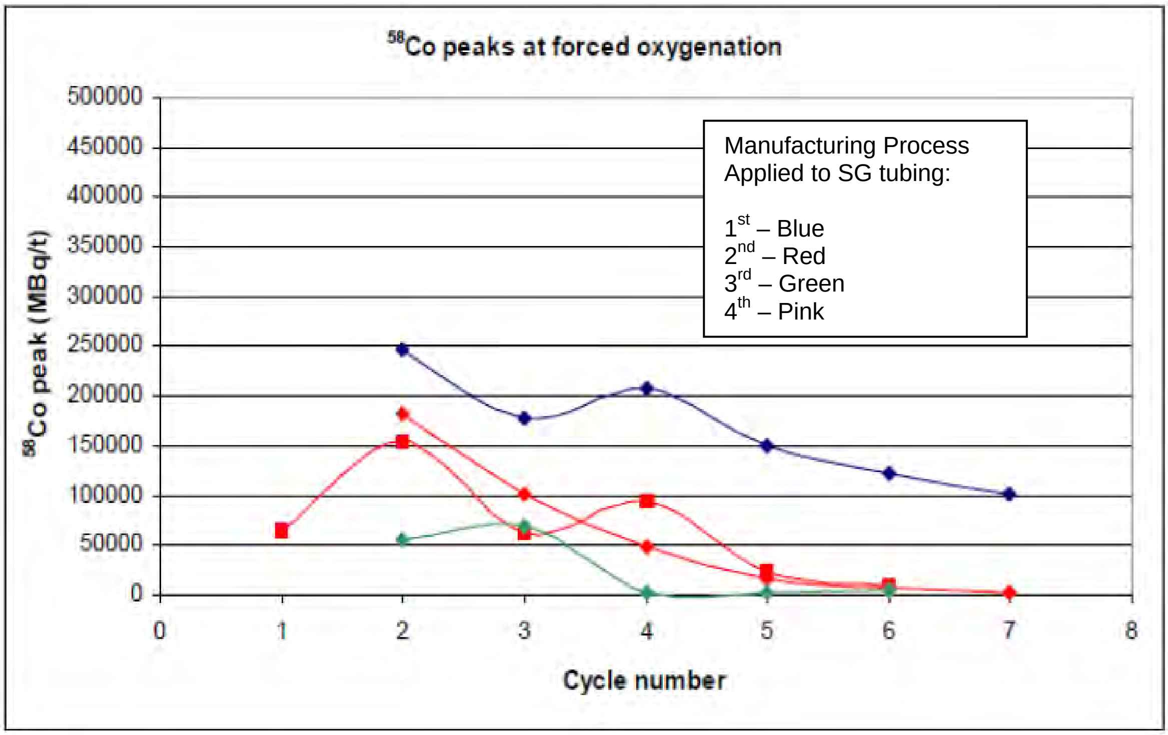


Figure 9: Comparison of Peak in ^{58}Co Production at Forced Oxygenation in the N4 Reactors Following SG Replacement with Inconel 690

303 The improvements in mass release rates are exemplified in the data below (from TQ-EPR-1197 (Ref. 8), which shows total and average release rates for SG tubes manufactured in 1987 and 2007 by the same manufacturer:

[redacted]

Figure 10: Comparison of Measured Release Rates for Steam Generator Tubing Produced by Different Manufacturing Processes

304 EDF and AREVA also presented data for the two main European manufacturers of tubing which showed that they could now achieve similar, although not identical, corrosion performance. The results were very similar but still varied by factors of around 3, albeit at low values. It is clear from the data that variations between manufacturers seem to exist, with some manufacturing routes appearing to produce better quality tubing from a corrosion release perspective. The information provided by EDF and AREVA matched that obtained by Office of Nuclear Regulation (ONR) from other sources (Refs 143 and 144).

305 I queried how ‘low’ release tubing would be assured for UK EPR in TQ-EPR-1236, Ref. 8. In response EDF and AREVA referred to TQ-EPR-1197, Ref. 8. This TQ was raised to cover surface finishes. Standards for tubing finish have been defined by ASME and others (Refs 118 and 144) but EDF and AREVA replied that surface roughness was generally controlled to the RCC-M standards ($R_a \leq 6.3$ μm for machined and ground surfaces), but these do not provide sufficient control for SG tubing, for which they apply a tighter specification ($R_a \leq 0.8$ μm). Micrographs and corrosion test results were presented illustrating the orders of magnitude improvement in metal smoothness and corrosion rates achieved for AREVA in tubes manufactured between 1987 and 2007. Pilgering can produce SG tubing that is so smooth that conventional grit polishing would make it rougher. However rigorous control is needed to ensure that the lubricants used in fabrication (pilgering) do not permanently contaminate surfaces.

306 In my technical meetings with EDF and AREVA during September and November 2010, I emphasised the importance that they should have good controls over the production of components such as the SG tubing, in order to control corrosion release and radioactivity. In response, EDF and AREVA provided Ref. 119 on the manufacture of SG tubing. This included surface finishing. Of the numerous processes applied to Inconel tubing, there is evidence that bright annealing after manufacture is one of the more significant steps in

reducing the potential for corrosion (Refs 144 and 148). To be effective, the process should use [redacted].

307 Overall, EDF and AREVA have described the SG tube manufacturing and conditioning processes to be applied to the UK EPR Inconel 690 tubing. These controls appear robust and consistent with other industry guidance, such as EPRI, Ref. 118. I am content that EDF and AREVA have demonstrated adequate controls are possible to assure 'low' release SG tubing for a UK EPR. The Licensee will be required to ensure this is progressed as part of their normal business.

308 Electro-Polishing (EP) can reduce the accumulation of radioactivity on out of core surfaces, but this process is expensive. EDF and AREVA provide details on EP in their response to RO-UKEPR-46.A1, Refs 9 and 13. EP was considered for the internal surfaces of the RCS coolant loops and the SG channel heads in UK EPR, but was not adopted for either.

- EDF and AREVA consider that adequate arrangements are already in place for the coolant loops to make an expensive EP treatment unjustifiable. Additionally there has been no experience in current plants of EP in such areas.
- Applying the procedure recommended by the UK Health Protection Agency, EDF and AREVA concluded that electropolishing the channel heads and water-chambers in the SGs was not justified in UK EPR, due to the low doses that would be saved. EDF and AREVA do recognise the benefits in EP of such areas, quoting the example of French 1300 Mega-Watt (MW) plants where dose rates in this region were 25 to 40% lower on plants which had an EP treatment. The main argument against such a treatment for UK EPR is the claimed higher corrosion resistance of Inconel 690 meaning less man-access and hence lower doses. In terms of reactor chemistry performance the decision to EP the channel heads is more of an ORE concern and I have shared this information with the Radiological Protection inspector during Step 4.

309 A high standard of surface finish should also be applied to surfaces that have been clad in stainless steel. This can be difficult if there has been repair-work that has led to regrinding of the surface, e.g. with castings. The control of surface finish has been covered by ND in the report on Structural Integrity, Ref. 116**.**

310 From my assessment of the surface conditioning and the control of radioactivity, I conclude that adequate detail has been provided by EDF and AREVA for the present stage.

Surface Cleanliness

311 When supplying and installing nuclear-grade equipment, attention must be paid to surface cleanliness.

312 EDF and AREVA has provided details of their general control over fabrication of tubing (Ref. 119), but it was not appropriate to assess detailed procedures for controlling foreign materials during fabrication as part of GDA. Foreign material is defined as undesirable material in or near a component which would not normally be present as part of the EPR design. Foreign material may be introduced as a result of operations such as manufacturing, installation, repair, maintenance, inspections, or other intrusive procedures. During these processes, extreme care should be taken to prevent entry of foreign materials into components after cleaning. The use of Foreign Material Exclusion (FME) barriers such as temporary plugs, covers, or seals is strongly recommended during any activity where foreign material may be introduced during installation, refuelling outage

maintenance, and repair activities where post activity cleanliness is restricted. Responding to TQ-EPR-1349 (Ref. 8), EDF and AREVA confirmed that a System Commissioning Program document would be produced specifically to control chemistry and purity during the erection and commissioning phases of UK EPR.

313 Sulphur, lead, copper, mercury, aluminium, antimony, arsenic, and other low-melting-point elements and their alloys and compounds should be restricted in their use as construction materials, erection aids, cleaning agents, and coatings. Contamination of stainless steel and nickel-chromium-iron alloys by copper, low-melting-temperature alloys, mercury, and lead should be prohibited.

314 The response to TQ-EPR-1197 (Ref. 8) states that; "*Requirements regarding the cleanliness of the components are given in RCC-M F6000. These requirements are particularly severe for all surfaces in contact with the primary fluid. The compliance to RCC-M cleanliness rules shall guarantee the absence of any harmful surface pollution, thus avoiding any degradation of the material corrosion resistance.*"

315 This reply implies that EDF and AREVA have yet to complete detailed specifications for UK EPR for detrimental materials applicable to the different alloys used. Possible sources of detrimental materials should be listed and controlled. Requirements should apply to all finally cleaned surfaces and to any surface prior to welding and post weld heat or thermal treatment. Controls on mercury and lead should apply at all stages of fabrication and operation. These requirements should be applicable to all surfaces that contact the operating fluid or maintain the integrity of the pressure boundary.

316 I have asked what documentation will be provided to the UK to enable suitable controls to be implemented, in TQ-EPR-1349 (Ref. 8). EDF and AREVA replied that documentation would be provided before operation of the reactor. Since some controls will need UK implementation before then, this should be followed up soon after Step 4. While EDF and AREVA have demonstrated an understanding of these principles I find that the licensee should specify arrangements for the control of foreign materials and contaminants during fabrication and site work. This is one of the objectives of an Assessment Finding **AF-UKEPR-RC-03** raised in Section 4.1.3.

4.2.3.2.2 High Cobalt Alloy Inventory

317 Cobalt absorbs neutrons easily and even small amounts of cobalt in the core can cause high levels of radiation from ^{60}Co, which is radiologically significant due to the high energy gamma it emits. Radioactive cobalt is principally an issue for ORE during shut-down, but it also impacts on waste production and decommissioning.

318 High cobalt alloys have had particular use as hard wearing alloys, particularly in the form of an alloy known as Stellite^{TM}. Cobalt alloys are commonly used in PWR components such as Control Rod Drive Mechanisms (CRDMs), valve seats and wear pads where this property is desirable. Cobalt input into the primary circuit from Stellite^{TM} arises from four potential mechanisms, namely, corrosion, erosion-corrosion, wear and valve lapping. The erosion-corrosion mechanism for material release occurs where large pressure drops across valves induce large flow velocities. Unfortunately, it has been demonstrated that these alloys have contributed much of the cobalt which caused significant radioactivity in older PWRs. It is not certain how much of this was due to operational wear, corrosion or poor maintenance. For instance, in-situ valve lapping (if allowed) may release cobalt particulate into the circuit. Use of replacement alloys may result in different amounts of wear and corrosion. Therefore, it is important that any Licensee should ensure there are appropriate instructions for fabricators and operators to install, commission or maintain

any hard-facing materials that may give rise to ^{60}Co dose. I consider this to be an Assessment Finding **AF-UKEPR-RC-08**.

319 Once Stellites™ were identified as significant, much work was undertaken, principally with the 'Konvoi' reactors in Germany, progressively to eliminate Stellite™ from various components, Ref. 157. The reduction in ORE reached a plateau at around 2 m^2 of remaining Stellite™ even though the reduction programme continued until there was only 0.17m^2 in the core, excluding the CRDMs, which are very similar in UK EPR. This is shown below (Ref. 13):

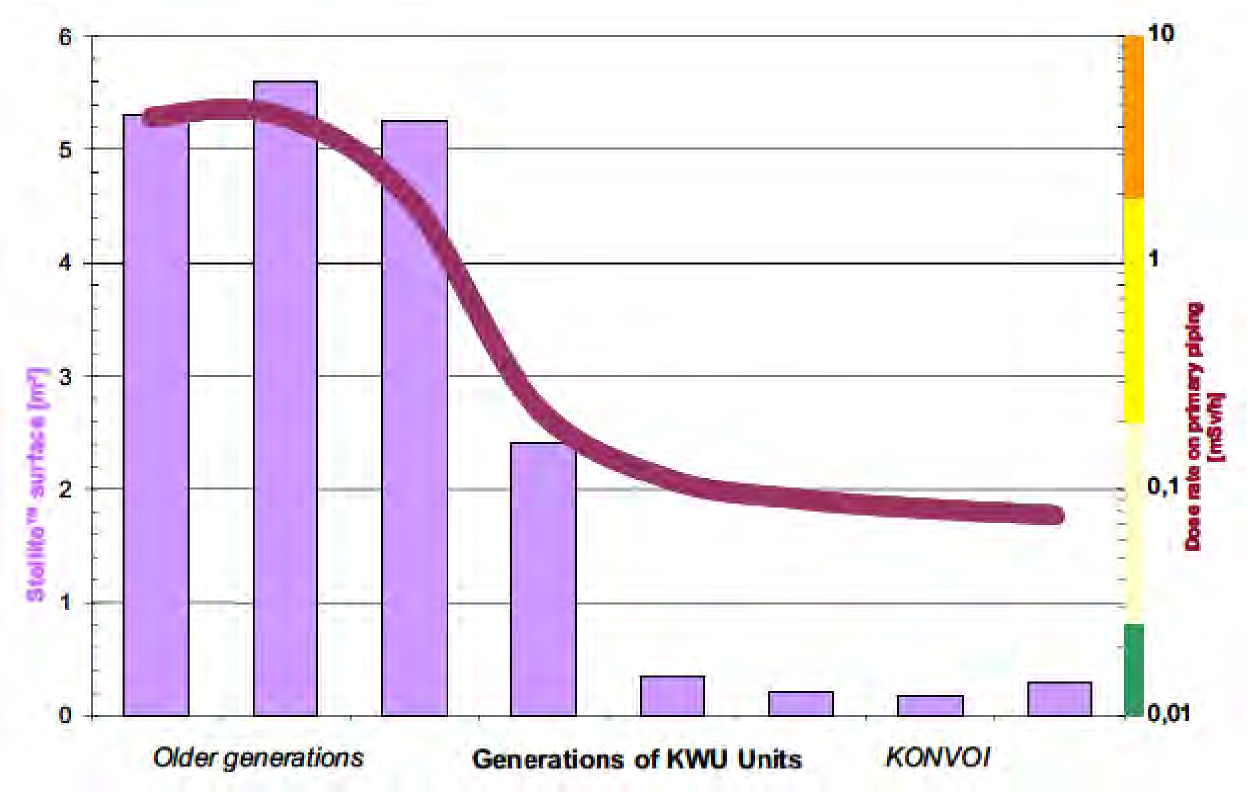


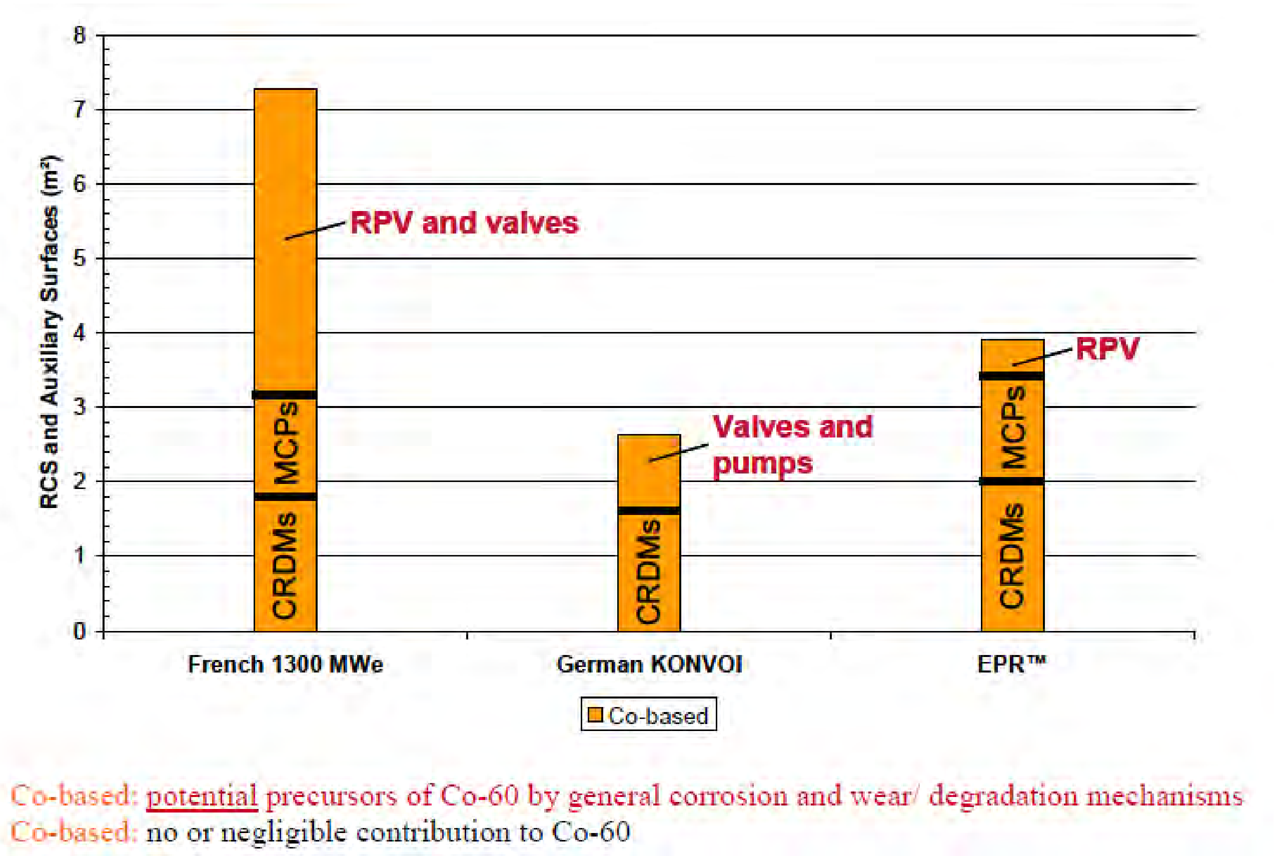
Figure 11: Evolution of Stellite™ Surface Area and Comparison to Primary Circuit Dose Rates in German PWRs

320 It was important, when considering any replacement for Stellites™ is not actually worse either in terms of its mechanical safety, but also corrosion of other elements in the alloy. The Mechanical Engineering aspects of Stellite™ use are assessed elsewhere (Ref. 115).

EDF and AREVA presented the reduction of High Cobalt alloys for UK EPR in the response to RO-UKEPR-46.A1 (Refs 9 and 13). Stellites™ have been replaced in most components outside the core of UK EPR. The designers decided that no fluid deemed to be radioactive should be in contact with valves or fittings containing Stellites™, and any Stellites™ normally in such locations should be replaced with iron-based alloys, Ref. 133. The main remaining areas of Stellite™ in UK EPR are:

- [redacted] m^2 in the CRDMs
- [redacted] m^2 in the RCPs
- [redacted] m^2 in the RPV and RPV internals
- Less than [redacted] m^2 in valves and other fittings

Thus the main areas remain in the control-rod drive mechanisms, main coolant pumps, together with a small area (less than 1m^2 inside the core as shown in the following comparison of EPR by AREVA with existing French and German reactors (Ref. 189):



Co-based: potential precursors of Co-60 by general corrosion and wear/ degradation mechanisms
Co-based: no or negligible contribution to Co-60

Figure 12: Comparison of Stellite^{TM} Surface Areas in the Latest Generations of French and German PWRs to UK EPR

321 The CRDM Stellites are not considered sources of cobalt in the coolant. As can be seen from the figure above, the overall wetted surface area of Stellite^{TM} in UK EPR is just under 2 m^2 (actually [redacted] m^2).

322 In order to clarify where replacements had actually been made and how much Stellite^{TM} was left in the design of UK EPR, TQ-EPR-907, 1190 and 1236 (Ref. 8) were raised. In their responses EDF and AREVA confirmed their CRDM design is similar to the Konvoi design and there is very little Stellite^{TM} in the CVCS. Details of the Stellite^{TM} replacements in the CVCS are described in Section 4.2.3.2.5 of this report, which although relatively small in terms of surface area could be more important to cobalt release due to higher wear or corrosion rates.

323 In response to RO-UKEPR-46.A1 (Refs 9 and 13) EDF and AREVA identified the in-core Stellite^{TM} inventory as warranting particular attention. They described how "*several options for Stellite™ reduction were studied, taking into account factors such as radiation protection (corrosion product source term), mechanical behaviour, availability of alternate Cobalt free materials, and the associated industrial risk*". This process roughly halved the inventory of in-core Stellites^{TM} from the initial to current UK EPR design. This still represents a quarter of all the Stellites^{TM} remaining in UK EPR.

EDF and AREVA justified the amount of Stellite™ in the response to RO-UKEPR-46.A1 (Ref. 13) by claiming it was a small fraction of the Stellite™ originally in PWRs and thus any dose reduction would be subject to statistical uncertainty. EDF and AREVA also point out that there is a balance between reducing quantities of cobalt and ensuring the reliability of components, which I accept.

324 Therefore the principal source of cobalt from Stellite™ use in UK EPR will be from the main coolant pump bearings. The coolant pump bearings have a similar design to those used in other French reactors. They are hydrodynamic bearings that are not supposed normally to wear. Any material lost should be picked up by the seal water return filters in the CVCS and not return to the coolant. The bearings have been subject to extensive testing for wear.

325 EDF and AREVA believe that most of the ^{60}Co in UK EPR will come from sources outside the core, and this measure is predicted to reduce the ^{60}Co source term by 39% compared to French plants. Overall, they have made reasonable arguments to support the claim that the high cobalt alloy inventory in UK EPR has been reduced SFAIRP, based upon the current knowledge in this field. I am satisfied that EDF and AREVA have incorporated OEF from the latest French and German PWRs in minimising the inventory of high cobalt alloy in UK EPR. Currently some use of cobalt alloys seems unavoidable and other chemistry measures outlined in this report can be optimised to make control of ^{60}Co releases effective. However, as this is an on-going area of research, a future Licensee for UK EPR should ensure no suitable alternative to Stellite™ exists before acquiring significant equipment containing hard-facings in contact with primary coolant. I consider this to be an Assessment Finding **AF-UKEPR-RC-09**.

4.2.3.2.3 Trace elements

326 In addition to the cobalt in Stellite™, there may be trace levels of natural cobalt or other elements in other steels used to construct the reactor. High levels of cobalt impurity in structural metals are associated with higher ^{60}Co levels. Cobalt levels in SG tubing have been steadily reduced in French reactors and EDF and AREVA believe that this has been more responsible for reductions in ^{60}Co, rather than Stellite™ removal. Cobalt in other alloys and other trace-elements also has an effect. In general EDF and AREVA control these elements mainly through application of the RCC-M metallurgical codes listed in Refs 96 and 149. The residual cobalt levels applied in the principal alloys are summarised as below;

Location	Co maximum / wt. %
SG tubes	[redacted]
Stainless Steels or Ni-Cr-Fe alloys (other than tube bundle) – in-core	0.06
Stainless Steels or Ni-Cr-Fe alloys (other than tube bundle) – out-of-core	0.1

Table 8: UK EPR Cobalt Impurity limits in Primary Circuit Materials

327 It is not practicable (or even possible) to completely eliminate cobalt from metals but EDF and AREVA have specified tight controls to limit cobalt in steam-generator tubing [redacted], materials subject to neutron irradiation (<0.06%) and not subject to neutron irradiation (0.1%), Ref. 189. This emphasis reflects the relative areas of these metals and their significance in cobalt production.

328 The RCC-M specification for SG tubes specifies a residual level of 0.018 wt. % cobalt, which is higher than that specified by EDF and AREVA for UK EPR (TQ-UKEPR-1236 (Ref. 8). EDF and AREVA quote international OEF to support the lower levels, as exemplified below (from TQ-UKEPR-1236). The figure below shows the levels of SG tubing cobalt influencing primary circuit contamination levels:

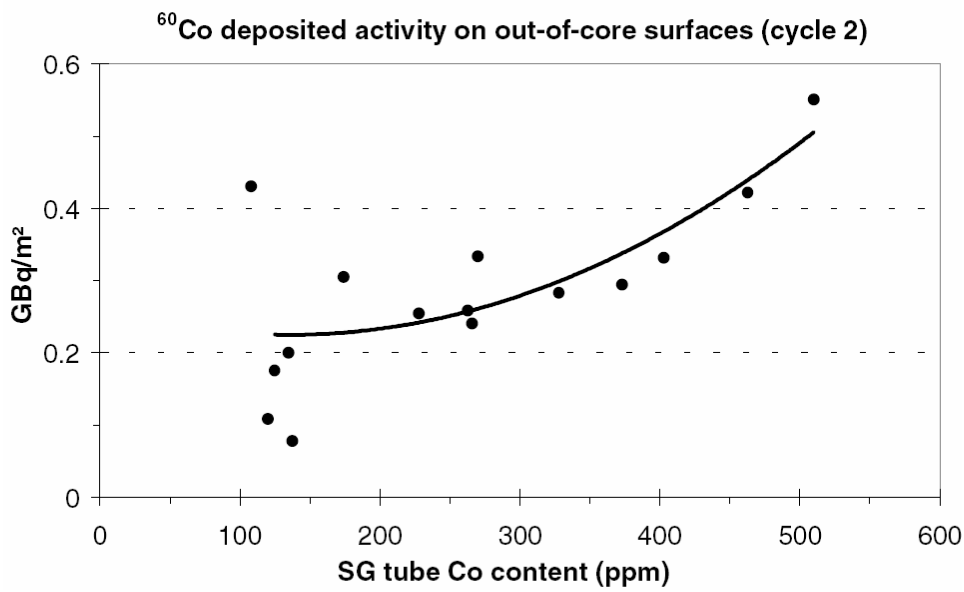


Figure 13: Influence of Steam Generator Tubing Cobalt Content on Primary Circuit Contamination

329 The SG tube specification does allow some variations in SG tube cobalt content by "*the cobalt content in heat analysis shall be less or equal to 0.035 wt. %. The average cobalt content for all heats constituting each bundle, weighted by the number of tubes in each heat, shall be less than or equal to 0.015 wt. % during bundle procurement*". I queried whether this allowable variation would have any influence on SG tube releases in TQ-UKEPR-1236 (Ref. 8). EDF and AREVA responded that such variation has been used historically and has not been shown to influence releases.

330 In responding to TQ-EPR-1236 (Ref. 8), EDF and AREVA said they would control the specification of impurities, such as cobalt in alloys other than Stellite^{TM}, at the RCC-M specification or may apply more restrictive specifications. EDF and AREVA will not make specifications less restrictive than RCC-M. This also applies to welding materials.

331 In Ref. 13 EDF and AREVA also point out that the cobalt content of the ferritic alloy of the reactor vessel will also be controlled at a low level [redacted] This is not in contact with the coolant but is an important contributor to radiation fields due to activation.

332 The presence of other trace-elements in metals, such as sulphur and phosphorus, impacts on all the properties of the metal, including corrosion. In Ref. 13 EDF and AREVA state that other impurities in metals, such as sulphur and phosphorus, will also be given tight limits. Many of these are related to Structural Integrity and are assessed elsewhere (Ref. 96).

333 Antimony, tungsten and silver are covered in the next section below.

334 There has been a general trend towards better control and lower limits for trace-elements in metals. I am satisfied that these specifications provided by EDF and AREVA are appropriate at the present stage and that impurities can be controlled to very low levels.

This will require careful controls during manufacturing to ensure such limits are accurately and rigorously enforced, but EDF and AREVA have adequately demonstrated how this might be achieved for UK EPR.

4.2.3.2.4 Other Materials - Antimony and Silver

335 Any silver lost by materials in the reactor would be activated to ^{110m}Ag in the core; similarly any antimony would be activated to ^{122}Sb, ^{124}Sb or ^{125}Sb. These nuclides are intensely radioactive and tend to plate out on surfaces outside the core and in fuel pools if released. Once plated out, they are difficult to remove. Both silver and antimony components have been used in the ancillary circuits of French N4 reactors in the past.

336 In Ref. 13, EDF and AREVA state that use of antimony and silver is forbidden anywhere in the reactor building. However, Ref. 13 goes on to say that temporary use will be permitted in controlled circumstances if no alternative exists. A list of "*activatable elements*" will be provided to all potential suppliers of components in contact with primary coolant.

337 Antimony is used within the UK EPR secondary neutron sources. While these are clad and not expected to be exposed to the primary coolant, any leaks in the cladding will result in dissolution and transfer of antimony to the coolant, Ref. 196. The specifications for secondary neutron sources should be kept under review by the Licensee and alternatives considered, if a substitution can safely be made. I consider this to be an Assessment Finding **AF-UKEPR-RC-10**. This is also a radwaste question, since the disposal of a used neutron source can be difficult.

338 In UK EPR the control-rod used for adjustment of reactor power are made from a Silver-INdium-CADmium (SINCAD) alloy and Boron Carbide (B_4C) pellets inside a stainless steel tube. Like all PWR control rods these will have a defined service life and potentially suffer from swelling. Any silver that escaped from an aged or damaged control-rod would present a significant contamination risk in a reactor. The management of control rods to ensure replacement before material is released should be part of the normal licensee activities.

339 Preventative surveillance of control rods and secondary sources should therefore be reviewed and justified by the Licensee. I consider this to be an Assessment Finding **AF-UKEPR-RC-11**.

4.2.3.2.5 CVCS Materials

340 I requested details of the materials of construction of the reactor through TQ-EPR-900 Ref. 8) and in the CVCS specifically through TQ-EPR-907 (Ref. 8). While the CVCS may make up relatively little surface area of the primary circuit, it does contain numerous valves and other working parts that could release corrosion or wear products into the RCS. For instance, the pipework and tubing in CVCS will be similar to AISI 304L and 316L, grades which are known to have good corrosion resistance for this type of duty. The RCC-M requirements for surface finishes are maintained, although the allowable piping roughness is higher than the RCS at $\leq 12.3\ \mu$m (TQ-EPR-1197 (Ref. 8)).

341 In response to these TQs, EDF and AREVA have confirmed that:

- There are no cobalt-based alloys in contact with primary coolant in CVCS. There are two small valves which do contain cobalt-bearing Stellite^{TM}, not in contact with coolant. Their entire surface area is less that 0.003 m^2.

- Hard-facing valve components will be made from NOREM^{TM}, an alloy of iron, chromium and nickel containing less than 0.2 % cobalt, or from grade 4/5 hardfacing nickel alloy containing up to 1.5 % cobalt. NOREM^{TM} valves have a surface area of around 0.5 m^2, with the nickel hard facing at less than 0.1 m^2.
- Hard-facing pump components will be made of Colmonoy^{TM} 62, an alloy of nickel and chromium, containing less than 0.2 % cobalt. Their entire surface area is around 0.3 m^2.
- The use of materials containing silver or antimony in contact with primary coolant will be forbidden unless there is no alternative. There are no "*tangible*" quantities of silver or antimony in CVCS.

342 The specification of replacements for Stellite^{TM} requires some care, because replacement materials can wear or corrode more than Stellite^{TM} in harsh environments. EDF and AREVA recognise this fact and indicate that such replacement materials for UK EPR were subjected to qualification testing "*regarding the friction behaviour and corrosion resistance in environments representative of normal operation and shutdown conditions*".

343 I was content with the arguments put forward by EDF and AREVA regarding CVCS material choices to reduce radioactivity. The removal of Stellite^{TM} from CVCS valves is a positive step in this regard and EDF and AREVA have recognised the need to test replacement materials thoroughly.

4.2.3.3 Water Chemistry

344 In RO-UKEPR-46.A2 (Ref. 9), I asked EDF and AREVA to provide justification that the chemistry of the primary coolant would be controlled so as to reduce levels of radioactivity SFAIRP. Their response (Ref. 161) outlined the chemistry needed to minimise the concentration of corrosion products in the coolant and minimise their deposition on fuel cladding and limit accumulation on out-of-core surfaces. In general terms this can be achieved by controlling the pH at an appropriate value throughout the cycle, avoiding oxidising conditions at power and preventing the ingress of impurities, such as chloride, which are known to cause corrosion. The addition of zinc is discussed in Section 4.2.6 and should also help to limit radioactivity in the reactor. Identification of the chemistry environment in contact with circuit materials during all stages of operation was reviewed for ND (in Refs 148 and 149) and is not a simple task. Hydrogen must be added to suppress radiolysis and to maintain reducing conditions but can have other specific effects on the corrosion behaviour of materials. Nucleate boiling significantly enhances the possibility that soluble species precipitate on the fuel surfaces forming fuel crud. The formation of fuel deposits will increase the time that species carried by the coolant reside in the neutron radiation of the core and so increase the quantity of activated species.

345 There are two major objectives of primary coolant chemistry for control of radioactivity:

- Reduction of the rate of metal release from primary circuit materials as a consequence of general corrosion.
- Avoiding the redeposition of the corroded material (or other impurities) as crud on the fuel.

346 Chemistry is controlled to minimise the corrosion rates and to keep as much of the radioactive species as possible in solution so that they can be removed by the ion exchange units in the Chemistry and Volume Control System (CVCS) as the plant is shut down, Section 4.2.11 (Ref. 156). In addition the water and the species added to the

coolant to control the chemistry environment are themselves subject to the neutron radiation field and can produce activated species. Some of these are unavoidable (such as ^{16}N and ^{14}C), but many can be controlled and minimised, depending upon the chemistry. Some of the most common are given in the table below:

Nuclide	Production	Approximate half life	Production Source
^{3}H	$^{10}B\ (n,2\alpha) \rightarrow {}^{3}H$	12.3 years	Boric acid
	$^{6}Li\ (n,\alpha) \rightarrow {}^{3}H$		Lithium hydroxide
	$^{7}Li\ (n,n\alpha) \rightarrow {}^{3}H$		Lithium hydroxide
^{7}Li	$^{10}B\ (n,\alpha) \rightarrow {}^{7}Li$	stable	Lithium hydroxide
^{14}C	$^{17}O\ (n,\alpha) \rightarrow {}^{14}C$	5730 years	Water
	$^{14}N\ (n,p) \rightarrow {}^{14}C$		Dissolved nitrogen gas
^{16}N	$^{16}O\ (n,p) \rightarrow {}^{16}N$	7.1 seconds	Water
^{32}P	$^{35}Cl\ (n,\alpha) \rightarrow {}^{32}P$	14.3 days	Contamination
	$^{32}S\ (n,p) \rightarrow {}^{32}P$		Contamination
	$^{31}P\ (n,p) \rightarrow {}^{32}P$		Contamination
^{35}S	$^{35}Cl\ (n,p) \rightarrow {}^{35}S$	87.5 days	Contamination
^{41}Ar	$^{40}Ar\ (n,\gamma) \rightarrow {}^{41}Ar$	1.8 hours	Argon in air

Table 9: Significant Radionuclides Produced from RCS Chemical Additions and Impurities

347 Tritium (^{3}H) and ^{14}C, are discussed further in Sections 4.2.3.3.3 and 4.2.3.3.4, below. During reactor operations ^{16}N is the dominant nuclide in the coolant and due to its high activity and highly energetic γ decay (around 6 MeV) access to the RCS is restricted and is the main reason for shielding around the RCS. However, with a half life of only 7 seconds the activity follows the reactor power (i.e. neutron radiation) almost instantaneously so is not an issue at shutdown. ^{16}N is used as an indicator of SG tube leaks via gamma detectors in the main condenser off gas system. Although ^{32}P and ^{35}S are only of minor concern from a dose perspective, they are of concern due to their release to the environment from PWR operations. Both are produced from impurities in the coolant, mainly chloride and phosphorus via the reactions given above. The operators of water reactors do all they can to eliminate sulphur, chloride and phosphorus. Methods used to eliminate these elements include preventing their ingress or removing them on the CVCS mixed bed resins. ^{41}Ar is of little radiological consequence but is used as an indicator for air ingress to the RCS.

4.2.3.3.1 Effects of Chemistry Controls on Radioactivity

348 As stated in Section 4.2.1, EDF and AREVA provided details of the expected chemistry regime to be applied to the primary circuit in UK EPR. In response to RO-UKEPR-44.A1 (Refs 9, 172 and 51), EDF and AREVA proposed the following primary circuit chemistry for UK EPR:

- A constant $pH_{300°C}$ as early as possible in the fuel cycle, with a target value of $pH_{300°C}$ = 7.2. A maximum lithium concentration of [redacted] mg kg^{-1} at Beginning Of Cycle (BOC) in combination with the use of Enriched Boric Acid (EBA).
- A minimum hydrogen concentration of 17 cm^3 kg^{-1}, assessed in Section 4.2.7.
- Limitation of impurities to avoid localised RCS and fuel materials corrosion.
- Add zinc acetate to achieve 10 ± 5 μg kg^{-1} zinc, assessed in Section 4.2.6.

349 In their response to RO-UKEPR-46.A2 (Refs 13 and 161), EDF and AREVA justified these specifications in terms of the "*improvements that have been made to optimise the radioactivity level in primary circuit*". EDF and AREVA concentrated on the minimisation of corrosion product formation, activation and deposition. Their strategy considered the primary coolant pH and hydrogen concentration for the normal operating chemistry of UK EPR. Additional sections of Ref. 161 concentrated on start-up and shutdown (see Section 4.2.11 in this report) and Hot Functional Testing (HFT) (Section 4.2.12 of this report). Their report (Ref. 161) outlined how the chemistry in each of these areas was justified for UK EPR. Information in this report was supplemented by TQ-EPR-1234 and 1235 (Ref. 8). In these reports, EDF and AREVA gave attention to the effects of the reactor design on tritium and ^{14}C. However, I considered that the reactor power, flowrates, boiling and generally how EPR is operated influenced radioactivity to a greater extent than this, and I requested further justification for the design choices made for UK EPR, which is summarised in the remainder of this section.

350 In addition to helping to reduce the corrosion rates of primary circuit materials the operating chemistry can influence the extent to which soluble corrosion products deposit on the fuel surfaces and form fuel crud. As more fuel crud is produced the amounts of activatable corrosion products in the RCS increases, as the residence time within the neutron radiation field increases. Reactors can operate safely with some crud but with more crud, more radiocobalt is produced. Radiocobalt is a significant contributor to out-of-core radiation fields and contamination in spent fuel pools. It can be shown that reactors with the best controls over fuel crud also tend to have lower radiation fields. The production of fuel crud is a complex process which also involves aspects of the design which are not related to the operating chemistry, such as the amounts of boiling and core thermal hydraulic performance. Fuel crud can have other effects on reactor safety. This section of the report only deals with the production of radiocobalt rather than any effects on cladding corrosion or neutron control, which are discussed more fully in Section 4.2.5.

351 With the use of EBA, UK EPR is capable of operating with a constant pH "*coordinated chemistry*" regime. In this type of regime the pH at temperature ($pH_{300°C}$) is maintained constant and the lithium concentration is balanced with the reducing boron content throughout the cycle. This is possible in UK EPR due to the EBA enrichment used, which determines the pH at the start of cycle. EDF and AREVA expect a minimum $pH_{300°C}$ of 7.2. The control regime for lithium and boron in FA3 is shown below (Ref. 120), with 37% EBA:

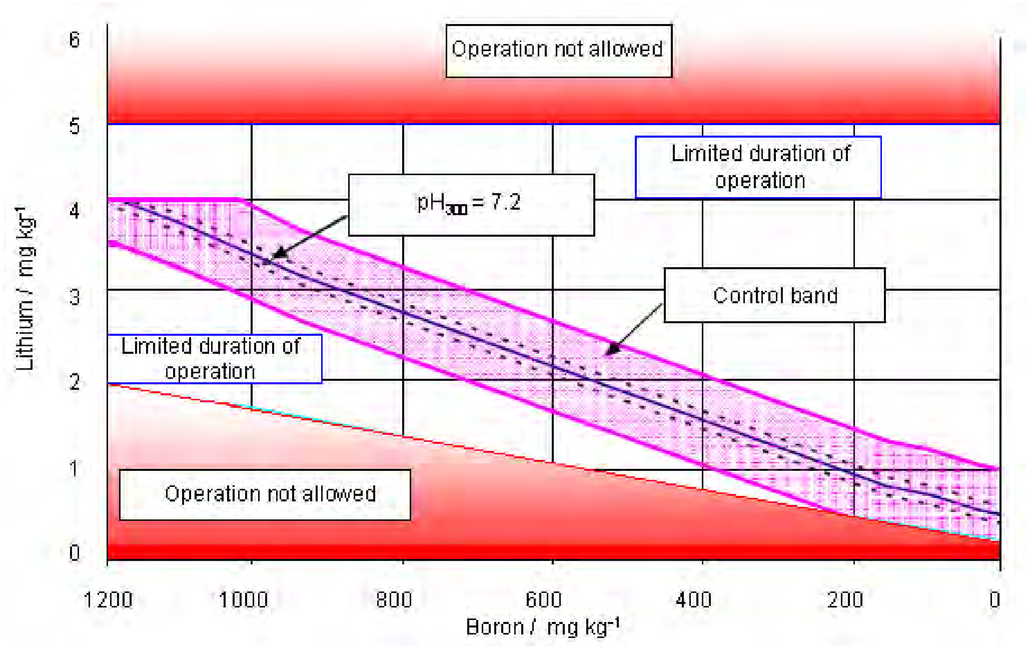


Figure 14: Typical EPR Boron-Lithium Coordination (for FA3 with 37% EBA)

352 In Refs 161 and 172, EDF and AREVA provide arguments for the adoption of $pH_{300°C}$ 7.2 for UK EPR. Based on thermodynamic calculations, $pH_{300°C}$ in the range 6.9 – 7.4 is good for iron control and 7.6 – 8.5 better for nickel control in the core. High pH tends to precipitate more iron in the core. These calculations were performed by the PHREEQC and the Multiple Equilibrium (MULTEQ) chemistry codes that do not consider flow or boiling. EDF and AREVA concluded that a $pH_{300°C}$ in the range 6.9 to 7.4 was optimal for radiation field control, when balanced with other effects. This is consistent with plant OEF and industry guidance such as EPRI (Ref. 27) and VGB (Ref. 29). Based on the plant OEF cited in the response to RO-UKEPR-46.A2 (Ref. 161), which included UK, US, French and other European plant data, and the design of UK EPR, including the use of EBA, EDF and AREVA have selected a $pH_{300°C}$ 7.2 for UK EPR.

353 The pH programme in most water reactors is designed to reduce the deposit of metallic compounds in the core. I raised TQ-EPR-1234 (Ref. 8) to explore the possibility of a higher $pH_{300°C}$ than 7.2, such as had been used elsewhere. EDF and AREVA concluded that high pH could not be achieved at BOC without increasing lithium above [redacted] mg kg^{-1} (as was tested at Comanche Peak, Ref. 164) and this had never been attempted in France. Alternatively the enrichment of EBA could be increased or the fuel management altered, both of which are significant changes not considered viable by EDF and AREVA.

354 Since boiling is believed to have a significant effect on crud deposition, the rate of boiling is controlled at the start of cycle in some reactors. EDF and AREVA have not commented on this method of controlling crud build-up. Boiling data representative of UK EPR only became available in December 2010, and this is still being assessed through **GI-UKEPR-RC-02**, along with a new report by EDF and AREVA on crud build-up, Ref. 112**.**

355 Roughly about half the activity carried around the coolant in many reactors takes the form of microscopic particulates. These have a different physical and chemical behaviour to dissolved species. Responding to TQ-EPR-773, EDF and AREVA said that coolant chemistry in UK EPR maximised the soluble fraction of corrosion products to permit more effective removal by ion-exchange in the CVCS.

356 EDF and AREVA also consider the dissolved hydrogen concentration as the other principal normal operating chemistry parameter that influences the control of corrosion products in UK EPR. The response (Ref. 161) to RO-UKEPR-46.A2 (Ref. 9) contains detailed evidence to support this claim citing both plant data and theoretical evaluations. The effects of coolant hydrogen content are assessed further in Section 4.2.7.

357 During Step 4, the only estimates for the levels of corrosion products in UK EPR were based on the source terms defined in Ref. 60. These sources were estimated for UK EPR based upon the French N4 plant data. EDF and AREVA claim credit for "*improvement in the manufacturing processes of SG tubes on the EPR*" to use these values as pessimistic bounding values. This is stated not to take credit for other improvements on the source term such as reduction in the quantity of Stellites^{TM}, improved passivation treatments and pH optimisation. Thus the analysis is based on the statistical analysis of activity recorded on the N4 series:

- Realistic source term – In steady-state operation, the selected activity values are equal to the mean values observed on all units in the N4 series. In shutdown transients, the selected activity values are equal to the mean values of the oxygenation peaks of the N4 series.
- Biological shielding design source term – In steady-state operation, the selected activity values are equal to the maximum values observed on all units in the N4 series. In shutdown transients, the selected activity values are equal to the maximum values of the oxygenation peaks of the N4 series.
- Effluent treatment system design source term – In steady-state operation, the selected activity values are equal to the maximum values observed on all units in the N4 series. In shutdown transients, two types of activity value are considered; maximum value transient observed in the power transients (load reduction) of all units in the N4 series and maximum value oxygenation observed in oxygenation peaks of the N4 series.

358 Thus far, responses by EDF and AREVA to my assessment all took the form of qualitative comparisons of UK EPR with other reactors, concluding that radioactivity might be relatively higher or lower. I requested estimates that were based on methods which took account of the specifics of the UK EPR design, such as the size of the reactor and boiling rates. In order to understand the consequence of this further I undertook three strands of assessment, namely:

- At my request, EDF and AREVA provided estimates for the crud produced in the first core design for UK EPR (Ref. 112). These calculations were based upon using the EPRI code for Boron Offset Anomaly analysis (BOA version 2) code, which was state-of-art when the calculations were performed in 2010.
- In TQ-EPR-1095 (Ref. 8) I also requested EDF and AREVA perform a comparison of their calculations against the measured quantities of crud actually produced at the Callaway reactor in the US, at a time when this plant was experiencing higher levels of fuel crud production. Callaway has a high boiling duty, but had different SGs at the time. The purpose of this request was to "*benchmark*" the EDF and AREVA calculations against known plant data.
- Finally, I also commissioned expert analysis (Ref. 133) for the likely quantities of crud expected, using the same base data (from TQ-EPR-716 (Ref. 8)) as the EDF and AREVA calculations. These calculations were based on in-house methods that are the basis for the (at the time unreleased) BOA v3 code. My TSC also reviewed the

EDF and AREVA calculations and provided estimates for radioactivity transport around the UK EPR RCS.

359 The results from these comparisons are discussed in more detail in Section 4.2.5 of my report. It is important to stress that the purpose of using these new methods is to develop our understanding of the relative importance of various underlying phenomena. Some of the more important conclusions of the independent TSC analysis of UK EPR (Ref. 133) from a radioactivity perspective are that:

- The calculations indicate the ^{58}Co radioactivity levels in the UK EPR may be higher than a standard non-boiling 4-loop PWR. However, this increase is within the normal observed plant to plant and cycle to cycle variations, and does not necessarily indicate UK EPR will experience excessive ^{58}Co radioactivity levels.
- The relatively low inventory of Stellite material in this plant will also help to maintain a relatively low ^{60}Co level.

360 Overall the initial results from my simulation work (Ref. 133) tended to agree with the initial claims made by EDF and AREVA but it should be recognised that UK EPR is substantially larger than existing PWRs and will produce more radioactive material per reactor than a smaller station, but this needs to be balanced against the higher electrical output. Our modelling has indicated parameters which should help the licensee to identify factors of importance and aid regulation until operational data become available. My assessment of crud continues in Section 4.2.5.2 of this report, where GDA Issue **GI-UKEPR-RC-02** is described.

361 In January 2011, I raised TQ-EPR-1455 (Ref. 8), asking EDF and AREVA to provide an update of their latest data on corrosion and cobalt production. Their data arrived too late to incorporate into our simulations for Step 4 of GDA.

362 Overall, EDF and AREVA expect the contribution of ^{60}Co to dose rates in UK EPR to be as low as the ^{58}Co contribution and I would agree with this conclusion. However it will be important to keep up the assessment of radioactivity production, as solid improvements made in the design of UK EPR could be easily undone in the implementation.

363 Since the build-up of mobile radioactivity is significantly dependent on the corrosion release of nickel and cobalt into the coolant, there should be target specifications in place for the start of active operations that establish limits for the starting chemistry of the coolant. I find that this will be an important factor in determining the radiation characteristics of the reactor. This is part of Assessment Finding **AF-UKEPR-RC-21**.

4.2.3.3.2 Boron Recycle

364 As described in Section 4.2.2.3.3, UK EPR will make use of boron recycling to retain the expensive EBA within the plant. This could potentially influence the accumulation of radioactivity within the coolant as the process will also inevitably concentrate some activity within the concentrated boric acid returned to the RCS. Other species may accumulate in the distilled water, should this be reused. The impact of boron recycle will be different depending upon the properties of the radioactivity in the coolant; tritium will mainly transfer to the distilled water while non-volatile species will remain in the boron concentrate.

365 EDF and AREVA did not include consideration of this aspect in their response to RO-UKEPR-46.A2 (Ref. 161) so I queried this further in TQ-EPR-1234 (Ref. 8). The response to this TQ was not sufficient in providing the requested information. As such I raised RO-

UKEPR-74 (Ref. 9) to understand how the specific features of UK EPR, including the boron recycle system, would influence radioactivity within the Nuclear Island systems.

366 Action 1 of RO-UKEPR-74 (Ref. 9) concerned tritium and is discussed further in Sections 4.5.1, 4.2.11 and 4.3.2.3. As discussed earlier, Section 4.2.2.3.3, EDF and AREVA now propose to dispose of the majority of the recycled distillate in UK EPR, meaning minimum accumulation of tritium within the plant via these means.

367 Actions 2 and 3 of RO-UKEPR-74 (Ref. 9) concerned other (non-volatile) species and are discussed further in Section 4.3.2.3. As per Section 4.2.2.3.1, the addition of the further ion exchange bed in the CPS before evaporation should help to reduce these effects in UK EPR by further purifying the coolant before recycling. EDF and AREVA did not completely respond to this RO during Step 4, and I have raised this as part of GDA Issue **GI-UKEPR-RC-02**, which is discussed further later in my report.

4.2.3.3.3 Tritium

368 Tritium is a radioactive by-product of water reactors which can contribute to operator exposure and is an important nuclide subject to environmental control. Tritium is, and has been, a key feature in determining the shutdown profile in a number of PWRs. It is produced by neutron bombardment of boron and lithium and also escapes slowly from fuel pins, secondary neutron sources and some control-rods.

369 The amount of ^{10}B in the coolant is determined by other safety considerations and cannot be altered. EDF and AREVA have indicated that the FA3 EPR will use enriched boron, which contains around 37 % of the useful ^{10}B isotope. The precise value for UK EPR will be determined by the Licensee once detailed fuel management arrangements are known. The amount of lithium in the coolant is determined by the total amount of boron needed to reach the target pH without leading to corrosion of the cladding. This is the primary advantage of enriched boron in that it requires less lithium to compensate for the acidity of the boric acid. This has consequential effects on reducing the tritium produced during a cycle.

370 EDF and AREVA indicate in response to RO-UKEPR-46.A2 (Ref. 161) that UK EPR will use 99.9% enriched ^{7}Li and this is used in the safety case to determine tritium production. The cheaper and more commonly available 98.4% enriched ^{7}Li produces 16 times as much tritium by neutron absorption compared to 99.9% enriched. The use of the higher enriched lithium can be seen to be ALARP.

371 Secondary neutron sources are included within the core to provide a measureable background neutron count-rate for the core detectors. The UK EPR design proposes the use of Sb-Be sources. Beryllium in the source generates significant quantities of tritium via the two step reaction $^{9}\text{Be}\ (n,\alpha)\ ^{6}\text{Li}\ (n,\alpha)\ ^{3}\text{H}$. This tritium readily diffuses through the stainless steel cladding into the primary circuit coolant. Evidence from other PWRs indicates that the presence of Sb-Be sources causes the tritium levels in the primary circuit to build up over and above that expected due to other mechanisms. This is related to Assessment Findings **AF-UKEPR-RC-10** and **AF-UKEPR-RC-11**.

372 Tritium is generated by fission of the nuclear fuel and a small percentage diffuses through the cladding of the fuel into the coolant. UK EPR will use M5® fuel cladding. EDF and AREVA use a figure for tritium release from fuel of 0.01%. I queried and obtained references for the source of this information through TQ-EPR-836 (Ref. 8). The niobium content of M5® reduces tritium escape from fuel and EDF and AREVA claim that 0.01% is a bounding estimate. Whilst EDF and AREVA are confident of this conclusion, it seems to rely on the impermeable nature of the oxide film that develops on M5® cladding, rather

than the thickness of the metal. An increase in this rate would make little difference to the overall coolant tritium activity in UK EPR which is dominated by the reactions with the soluble boron and lithium.

373 High levels of tritium mid-cycle would become a problem if it was necessary to lift the reactor head under such circumstances. In the UK, there are limits on tritium to prevent operator dose and uncontrolled discharge to atmosphere through the auxiliary building. Section 4.2.11 of this report contains my assessment of head-lift control in UK EPR.

4.2.3.3.4 Carbon-14

374 The ^{14}C produced in a PWR is minor in terms of dose and discharges from the station but ^{14}C can become an issue for waste accumulation on sites where strict ^{14}C limits apply, Ref. 173. ^{14}C is mainly produced from reaction of the water, which is unavoidable, or from dissolved nitrogen present in the coolant. As described in Section 4.2.2.3.4, there are a number of design features of UK EPR which may mean that the levels of dissolved nitrogen in the coolant may be higher than other PWRs.

375 The UK EPR source term (Ref. 60) states that UK EPR will produce 518 GBq of ^{14}C per year. Of this 80% of the ^{14}C comes from the ^{17}O reaction, with the remaining 20% from ^{14}N dissolved in the coolant. EDF and AREVA have considered the nitrogen blanketing of the VCT and other vessels in calculating this figure, assuming a dissolved nitrogen concentration of 27 mg kg^{-1}. This value was calculated based upon the maximum (saturation) value of the VCT and assumes the whole RCS reaches this value, which is unlikely.

376 The estimates of the amount of ^{14}C discharged to liquid and solid wastes provided by EDF and AREVA in TQ-EPR-773 (Ref. 8) and elsewhere, were roughly 80% discharged to atmosphere, 5% to liquid discharges and 15% to solid wastes. In other words, based on the French data, there could be a discharge of 67 GBq of ^{14}C to a low-level repository per year. Data collected from the Ringhals plant, Ref. 139, suggests up to 10% of the ^{14}C ends up in solid waste, with 0.26 % in liquid wastes. It is thought that oxidising conditions make the ion-exchange resins absorb more ^{14}C as carbonate. I have shared these results with both the Environment Agency and the Radwaste and Decommissioning inspectors.

377 At several meetings with EDF and AREVA, I have discussed the fate of ^{14}C and experience at one US reactor where a measureable quantity of solid ^{14}C was found, Ref. 140. In their view, the latter could be explained as a one-off event. Further assessment of the fate of ^{14}C in UK EPR is given in Section 4.2.6.1.2 of my report.

4.2.3.4 Summary

378 Based upon the evidence presented during GDA, the main conclusions I draw for the primary radioactivity assessment are:

- EDF and AREVA have provided detailed information on how the material and chemistry choices in UK EPR are predicted to influence the plant radiation fields, however most of this information is based on OEF from other reactors and not on analysis specific to UK EPR.
- Specifically the data for the radiochemical performance of UK EPR was not distinguishable from any other PWR made of similar materials. Since the radiochemistry of a reactor also depends on its size, power and other factors, I have commissioned a comparative review and theoretical calculations from internationally recognised experts in these fields. At my request EDF and AREVA have provided

design data to support these calculations and recently completed their own analysis for UK EPR.

- The calculations suggest that surface activities may be similar to existing plants if managed correctly. Total activity may be slightly higher than existing plants but this should be proportional to the power of the reactor. The significance of zinc, Stellite^{TM}, boiling and surface areas have been identified. Parameters will be identifiable for subsequent stages of the project. These key parameters include; the release rate from steel surfaces in the reactor and the effect of zinc, and the level of dissolved (and particulate) corrosion product at the start of cycle.
- Overall, UK EPR follows the well established and developed approach of restricting the material in contact with the primary coolant to mainly austenitic stainless steels (or cladding) or Ni-Cr-Fe alloys. EDF and AREVA have specified restrictive levels for impurities in these alloys and have described how the important factors such as conditioning and surface treatments will be specified to ensure releases are effectively controlled. I am content with the material choices for UK EPR and am content that EDF and AREVA have made an adequate ALARP argument for UK EPR, notwithstanding my specific comments highlighted above.
- I have particularly considered the CVCS materials and note that EDF and AREVA have taken great strides in removing cobalt alloys from wetted CVCS components which is a positive benefit. EDF and AREVA note the care needed in removing proven materials and state extensive test work to support this approach. They also intend to eliminate the antimony and silver that was used in ancillaries of the N4 reactor.
- Overall, EDF and AREVA have presented reasonable arguments that cobalt radioactivity in UK EPR will be significantly lower than in earlier generations of PWR made with different materials.
- A number of contaminants (such as silver (by activation) or chloride (by corrosion)) can increase the radioactivity produced by any reactor and strict controls should be developed to prevent their ingress at all stages from fabrication, through commissioning to operations. Preventing this is one of the objectives of Assessment Finding **AF-UKEPR-RC-03** raised in Section 4.1.3.

379 I judge that the claims, arguments and evidence as presented for primary circuit radioactivity in UK EPR appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA, although I note this area is closely linked to the **GDA Issue** on ex-core radioactivity in UK EPR (**GI-UKEPR-RC-02**).

4.2.3.5 Assessment Findings

380 Based upon the assessment of radioactivity in the primary circuit of UK EPR described in Section 4.2.3 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-07*** *– The Licensee shall ensure that a complete and unambiguous specification exists for all the materials to be used in UK EPR that could contact primary coolant. This should include trace elements prone to activation and be sufficiently detailed to allow sound procurement specifications to be produced This Assessment Finding should be completed before such materials are delivered to site, but certain aspects may need earlier consideration, for example, to ensure*

rigorous control during procurement activities. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.

AF-UKEPR-RC-08 *– The Licensee shall ensure there is sufficient control over fabricators and operators that install, commission and maintain any hard-facing materials, including lapping, that may give rise to ^{60}Co dose. This Assessment Finding should be completed before operations creating loose cobalt may take place on site, but certain parts may be necessary earlier, for example during component manufacture. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

AF-UKEPR-RC-09 *– The Licensee shall review and consider alternative materials to Stellite^{TM} for applications within UK EPR, and ensure that the final selection of materials is ALARP in this respect. This Assessment Finding should be completed before such materials are delivered to site for installation. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

AF-UKEPR-RC-10 *– The Licensee shall keep the specification of secondary neutron sources under review and consider suitable alternatives. This Assessment Finding should be completed before reactor operations. Target Milestone – Initial criticality.*

AF-UKEPR-RC-11 *– The licensee shall define a surveillance programme for control rods and secondary neutron sources. The programme shall prevent the release of materials such as tritium and antimony before there is significant contamination of vessels or pipework. This Assessment Finding should be completed before nuclear operations. Target Milestone – Initial criticality.*

4.2.3.6 GDA Issues

381 Based upon the assessment of radioactivity in the primary circuit of UK EPR described in Section 4.3.2 above, I have identified no Reactor Chemistry GDA issues in this area. However this area is closely linked to the GDA Issue on control of ex-core activity in UK EPR (**GI-UKEPR-RC-02**), detailed in Section 4.2.5.

4.2.4 Assessment – Material Integrity and Corrosion Control

382 The metals used for the RPV and other parts of the primary circuit must maintain their integrity for the lifetime of the reactor, where these cannot or will not be replaced. This means that they must have sufficient strength and not experience corrosion which would reduce this strength to a degree that allows damage such as leaks or failures. Corrosion may begin on the inside of the reactor, as a result of poor primary coolant chemistry control, or may begin from the outside of the reactors primary circuit.

383 The areas that might be areas of concern for corrosion include:

- The main stainless steel pipework of the coolant circuits that retain pressure.
- Heat exchanger tubing that acts as a barrier between the radioactive primary circuit and the nominally clean secondary circuits, particularly the steam-generator tubing for which it is harder to isolate a leak.
- Internal components, such as of the control – rods and safety valves, for which alignment and functional integrity are important.

- The stainless-steel cladding that protects the low-alloy steel of the major reactor pressure vessel and other components from the coolant.

384 Due to the types of alloys used, general primary side corrosion can be measured in μm per year. General corrosion from the inside is not a threat to modern PWRs as it is slow and easily detectable. However, if the materials and coolant chemistry were mismatched, localised corrosion phenomena, such as Stress Corrosion Cracking (SCC) or Intergranular Attack (IGA) may occur that would be a concern if not detected in time:

- SCC requires a conducive environment to occur, meaning both a susceptible material and a poorly controlled chemical environment. In PWRs one of the main threats to integrity is as a result of an interaction between mechanical stress in the material and the cooling water, a phenomenon known as Primary Water Stress Corrosion Cracking (PWSCC). It may also be assisted by irradiation in Irradiation-Assisted Stress-Corrosion Cracking (IASCC).
- IGA mainly affects certain stainless steels subjected to a final heat treatment, and exposed to coolant impurities such as chlorides, sulphates or fluorides at concentrations outside normal PWR conditions. Steels that can be sensitised in this way usually have a high-carbon content, which is why low-carbon grades (L suffix) are often specified. There are tight controls on welding needed to minimise the effects from local heating.

385 Nickel-based alloys, such as Inconel, may experience both IGA and Inter-granular Stress Corrosion Cracking (IGSCC). Reactors containing Inconel 600 suffered a number of problems of the use of this alloy. PWSCC of Inconel 600 remains a serious problem in early PWRs and once the extent and cause of the problem was understood, operators in France, the UK and USA switched to using Inconel 690. Operators in Germany and Canada switched to alloy 800. Both alloys have much improved resistance to PWSCC. All Inconel 600 has been engineered out of UK EPR and EDF and AREVA has specified Inconel 690 which contains more chromium, which protects the alloy grain boundaries, Refs 148 and 152. The nickel-chromium-iron pressure boundary components are now limited to Inconel 690 and its associated weld-metals Alloy 52, 52M and 152. Steam Generator (SG) tubes use Inconel 690 in its thermally treated form. EDF and AREVA consider the chemistry that limits cracking of Inconel 600 will also be beneficial to modern alloys and have presented a chemistry regime compatible with this.

386 Corrosion of the SG tubes which starts from the secondary side is covered in Section 4.4.3 of this report.

387 External corrosion, as can occur from when boric acid is allowed to leak and concentrate by evaporation on external primary circuit surfaces such as happened at Davis Besse in the USA (Ref. 31), is mainly an inspection matter and was covered briefly in my assessment. In this section I mainly assess the potential for cracking of the reactor from the inside, caused by primary coolant. Chemistry affecting the integrity of the fuel cladding is described in Section 4.2.5. The containment building, which is the outmost barrier for protection of the public, is covered in Section 4.2.8.2.

388 Whilst it was clear from my assessment in Step 3 of GDA that coolant-assisted cracking should be less of a problem with a new PWR than it has been in the past, EDF and AREVA still needed to provide evidence for the chemistry and material choices made in UK EPR. I raised RO-UKEPR-44.A1 (Ref. 9) requesting a topic report on chemistry, the response to which (Ref. 172) covered some of the material integrity aspects. In TQ-EPR-614 (Ref. 8), I asked EDF and AREVA to identify areas of the design where they had needed to make alterations to account for the potential for cracking. They initially replied

that no changes were made to the design of UK EPR to account for cracking. In order to understand the precautions taken in the design of UK EPR, I raised TQ-EPR-1235 (Ref. 8). My assessment in this area for UK EPR is described below.

4.2.4.1 Material Selection for Corrosion Prevention

389 The major materials of construction of UK EPR were identified by EDF and AREVA in response to RO-UKEPR-46.A2 (in Ref. 161) and the responses to TQ-EPR-900 and 907 (Ref. 8). The main material choices for UK EPR are listed in Table 7 in Section 4.2.3.2. Other than the Inconel, primary circuit components identified as areas potentially susceptible to PWSCC or IGA employ high grade stainless steels on their wetted parts. These are all valuable design choices in UK EPR:

- The low-alloy steels, from which the reactor vessel and certain other components are made, do corrode in water and will be clad in RCC-M grades of stainless steels.
- Other structural components inside the reactor core will be made from RCC-M grades of stainless steels.
- All piping will be fabricated from austenitic stainless steel with the minimum number of welded joints. Pipework is stress-relieved subsequent to bending or other fabrication operations thereby minimising the potential for the build up of residual stress.
- Valve components are manufactured from stainless steels.

390 Materials selection requires a balance between structural integrity, cost and minimising radioactivity. I procured TSC support in reviewing the selection of materials for UK EPR, the scope of their review covered compatibility of the metals chosen with the primary coolant chemistry (Ref. 149). Their review of the response to RO-UKEPR-46 in Ref. 13 noted that the actual grades of alloy listed were not specified either by their AFNOR grade or by chemical composition. The alloys were referred to only by their broadest RCC-M designation e.g. RCC-M-4000 (i.e. a generic nickel-based alloy) therefore this identification gave an impression of a precise materials selection whilst in fact it meant a very open ended range of possible materials. More detailed material specifications on the wetted materials were obtained by raising a series of TQs. Whilst my TSC reviewed principally in terms of radiation, they examined specifications for hydrogen and the wetted surface areas of welds, and concluded:

- The weld area may be important, as the susceptibility of welds to corrosion can potentially have high consequence outcomes. EDF and AREVA confirmed that the wetted surface area of Dissimilar Metal Welds (the welds of greater concern) has been minimised at 0.59 m^2 per plant, and is significantly smaller than the wetted surface area of homogeneous (stainless steel) welds at 1.3 m^2 per plant. Both are small in comparison to the tubesheet / SG welds, at 50.5 m^2 per plant. This approach is clearly the correct philosophy, minimising the risk of weld failure, TQ-EPR-900 and 1194 refer (Ref. 8).
- Ref. 149 noted that nickel-based alloys do not require oxygen for SCC to occur, but that hydrogen levels are normally used to control crack initiation and growth. It may not be possible to reduce the hydrogen level (as proposed for UK EPR) low enough to reduce crack initiation at T_{cold} . Furthermore, over the 60 year operating life of a reactor, EPRI believes that cracking would have initiated anyway. Therefore, EPRI believes that hydrogen concentrations should be higher, to limit crack growth. EDF and AREVA claim that since cracking has never been observed in Inconel 690 in

service, the UK EPR specifications for hydrogen are not based on cracking criteria. This is discussed further in Section 4.2.7.

391 In order to assess the potential for SCC in UK EPR I commissioned TSC support to review recent experience from other water reactors and look for systematic features of other designs that were vulnerable to PWSCC (Ref. 145) and might be similar to UK EPR. This review included SCC of Inconel 690, stainless steels and claddings in other reactors.

- There have been no instances of PWSCC of Inconel 690 after more than 20 years of reactor service in the UK and elsewhere. If deliberately stressed in the laboratory, cracks in Inconel 690 can be made to propagate when exposed to hydrogen at low temperatures. Low-Temperature Crack Propagation has not been a problem in operating reactors under normal operations. Start-up and shutdowns are discussed in more detail in Section 4.2.11.
- In stainless-steel, most instances of cracking occur as a result of non-uniform cold work remaining from fabrication or occurred in regions of low coolant flow, such as found near the control rods or in the pressuriser.
- Alloy X750 springs have also been subject to cracking (Ref. 142).
- The stainless-steels that clad the low-alloy structural components are designed to be ductile. The pressure-vessel materials and welding procedures are chosen to avoid underclad cracking.
- All wetted materials inside the reactor will be specified to be resistant to SCC under normal operating conditions without repair or replacement for the entire life of the reactor. The base metal will be alloy 20MND5.
- Use of sensitised austenitic stainless steel is prohibited anywhere inside the reactor vessel.
- The control-rods will be made of 3 types of alloy; stainless steels, Inconel alloys and a small amount of cobalt-based alloy, in addition to the control materials themselves, which are clad.
- The reactor vessel head penetrations will also be made from Inconel 690.
- Any heat-treatments will be tightly controlled to avoid sensitisation.
- High levels of cleanliness will be maintained to minimise any risk of localised corrosion such as IGA or SCC.

392 The TSC reviews of other reactors (Refs 145 and 152) identified a few instances of cracking occurring in regions of stagnant coolant, such as canopy seals or dead-leg pipework, where impurities can accumulate. This is especially true in crevices. These reviews also noted several failures of Pressuriser Heaters, including one recent failure in the UK. In conjunction with the TSC review, I assessed the specific material choices and design features of UK EPR that might be sensitive to cracking (Refs 145 and 152). The initial response to TQ-EPR-614 (Ref. 8) stated that no areas of UK EPR were potentially susceptible to SCC. EDF and AREVA were essentially claiming that SCC had been designed out of UK EPR by appropriate selection of materials and fabrication processes. I was not content with this response as it did not provide any evidence. I discussed this response with EDF and AREVA who provided an updated reply contained a number of specific examples where design or material changes have resulted in reduced potential for SCC, some of which are assessed in the following paragraphs.

393 Residual stresses remaining from fabrication, called cold work, can also increase cracking susceptibility. I raised TQ-EPR-1235 (Ref. 8) to clarify part of the response to RO-UKEPR-44.A1 (Ref. 172), which suggested that lithium was limited in UK EPR partly due to its effect on Irradiation Assisted SCC (IASCC) of core baffle bolts. This TQ specifically addressed materials integrity, by asking EDF and AREVA to identify regions where highly alkaline chemistry could develop, and whether any parts of UK EPR were susceptible to cracking assisted by irradiation and lithium. In response to TQ-EPR-1235 (Ref. 8), EDF and AREVA replied that the only region where highly alkaline chemistry could develop was around the heaters in the pressuriser. The pressuriser heaters would be nickel plated in UK EPR to compensate for this. EDF and AREVA believe that the influence of lithium on IASCC is unproven and responded to TQ-EPR-1235 by saying that there were no baffle-bolts in UK EPR; instead, the heavy reflector that replaces the baffle is fixed by tie-rods connected to forgings.

394 I raised TQ-EPR-1271 (Ref. 8) requesting further details of the nickel plating being applied to the pressuriser heaters. In their reply, EDF and AREVA summarised the testing undertaken and provided details of their manufacturing process. These have been assessed in the Structural Integrity Report Ref. 116. Whilst EDF and AREVA claim that 500 hours of an accelerated corrosion test justifies the lifetime of the heater, nickel plating is not always durable and nickel loss would increase levels of ^{58}Co in the circuit as well as other elements if not strictly controlled. A heater failure would place debris into the circuit, where it could potentially damage fuel. I find that the licensee should justify the nickel plating process being adopted for the pressuriser heaters. I consider this to be an Assessment Finding **AF-UKEPR-RC-12**. This supplements Ref. 116, which concludes that a heater failure would not be a major threat to the pressure boundary.

395 The M5® fuel does not use X750 springs (TQ-EPR-320) and the CRDM springs have been replaced by thermally-aged Alloy 718 (Ref. 148) in UK EPR.

396 There are differences between specifications for alloying elements (such as manganese) between some AFNOR grades and British Standards, although it is anticipated at this stage that the comparable levels of chromium and nickel should maintain corrosion resistance within the UK EPR.

397 Overall, I consider the material choices made for UK EPR are adequate except for my questions regarding plating of the PZR heaters, for which I have still to see good justification.

4.2.4.1.1 Surface Conditioning and Finishes

398 In addition to alloy substitution, SCC can be minimised by removing either the conducive environment or residual material stresses. As such the finishing stages of fabrication can be used to treat metal surfaces to minimise SCC. Extensive fabrication controls for UK EPR include:

- EDF and AREVA have specified detailed procedures for the control of tubing manufacture. Modern tube drawing methods result in surfaces which are inherently very smooth. Thermal treatments will be tailored to control carbide formation and grain sizes. The final stage will include bright mill-anneal under a hydrogen atmosphere (Ref. 119). ND commissioned a TSC review of SG tubing manufacturing routes (Ref. 144). EDF and AREVA procedures are consistent with that review.
- The external surfaces of the pressuriser heaters will be electroplated with nickel to requirements specified by EDF and AREVA (TQ-EPR-1271 (Ref. 8)). This area is assessed as part of the Structural Integrity assessment of UK EPR (Ref. 116).

- Welds in stainless steels will be subject to an RCC-M intergranular corrosion test.
- Welds between stainless steel and Inconel 690 weld-materials should be subject to additional controls for impurities.

399 Several surfaces in the reactor are built up by cladding tough Ferritic structural steel with a corrosion-proof stainless steel or nickel alloy cladding. Controls over the cladding process that prevent corrosion are important, as the barrier between the coolant and the base metal must be complete. As this is primarily a Structural Integrity concern this is assessed elsewhere (Ref. 116).

400 My TSC also conducted reviews of the conditioning methods that could be applied to surfaces to reduce the potential for corrosion. Such methods generally involve modifying the surface stress to make SCC less likely, Ref. 134, 117 and 152. The variety of methods can be used include shot and laser peening but in general, EDF and AREVA have not specified peening but prefers to rely on the correct thermal finishing of alloys to procedure M4105 in the RCC-M code. The overall conclusion of this review was that; "*Overall, at this stage of GDA, the UK EPR materials pre-conditioning and optimisation are considered adequate with regards to PWSCC mitigation and radiation protection. The material selection and information regarding the thermal and mechanical processing are consistent with good practice."* Controls over surface roughness would be specified by the supplier (for approval by the Licensee).

401 Austenitic stainless steels and nickel-based alloys should be handled, protected, stored and cleaned to minimise pick-up of contaminants that could lead to IGA or SCC later in life. Of particular concern are low melting point metals, such as lead and mercury. These controls extend to tools and consumables, such as gloves used during welding. As described in the section on surface cleanliness in Section 4.2.3.2.1, EDF and Areva do require material suppliers to submit manufacturing, inspection and cleanliness procedures for approval. These must align with the governance outlined in RCC-M (Ref. 96), which states that; "*Requirements regarding the cleanliness of the components are given in RCC-M F6000. These requirements are particularly severe for all surfaces in contact with the primary fluid. The compliance to RCC-M cleanliness rules shall guarantee the absence of any harmful surface pollution, thus avoiding any degradation of the material corrosion resistance.*" The requirements of RCC-M for cleanliness apply from the final stage of manufacture through storage and transport to erection at site. It will also be necessary to specify the control procedures that assure cleanliness and prevent contamination before it occurs, as well as fabrication procedures that are specific to the combinations of materials actually used in UK EPR. This requirement is covered by **AF-UKEPR-RC-03** in Section 4.1.3.

402 I conclude, for surface finishing, that EDF and AREVA have demonstrated a good understanding of the principles. These may still have to be translated into documentation for suppliers and fabricators.

4.2.4.2 Chemistry for Materials Integrity

403 EDF and AREVA consider the chemistry that limits cracking of Inconel 600 will also be beneficial to modern alloys and have presented a chemistry regime compatible with this (apart from the hydrogen specification). Even with the introduction of Inconel 690 for SG tubing and other components, I agree with EDF and AREVA that equivalent rigorous chemistry controls and appropriate inspection programmes are needed, as for PWRs with Inconel 600, due to the 60 year design-life of UK EPR. Control of chemistry is still an important means of ensuring the integrity of SG tubing and other components over such timescales and it is likely that chemistry will remain a significant factor determining reactor

lifetimes of many decades. EDF and AREVA described the influence of coolant chemistry on material integrity matters in the response (Ref. 172 and 51) to RO-UKEPR-44.A1 (Ref. 9). In this response EDF and AREVA described the impact of the main parameters affecting integrity as; proposed pH control program, EBA use, maximum lithium concentration, hydrogen concentration range, and impurity limitations. These specifications for UK EPR are based on current technical know-how and plant experience.

404 EDF and AREVA have proposed using zinc at low concentration for dose control, as discussed in Section 4.2.6, they do not claim a benefit from zinc for SCC resistance.

405 Good control of primary coolant chemistry is needed to avoid corrosion of the primary circuit materials. EDF and AREVA states that a constant target $pH_{300°C}$ of ≥ 7.2 is expected. This will be achieved by the controlled addition of lithium hydroxide at a [redacted] $mg\ kg^{-1}$ upper limit of lithium.

406 The concentrations of additive species such as boron and lithium have little effect on PWSCC in Inconel 690 type alloys. Based on analysis of Inconel 600 SCC data using high lithium concentrations (up to 7.6 $mg\ kg^{-1}$ and $pH_{300°C}$ 7.4) EDF and AREVA claim that statistical analysis indicates negligible impact on SCC initiation rates. While based on Inconel 600, EDF and AREVA expect Inconel 690 to perform even better, given its higher resistance to SCC. This is exemplified by the 20 years OEF in PWRs without SCC and the higher degree of resistance seen in laboratory tests. EDF and AREVA consider lithium and pH in normal PWR ranges to be only a "*second order*" factor in SCC of Inconels. EDF and AREVA consider alkalinity values much higher than specified for UK EPR are needed to make austenitic stainless steels susceptible to SCC, given the low residual stresses specified.

407 There has been much experimental work on irradiation-assisted stress corrosion cracking of other steels with high lithium in recent years. Work in this area has concentrated on in-core components such as baffle-bolts. EDF and AREVA have removed this potential concern in UK EPR by design and specification of a modest lithium upper limit, see Section 4.2.2.2**.**

408 Of the primary chemistry parameters those that have the greatest influence on localised corrosion phenomena are the hydrogen and impurity levels.

409 Nickel-base alloy materials, such as Inconel 600 may be susceptible to various forms of SCC. PWSCC is influenced by many non-chemistry environmental factors (such as residual stress and operating temperature) but the main chemistry influence is provided by the hydrogen concentration which influences the electrochemical potential. In UK EPR EDF and AREVA expect hydrogen gas to be added to the coolant at levels between 17 and 30 $cm^3\ kg^{-1}\ H_2$, compared to most PWRs which have a nominal operating profile between 30 and 40 $cm^3\ kg^{-1}\ H_2$. In response to RO-UKEPR-44.A1 (Ref. 172 and 51), EDF and AREVA state that the main guidelines relating to hydrogen are:

- EPRI - [redacted] $cm^3\ kg^{-1}$
- VGB - [redacted] $cm^3\ kg^{-1}$
- EDF - [redacted] $cm^3\ kg^{-1}$
- Mitsubishi Heavy Industries (MHI) - [redacted] $cm^3\ kg^{-1}$

410 The primary coolants of PWRs have been successfully dosed with hydrogen for many decades. Whilst there is consensus on the magnitude of the protection afforded by hydrogen, current opinions differ on the exact concentrations of hydrogen needed. Issues

related to the application of hydrogen are discussed under Section 4.2.7 in more detail, but clearly EDF and AREVA intend UK EPR to operate at or below the lower end of current plant operating experience.

411 In the response to RO-UKEPR-44.A1 (Ref. 172 and 51), EDF and AREVA discussed the potential for Low Temperature Crack Propagation (LTCP). Laboratory test results indicate that the fracture resistance of Alloys 600 and 690TT (TT - Thermally Treated) as well as their compatible weld metals, Alloys 182/82 and Alloys 152/52 respectively, is lower in low temperature PWR primary water than in air. The phenomenon is believed to be a form of hydrogen embrittlement that depends on the concentration of hydrogen in the water. UK EPR uses both Inconel 690 and 52. LTCP has not been experienced in operating plants, but has been studied extensively in laboratory testing. EDF and AREVA conclude that; "*Since LTCP only occurs at temperatures below 150 °C and with hydrogen in the primary coolant, it is thus not an issue:*

- *during normal operation or during those stages of plant cool-down and start-up when the temperature of the primary coolant is above 150 °C*
- *during plant shutdown when the temperature is below 150 °C and in oxidizing environment, i.e., during cold shutdown after dehydrogenation and oxygenation*
- *during plant start-up for temperature below 150 °C and without hydrogen because the primary coolant is hydrogenated only after the temperature increase of step*

On the contrary LTCP could occur during plant shutdown for temperature below 150 °C in reducing environment and H_2 *concentration superior to a threshold included between 10 and 30* cm^3 *kg*". I agree that this phenomenon is not a concern during normal operations so it is discussed further in Section 4.2.11, under start-up and shutdown chemistry.

412 Other forms of corrosion that Primary System materials are susceptible to, such as Intergranular Stress Corrosion Cracking (IGSCC) and Intergranular Attack (IGA), are more directly influenced by impurities in the water. IGSCC or IGA can be initiated and propagated in the presence of a sufficient concentration of inorganic ions (halides such as chloride and fluoride, and other ions such as sulphate) and dissolved oxygen. High impurity levels have the potential to cause SG tube rupture within one cycle of operation and the control of chemistry remains a primary means of preventing this type of failure.

413 The levels of aggressive species present within the primary coolant are monitored and controlled in UK EPR. Of particular importance are the levels of chloride and oxygen which can lead to Intergranular Stress Corrosion Cracking (IGSCC) of stainless steels under stressed conditions. Consequently, EDF and AREVA propose maximum oxygen, chloride and fluoride concentrations, which are [redacted] and [redacted] $\mu g\ kg^{-1}$ for oxygen and chloride or fluoride respectively. Operating concentrations are expected to be orders of magnitude lower. These values (or similar) have been used successfully in PWRs for many decades and have been shown not to initiate SCC in stainless steels, irrespective of sensitised condition. EDF and AREVA propose the same limits for sulphate ([redacted] $\mu g\ kg^{-1}$), even though the synergistic effects of chloride and sulphate are not seen at such low levels. These are similar to the latest guidelines recommended by EPRI (Ref. 27) and others.

414 EDF and AREVA also propose to limit the sodium concentration in the primary coolant, mainly "*due to the sodium concentration which can create locally an aggressive caustic environment for stainless steel and thus leads to general corrosion, localised corrosion, intergranular corrosion and stress corrosion*." This will be limited to ≤ [redacted] $\mu g\ kg^{-1}$. Such a requirement is not specified in other guidelines, but appears to have originated from EDF plants.

415 It is known that limiting the concentration of anions like fluoride at all times and maintaining reducing conditions in operation will prevent other types of corrosion in most of the circuit. Since the effect of anions on stainless steel has been well known since the earliest reactors, the tight limiting concentrations for most anions defined for UK EPR are generally adequate. These are discussed further in the CVCS specific assessment (Section 4.2.2).

416 Almost all operators are well aware of the need to prevent impurity ingress and control of materials such as Teflon and EDF and AREVA have demonstrated an understanding of these principles. The demineralised water make-up system is assessed further in Section 4.4.2.1.8.

417 The chemistry controls proposed by EDF and AREVA for UK EPR appear reasonable from an integrity and corrosion control perspective. These are based upon current industry experience and knowledge and have been applied successfully in many PWRs for a number of decades, subject to my finding on hydrogen levels, in Section 4.2.11.

4.2.4.3 External Corrosion

418 Boric acid is corrosive and there have been a number of high-profile events where boric acid has caused substantial thinning of pressure-vessel walls from the outside (see Refs 31 and 122 for many examples). As this aspect is not a fundamental Reactor Chemistry design issue, it is more appropriately assessed at a later stage and was not considered further in my assessment. I would expect a Licensee to implement appropriate controls, including an inspection and maintenance programme, to prevent and detect external corrosion as part of their normal inspection and maintenance procedures. This is primarily within the remit of the Licensee to develop as part of the plant operating instructions; during my assessment I have not noted any reasons why such a strategy cannot be implemented in UK EPR.

4.2.4.4 Summary

419 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of primary circuit integrity are:

- The selections of materials that have been made by EDF and AREVA for UK EPR are generally high-grade and offer good resistance to corrosion, and EDF and AREVA have demonstrated how to prevent the use of inappropriate materials or materials in an inappropriate condition. The UK EPR primary circuit is comparable with good practice and incorporates advantageous design features which include:
    - i) Removal of Inconel 600 and replacement by thermally treated Inconel 690, including their associated weld metals.
    - ii) Susceptibility to SCC has been designed out, by eliminating certain geometry and controlling residual stresses and cold work.
    - iii) Avoiding sensitisation and adoption of low carbon stainless steel alloys, where possible.
- During normal operations the controls on chemistry described in Section 4.2.10 should offer sufficient protection to the primary circuit materials to remove the possibility of integrity damage by general corrosion.
- The lithium and boron levels in the coolant should not adversely affect crack growth rates in the materials chosen and are consistent with current international primary

water chemistry guidelines. Similarly, the controls suggested for impurity levels in the primary coolant are compatible with industry experience and the latest recommendations in numerous international guidelines.

- Hydrogen levels, assessed in Section 4.2.7, are below or at the lower end of current operating experience.
- Experience of Inconel 690 has been excellent but it should still be subject to normal inspections and controls for aging, especially in cooler parts of the primary circuit. EDF and AREVA have put robust procedures in place to provide potential operators with the information they need to control corrosion in the field.
- I would expect a Licensee to implement appropriate controls, including an inspection and maintenance programme, to prevent and detect external corrosion as part of their normal inspection and maintenance procedures.

420 When taken as a collective answer, the TQ and RO responses under this area add significantly to the UK EPR safety case for primary circuit integrity. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.4.5 Assessment Findings

421 Based upon the assessment of primary circuit integrity in UK EPR described in Section 4.2.4 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-12*** *– The Licensee shall generate evidence to support the lifetime behaviour of the nickel plating to be adopted for the pressuriser heaters in UK EPR. This should include consideration of material losses from the plating on radioactivity. This Assessment Finding should be completed before installation of the pressuriser is complete. arget milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components - delivery to Site.*

4.2.4.6 GDA Issues

422 Based upon the assessment of primary circuit integrity in UK EPR described in Section 4.2.4 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.5 Assessment – Fuel Integrity and Crud Formation

423 In UK EPR, as with other PWRs, the core is constructed from a number of zirconium alloy clad, uranium dioxide pellet fuel assemblies arranged in an approximately circular array. Each fuel assembly is itself constructed from a square array of fuel rods, control rod guide tubes and instrumentation tubes. Described in the PCSR (Ref. 11, Section 4), the core of UK EPR contains 241 fuel assemblies with each assembly in a 17x17 array. The number of fuel rods in each fuel assembly is 265 with 24 guide tubes. AREVA fuel is clad in M5® zirconium alloy which contains 1% niobium as the principal alloying element but has different impurity and annealing specifications to the Russian E110, which otherwise is similar. The grids and guide tubes in AREVA fuel are also made from M5® alloy (see TQ-EPR-320 (Ref. 8)). EDF and AREVA claim the new cladding should permit operation up to 62 or 70 MWd/tU (GWd/MtU) which is towards the top end of worldwide experience and around twice that currently applied in the UK.

424 The lifetime of the fuel is limited mainly by two factors, oxidation of the cladding and the internal pressure. Under PWR conditions the zirconium metal is very un-reactive and only corrodes very slowly to produce a zirconium dioxide outer layer. The depth of the zirconium dioxide layer on the fuel has a marked effect on the temperature of the zirconium metal surface, because zirconium dioxide transmits heat poorly. The hotter the surface of the zirconium the faster it corrodes, so there is feedback and the corrosion of PWR fuel accelerates above about 60 µm oxide thickness. These effects take place over periods of several months in a reactor, and are assessed in detail in the assessment on Fuels. The typical limit for oxide thickness is 100 µm. This affect is amplified when fuel crud deposits on top of the oxide layer. The PCSR (Ref. 11) does not discuss corrosion of the fuel, but the inclusion of the chemistry chapter in the consolidated PCSR (Ref. 105) rectifies this omission. Certain chemicals, such as high levels of lithium and fluorides are known to increase corrosion of the cladding surface and for this reason controls on the levels of various dissolved species are assessed below.

425 Over 99% of the radioactivity in a nuclear reactor is normally retained within the cladding of the fuel. The zirconium alloy cladding is roughly 0.6 mm thick to conduct heat, which makes it susceptible to damage by corrosion or wear if conditions are not carefully controlled. After the steam generator, the cladding of the fuel is the second largest surface area in PWR. Any leaks would noticeably increase radioactivity carried in the coolant and deposited around the circuit. If a thick layer of deposits (fuel crud) is allowed to form on the fuel, cladding corrosion rates will increase and boron in the deposits could distort the power profile of the reactor, if sufficiently deposited. The amounts of nickel and iron dissolved in the coolant with lithium and boron have a major effect on the build-up of crud, as does the total boiling area. The effect of crud on radioactivity is assessed in Section 4.2.3.4 of this report, the chemistry of crud itself and the calculations undertaken, by EDF, AREVA and by TSCs for ND, are assessed below.

426 Modern fuel rarely leaks. The values for fission product radioactivity originally used in the design of EPR were replaced in 2009 by Ref. 60. This report (Ref. 60) applies the measured data from the French N4 plants to the UK EPR. The values quoted differ to those for the N4 plants, but no rationale or explanation for the differences is presented in this report, but EDF and AREVA subsequently provided information on the differences in responses to RO-UKEPR-73 (Ref 9). Given good coolant control, the main causes of leaks would be mechanical wear due to debris. Even so, the consequences even of rare fuel leaks would be noticeable so that Reactor Chemistry relating to fuel considers:

- The chemical additions and exclusion of impurities that minimise Zircaloy corrosion in general, and M5® in particular.
- Minimising the build-up of fuel crud, so far as is reasonably practicable, to ensure safety margins are not eroded.
- Detection of any failed fuel, when, where and how much damage has occurred, in order to try to mitigate the effects of increased radioactivity in the coolant and in subsequent operations.

427 Continued operation with failed fuel increases the source term for releases and can lead to further fuel damage from hydriding. The safety case for operating the reactor will specify the maximum burn-up of the fuel and maximum tolerable leakage as important parameters. The PCSR for UK EPR (Ref. 11) contains a limit for radioactivity in the coolant, and infers an unspecified number of failed rods in Chapters 11.2 and 14.6, as does the PCER.

428 The effects of chemistry on the fuel were an important part of the request under RO-UKEPR-44.A1 (Ref. 9). I also raised several TQs on this topic, including TQ-EPR-716, 1095 and 1356 (Ref. 8). EDF and AREVA also provided their analysis of fuel crud production in UK EPR (Ref. 112) as part of the response to RO-UKEPR-74.A2 (Ref. 9). The response to these, amongst other EDF and AREVA documents, is described below. My assessment of the chemistry effecting fuel was supported by TSC reviews, Refs 148 and 149.

429 Due to the cross-cutting nature of these topics, I worked with the ND fuel design inspector to assess these topics and many aspects related to fuel performance are assessed elsewhere (Ref. 19).

4.2.5.1 Effects of Coolant Chemistry on Fuel Cladding

430 The effects of hydrogen, lithium and impurities, such as fluoride, on fuel cladding are discussed below.

431 In response to RO-UKEPR-46.A2 (Ref. 161), EDF and AREVA provided their justification for the [redacted] mg kg^{-1} lithium limit in UK EPR. This is based upon the claimed improved corrosion resistance of the M5® cladding. A high concentration of lithium on its own is known to be harmful to fuel cladding but it is always added in combination with boric acid and combining boric acid with the lithium makes it less harmful. Lithium has the greatest effect when the zirconium oxide layer is already > 60 – 70 µm. In response to RO-UKEPR-44.A1 (Ref. 172) EDF and AREVA presented data for the oxidation of M5® cladding, including data from the REGGAE tests, which showed that the oxide layers tend to be thinner on M5® than Zircaloy. This suggested the resistance of M5® cladding to lithium should be much better than the Zircaloy it replaces. In TQ-EPR-1234 (Ref. 8), I pointed out that the REGGAE tests were conducted with clean fuel and did not account for the thickness of crud on top of the oxide layer, or the wick boiling that takes place. In response, EDF and AREVA said they will be conducting tests in 2012, to simulate the effect of crud, although no details of how the crud would be simulated were given. They also provided plant data showing that oxide growth on M5® cladding was no greater under thick (100 μm) crud than without crud at all. I am content that the proposed lithium limit appears compatible with the use of M5® cladding.

432 The addition of Nb to M5® resulted in fuel cladding corrosion falling by 75% in the presence of hydrogen. However, without extra hydrogen dissolved in the coolant, the corrosion of M5® would be worse than the Zircaloy-4 it replaced (Ref. 148). Excessively high levels of hydrogen can lead to hydride embrittlement, so it is normal practice to specify lower and upper concentrations for hydrogen in a PWR. The actual specification of 17 to 30 cm^3 kg^{-1} for UK EPR is assessed elsewhere in this report, see Section 4.2.7, but the upper limit specified for EPR is low enough to avoid such concerns.

433 Impurities can increase the corrosion rate of fuel cladding. High fluoride levels have been shown to be detrimental to fuel cladding. The effect of chlorides and iodides is much smaller than fluoride (in fact EDF and AREVA claim chloride has no noticeable affect at mg kg^{-1} levels on M5® cladding) although fission-product iodide can accumulate on the inside surface of the cladding. The threshold level for fluoride affecting cladding is 10 mg kg^{-1}, but the ion-exchange resins in the CVCS will not remove fluorides efficiently (Ref. 148), so fluoride ingress must be prevented by effective purification of the feedwater. As per Section 4.2.4.2, fluoride is measured in the primary coolant and controlled to levels below [redacted] μg kg^{-1}. Other impurities such as sodium hydroxide, chlorides, sulphates and chromates can have a moderate effect, but less than lithium and fluoride. Such

effects are well understood and the “*routine*” controls suggested by EDF and AREVA are reasonable.

434 EDF and AREVA have specified zinc addition for control of primary circuit radioactivity, Ref. 153. Section 2 of this report covers the effects of zinc, which may also limit crud formation, see the following section.

435 From my assessment, it is clear that EDF and AREVA has taken account of the effects of levels of additives and impurities on the fuel in their specifications for UK EPR, but the chemistry of fuel clad corrosion was not discussed in the original PCSR. The corrosion effects outlined are slow and with planning, problems due to corrosion should be avoidable. I raised RO-UKEPR-44.A4 (Ref. 9) requesting a PCSR chapter. The draft PCSR chapter (Ref. 103), described in Section 3.2, contains much more information on the effects of chemistry on fuel integrity. This is much improved on the Step 4 PCSR (Ref. 11).

436 The effects of coolant chemistry on the fuel cladding are an important part of Assessment Finding **AF-UKEPR-RC-01**.

4.2.5.2 Fuel Crud

437 If the coolant contains a high level of dissolved solids, as might arise from excessive corrosion of SG tubing, these will deposit on the fuel as crud, especially if there is boiling in the core. In many PWRs limited (sub-nucleate) boiling of the coolant is permitted at certain times. Boiling is major factor in causing deposits (fuel crud) to accumulate.

438 The safety effects of fuel crud vary depending upon the amount that is produced. Any amount of fuel crud increases the plant radiation levels, as discussed in Section 4.2.3.4, generating additional waste as well as an ORE hazard. If even more fuel crud deposits this can result either in damage to the fuel cladding, via Crud Induced Localised Corrosion (CILC), or (if appreciable boron is absorbed in the crud) as a distorted power profile, called Crud Induced Power Shift (CIPS). If left to develop uncontrolled, CILC would result in undesirable leaks from the fuel and CIPS could lead to a loss of shutdown margin. In western PWRs, CILC has contributed to only around 6 fuel failures over the last forty years but more cases of CIPS has been observed. The most severe example was probably at Callaway in the US, when crud levels greater than 100 μm were formed on some of the fuel. To avoid an erosion of shutdown margin and excessive fuel temperatures, the power at Callaway had to be reduced for several cycles until the cause of the problem could be rectified (Ref. 151). Eventually, the Inconel 600 steam-generators at Callaway were replaced by Inconel 690 and the station began injecting zinc so that Callaway now operates without such extreme fuel crud problems.

439 In general terms a limiting value of crud thickness (as an addition to the oxide layer) below about 20 μm is thought not to be significant since empirical studies and modelling show that effects of boron absorption and on heat transfer are minimal. Hence the chemistry of the coolant should minimise accumulation of crud in the core, if not prevent it. EDF and AREVA believe they can control the build-up of fuel crud in UK EPR by adopting the following strategy:

- Operate at a minimum $pH_{300°C}$ of 7.2 (Ref. 172).
- Use of Inconel 690 rather than 600 for SG tubing, which generates fewer dissolved solids.
- Adding zinc and placing additional controls on the chemistry to avoid precipitation of zinc compounds on the fuel.

- Excluding silica from the core by such practices as avoiding use of glass-fibre filters.

440 CIPS is caused by a large mass (in the kg range) of boron absorbed in the crud, and a large boiling area is needed before effects would be noticeable. Early in Step 4, EDF and AREVA indicated that their intention was to run UK EPR at a low boiling rate and with minimal fuel crud. EDF advises that CIPS has never been observed in any of their N4 PWR with Inconel 690 tubing. Some localised CIPS has been observed in other PWR units after replacement of Inconel 600 steam generators with Inconel 690. To check that UK EPR would be more like the N4 units (in not suffering CIPS), I sought evidence for boiling rates and chemistry in UK EPR.

441 Because EDF and AREVA had not reported any predictions of expected boiling, radioactivity or crud specifically for UK EPR, I contracted TSC support to construct a chemical simulation of the phenomenon. I requested information on the boiling parameters for the core in UK EPR in TQ-EPR-716 (Ref. 8). I requested information on the area and the thicknesses of the crud, key determining factors for CIPS and CILC, in RO-EPR-74.A2 (Ref. 9). EDF and AREVA sought a number of opportunities to clarify the information that I had requested and initially said that such data would not be available because details of the core management for UK EPR had not yet been defined. Late in Step 4, EDF and AREVA provided boiling rate estimates for UK EPR (for a preliminary core management) which were higher than indicated in TQ-EPR-716 (Ref. 8), together with their own estimate of crud thickness in Ref. 112. I was able briefly to compare EDF and AREVA predictions with those of my TSC, during the writing of this report.

442 In this paragraph I summarise my TSC modelling results for UK EPR and a standard 4 loop PWR. My TSC applied their expertise in modelling reactor coolants to simulate the chemistry of corrosion products and fuel deposits in UK EPR, using the thermal and boiling data provided by EDF and AREVA and other key input parameters such as carry-over and stainless corrosion rates. My TSC estimated soluble cobalt activity (in MBq/m^3), surface activity (in $MBq\ m^{-2}$), crud masses (in kg) and crud thicknesses on the fuel (in μm), at selected locations in the reactor. They compared their results with equivalent calculations for a standard 4-loop PWR and other benchmarks and report all of their results in Ref. 133. My TSC did not take account of zinc addition in their calculations.

443 In summary my TSC calculations showed that:

- Crud thicknesses in UK EPR would not be sufficient to cause either CIPS or CILC, being well below the thickness needed to absorb boron, for instance.
- Levels of ^{58}Co may be slightly higher on average than other non-boiling reactors, but within the normal range of variation seen between different plants.
- Levels of ^{60}Co may be slightly lower than other reactors, due to the low Stellite^{TM} inventory.

444 EDF and AREVA used the same thermal and boiling data as was supplied to my TSC and their own estimates for other key parameters such as corrosion rates and carry-over. They produced estimates of crud thicknesses and masses using BOA version 2, but did not provide any figures for expected radioactivity during Step 4 as BOA did not predict radioactivity. I requested radioactivity figures via RO-UKEPR-74, EDF and AREVA will complete provision of activity data under the GDA Issue **GI-UKEPR-RC-02**, by estimating the material (crud) release and its activation. The calculations performed by my TSC were undertaken with a comprehensive model of the chemistry which included the effect of crud outside the core and predicted the production of radioactivity in crud.

445 In contrast to their earlier assurances to ND, the crud thickness provided by EDF and AREVA was sufficient to cause absorption by boron over a small area of the core. The total crud mass was also larger than expected, although it did not appear to be excessive.

446 I was surprised by these results from EDF and AREVA, and asked them to perform a comparison with their N4 series reactors, in TQ-EPR-1095. Their N4 reactors have not suffered from CIPs or CILC and if UK EPR generated less crud, I could see that CIPS and CILC would definitely not be a problem and radiocobalt would be low and controllable. The data they provided showed that thicknesses of crud in N4 and UK EPR would be similar to each other but the mass of crud in UK EPR would be (about 50%) greater. Because BOA version 2 only simulates crud on the fuel, this means that the fuel crud area must be larger in UK EPR than in N4 reactors.

447 The fact that EDF has not seen CIPS in the N4 plant is therefore not evidence that CIPS cannot occur, since there is more crud predicted in the UK EPR. While these arguments provide a degree of comfort for GDA, and more information on related matters will be provided as part of the resolution of **GI-UKEPR-RC-02**, the Licensee should repeat calculations with the most appropriate means available at the time, particularly where a more comprehensive model of the chemistry (especially outside the core region) is available. I find that the Licensee should conduct analyses of sensitivity to factors such as pH, boiling and dissolved corrosion products on crud build-up. These should be used to identify:

- Factors significant to the control of crud build-up on fuel.
- Criteria for technical specifications and limits.
- Margins to the chemistry limits.
- What corrective actions, if any, are needed for poor chemistry.
- Whether the specified pH_{300} range (7.2 to 7.4) is the most appropriate.
- Whether the specified range of hydrogen is the most appropriate.

448 This analysis will ensure an appropriate level of control assuring fuel integrity and the avoidance of CIPS. This is assessment finding **AF-UKEPR-RC-13**.

449 ND accepts that switching from the Inconel 600 to Inconel 690 will reduce the nickel release however the iron release rate from the stainless steel in the reactor would be unchanged. In the absence of a corrosion rate for the stainless steel pipework, some operators estimate iron from crud scrape data pro-rata to the nickel. However, in an Inconel 690 reactor, the iron/nickel ratio will be greater, so this would under-estimate crud production, EDF and AREVA will include the effect of iron in their response to **GI-UKEPR-RC-02**.

450 Exceeding some limits for a few hours may make little difference to the fuel, but in general the margins to boiling and chemistry limits for crud development need to be understood properly if a Licensee wishes to maximise electrical output.

451 Currently, EDF and AREVA use a limit of acceptability for crud recommended by EPRI and using the BOA code. This is based on a crud thickness limit of 30μm (in addition to any zirconium oxide) and appears to be independent of area. Based on my TSC calculations, I understand that absorption of boron can begin above around 15 μm crud thickness and increases with the thickness of the crud. Crud limits should be justified, because the mass of boron (and hence the potential to interfere with shutdown margins) could be roughly proportional to the product of the thickness and the area. I find that several chemical factors will be important considerations when defining the limits and

conditions for operation of UKEPR, see **AF-UKEPR-RC-02, AF-UKEPR-RC-13** and **AF-UKEPR-RC-14**. Specifically there may be periods when tighter controls may be needed to avoid dense fuel deposits.

452 My main concern with crud in UK EPR is for the production of radiocobalt rather than effects on cladding corrosion (CILC) or neutron control (CIPS). Because of other assurances provided by EDF and AREVA to the Fuels Inspector in ND, this would normally have resulted in an Assessment Finding for the Licensee. Since I wish to discuss these latest results and clarify some of the assumptions made by them, EDF and AREVA have accepted this as part of GDA Issue **GI-UKEPR-RC-02**.

453 The type of chemistry controls needed during commissioning are described in Section 4.2.12. Since large quantities of crud are created at this stage, the definition of suitable targets for measurements such as particulates and nickel at the end of HFT will be essential to demonstrate that radioactive crud can be controlled ALARP, see **AF-UKEPR-RC-21** in Section 4.2.12.2**.**

454 Providing that due care is taken during commissioning, and subject to calculations for the highest rated channels, I am satisfied that general levels of crud on fuel in EPR will not challenge the integrity of the fuel. This conclusion is also supported by the Fuels Inspector.

4.2.5.3 Summary

455 Based upon the evidence presented during GDA, the main conclusions I draw for the fuel and crud assessment are:

- Modern M5® fuel cladding proposed by EDF and AREVA for the first fuel cycle allows greater margins regarding end of life oxide thickness than the Zircaloy-4 cladding used in the past. The licensee should justify the limits of acceptability for crud area and thickness used in predicting fuel performance.
- It would be possible to run PWR chemistry so as to induce fuel failure, even with modern cladding. This is the reason that rigorous chemistry limits should be defined along with actions if the limits are exceeded. The PCSR discusses the effects of oxide and crud growth on heat output from the fuel, but globally these effects should be small. The basis for the various limits relating to fuel integrity control including chemistry and boiling should be documented by the Licensee.
- It is currently not clear whether or not there are levels of parameters (such as pH, carry-over or boiling) at which crud and radioactivity might suddenly increase, and what margins there are. EDF and AREVA have agreed to clarify some of these effects with their responses to **GI-UKEPR-RC-02** and **AF-UKEPR-RC-13**.
- I am content that UK EPR can be operated with a minimum $pH_{300°C}$ of 7.2 throughout the cycle and this should be beneficial in controlling crud levels.
- It is implicit in this assessment that operating documentation covers chemical phenomena affecting fuel integrity and CIPS, and identifies limits and controls that assure compliance with the Technical Specifications for fuel safety and coolant fission-product activity. This is one of the objectives of Assessment Finding **AF-UKEPR-RC-02**.
- Providing that due care is taken during commissioning, I am content that general levels of crud on fuel could be controlled in a UK EPR. Target parameters that control deposits on fuel from commissioning onwards should be identified.

- Regular monitoring of radioactivity in the coolant is required to ensure compliance with technical specifications and quantify the size of any failure in the unlikely event any fuel should fail. Failed fuel is not left in the reactor for more than one cycle and is normally segregated in the pool.
- EDF and AREVA have provided ND with a range of possible core designs for the first cycle of UK EPR. I am satisfied that operating parameters and chemistry could be selected to avoid CIPS and CILC and reduce radiocobalt production effectively. Wider ranges of operating parameters and chemistry should be possible with attention to core design and boiling.
- There seem to be different definitions of acceptability for crud thicknesses and areas and the Licensee for any UK EPR will need to justify theirs.

456 Overall, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.5.4 Assessment Findings

457 Based upon the assessment of fuel and crud in UK EPR described in Section 4.2.5 above, I have identified the following Assessment Finding whichs need to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as appropriate, during the design, procurement, construction or commissioning phase of the new build project:

- ***AF-UKEPR-RC-13*** *- The Licensee shall conduct sensitivity analysis for fuel crud formation in UK EPR. This should be used to demonstrate that levels of crud can be controlled and reduced So Far As Is Reasonably Practicable (SFAIRP) in UK EPR and should be based upon the detailed operating chemistry and core design for the UK EPR reactor. These calculations should provide balanced predictions of activity levels that allow the assessment of control measures including boiling patterns and Stellite*^{TM} *replacements, as well as the management of significant chemicals and radionuclides. The Licensee shall conduct analyses of sensitivity to factors such as pH, zinc, boiling and dissolved corrosion products on crud build-up. The analysis should be used to justify related limits, conditions and criteria. This Assessment Finding should be completed before nuclear operations, as this is when fuel crud is formed. Target milestone – Initial criticality.*

4.2.5.5 GDA Issues

458 Based upon the assessment of fuel integrity and crud in UK EPR described in Section 4.2.5 above, I have identified one Reactor Chemistry GDA issue which requires resolution:

> ***GI-UKEPR-RC-02*** *– Control and Minimisation of Ex-core Radiation – EDF and AREVA to demonstrate that ex-core radiation levels in UK EPR are minimised so far as is reasonably practicable and can be controlled.*

459 The complete GDA Issue and associated action(s) are formally defined in Annex 2.

4.2.6 Assessment – Zinc Addition

460 In accordance with their strategy of limiting the build-up of activated corrosion products in UK EPR, EDF and AREVA propose to dose the primary coolant of UK EPR with zinc. Worldwide, many PWR operators are now adding low levels of zinc (less than 20 μg kg^{-1}) where they have issues with radiation levels. A few operators are adding higher levels of zinc (20 to 50 μg kg^{-1}) where they have existing material integrity concerns. EDF and AREVA propose to add between 5 and 15 μg kg^{-1} zinc, in the form of depleted zinc acetate principally to control radiation fields. EDF and AREVA claim there is no detriment from adding zinc in terms of waste production and their case for structural integrity does not rely upon zinc addition. EDF and AREVA specify zinc to help control radiation levels from cobalt. No evidence was presented to support this design choice for UK EPR in the original Step 4 PCSR, although EDF and AREVA have since provided more information in the consolidated GDA PCSR (Ref. 105).

461 Up to 5 kg zinc would be added to UK EPR in each cycle in order to maintain 10 μg kg^{-1} in solution (TQ-EPR-1169 (Ref. 8)). Much of this would be absorbed on metal surfaces in the reactor as intended, but some would also be lost to the CVCS. Possible detrimental effects of adding this amount of zinc may include; formation of activated ^{65}Zn (if natural zinc is used), which can exceed the radioactivity of radiocobalt if not controlled, the formation of zinc deposits on the fuel, consumption of the ion-exchange beds and the influence of acetate on the fate of ^{14}C. These should be balanced against the possible benefits in terms of radioactivity and radwaste. These are assessed below.

462 Since I expected UK EPR to have relatively low cobalt radiation fields and no material integrity concerns, my assessment concentrated on the balance of benefits with the potential negative side-effects of adding zinc. My assessment of zinc in UK EPR was supported by TSC reviews, Refs 148 and 149.

463 At the end of Step 3, I raised regulatory observation RO-UKEPR-45 (Ref. 9), requesting justification for the addition of zinc to UK EPR. EDF and AREVA provided Ref. 153 in response. I subsequently raised TQ-EPR-733 to obtain the evidence to support a number of the claims and arguments presented in this response. In order to draw RO-UKEPR-45 and TQ-EPR-733 to satisfactory conclusions, I raised a second action under RO-UKEPR-45 (Ref. 9), to which EDF and AREVA responded with Ref. 154. The following sections present my assessment of the benefits and detriments of adding zinc to UK EPR, through these RO actions and TQs. Section 4.2.2.2.4 of my report deals with the capability of the design to provide zinc in the correct amounts.

4.2.6.1 Potential Zinc Detriments

464 The overall benefits of zinc are cited in many sources, both by EDF and AREVA and more widely in the nuclear industry, namely reducing radiation fields and protecting materials. There are several potential negative effects of zinc addition and my assessment of these follows:

4.2.6.1.1 Zinc precipitation and Effects on Fuel crud

465 It is thought that zinc is a component of some of the solid borates that can cause CIPS and zinc can react with lithium hydroxide to form solid zinc oxides.

466 Since zinc would not be added at the same point in the CVCS as lithium hydroxide or boric acid, see Section 4.2.2.2.4, I was content that zinc hydroxide and zinc borate would

not precipitate in the CVCS before reaching the main cooling circuit (TQ-EPR-773, Ref. 8).

467 Zinc should also not be added in such quantities as to increase crud formation, particularly if boron gets incorporated with zinc deposited on the fuel. My assessment of the formation of fuel crud in UK EPR appears in Sections 4.2.3.3.1 and 4.2.5.2 of this report. The effect of zinc specifically on crud is summarised below.

468 The formation of crud on nuclear fuel can be tolerated if the crud is porous. This allows boiling of the coolant within the pores of the crud, which is an efficient heat-removal mechanism. Species like silica form a denser crud that prevents this form of heat transfer, and higher fuel temperatures. This could result in fuel damage (CILC) if not controlled. Zinc silicate is particularly insoluble and for this reason, silica levels should be controlled to less than 1 mg kg^{-1} in high-duty cores with zinc addition, Ref. 148. Based on several years experience of zinc in French plants, EDF and AREVA confirmed that no changes to pH, boron, hydrogen or lithium specifications were needed to accommodate zinc addition, in TQ-EPR-773 (Ref. 8). Examples of ranges of these operating parameters which spanned the expected values for UK EPR were used to illustrate this. Control parameters for nickel, silica and the zeolite-forming metals (Ca, Mg, Al) are also specified in the response to RO-UKEPR-44.A1 (Ref. 153) and listed in Section 4.2.10 of this report. EDF and AREVA state that the nickel limit is specified as [redacted] $\mu g\ kg^{-1}$ because US plants have operated successfully without experiencing CIPS with nickel levels between 0.4 and 4 $\mu g\ kg^{-1}$. This limit is a total soluble and particulate concentration.

469 While EDF and AREVA limit nickel to less than [redacted] $\mu g\ kg^{-1}$, they specify no limit for iron. I see no reason why such controls are inappropriate for UK EPR and require the Licensee to justify controls on silica, iron and nickel in their plant specific chemistry plan. I consider this to be an Assessment Finding **AF-UKEPR-RC-14**.

470 EDF and AREVA claim that the precipitation of zinc can be ignored in UK EPR because:

- They have never experienced CIPS in the N4 reactors.
- The crud is predicted to be less than 30 μm thick in UK EPR.

471 Some zinc chemistry was included in the calculations by my TSC for UK EPR. It appears that appreciable zinc borate precipitation on the fuel begins above crud thicknesses of about 20 μm (Ref. 133). The area of crud thicker than this predicted by my TSC was small, but it was not clear how EDF and AREVA justified their 30 μm figure. Late in GDA, EDF and AREVA provided estimates for crud thicknesses in UK EPR that are higher than in FA3 or their N4 reactors, in Ref. 112. Therefore I conclude that zinc borate formation on the fuel in UK EPR cannot be ignored on the basis of the evidence provided so far. I have raised a GDA Issue (**GI-UKEPR-RC-02**) related to crud in UK EPR, which is also described in the section on radioactivity. EDF and AREVA have clearly indicated their intention to operate UK EPR as near to crud-free as reasonably possible, and the first symptom of crud would be increased radiation. I find that the Licensee should confirm the values of quantities such as area, thickness and boron mass that define limits of acceptability for M5® fuel; this is a part of finding **AF-UKEPR-RC-01**.

472 The visual appearance of corrosion products on fuel assemblies at zinc plants is distinctly different from non-zinc plants. After exposure to RCS zinc concentrations, the assemblies have been described as being covered by a uniform deposit that covers the full height of both heat transfer and non-heat transfer surfaces. This deposit has been described as black, sooty, dark-coloured, semi-reflective, and a darker-than-normal grey surface. The colour may relate to metallic nickel or to carbon from the reduction of acetate, the organic component of the zinc additive that is used. The levels suggested for UK EPR are within

current plant operating experience and therefore should not pose additional concerns regarding fuel crud.

473 Furthermore, there are some reports that fuel crud formed with zinc falls off the fuel more easily, once in the pond.

4.2.6.1.2 Effects of Acetate

474 In order to dose a reactor accurately to levels of μg kg^{-1}, a solution of zinc is normally added in the form of zinc acetate. The acetate is an additional source of carbon to the reactor. The addition of natural carbon (^{12}C) could effect the distribution of radioactive ^{14}C, as described below. The small VCT in the UK EPR CVCS may also impact on what happens to the acetate or its degradation products.

475 At non-zinc plants, around 90% of the ^{14}C is gaseous, with only 0.5% remaining in liquid waste. EDF and AREVA does not expect this proportion to change with the addition of zinc and acetate, quoting experience at Halden, when formate was added to the coolant and was fully decomposed by radiation in the core (Ref. 155).

476 ^{14}C production in UK EPR would amount to 2.7 g per year. ^{14}C is produced in a reactor mostly from ^{17}O oxygen as part of the water coolant. Not much ^{14}C comes from ^{12}C due to its low neutron cross section, however ^{14}C will exchange freely with all forms of carbon in the reactor, whether they arise from natural impurities or the deliberate addition of zinc acetate. EDF and AREVA calculate the total amount of natural ^{12}C entering UK EPR excluding acetate would be no more than 19 g per year (TQ-EPR-1169 (Ref. 8)). This figure seems very low, but even if actual CO_2 ingress was 100 times greater, it would still be smaller than the contribution from acetate which would be roughly 3,500 g per year (TQ-EPR-688 (Ref. 8)). Therefore carbon from acetate is certainly higher than other sources of natural carbon and several orders of magnitude greater than the mass of ^{14}C produced. As the dominating source is the acetate, the fate of ^{14}C will therefore be determined by the fate of acetate, which is a new additive in the UK context. There is little that can be done about this, for example, using formate instead of acetate would decrease the ^{12}C input due to zinc addition to 1,750 g per year, which is not thought to be a significant advantage.

477 In response to TQ-EPR-773 (Ref. 8), EDF and AREVA presented theoretical calculations to show that at power most of the carbon would take the form of methane. In shutdown, EDF and AREVA believe that most of the carbon would take the form of carbon dioxide and carbonates. These calculations were based on the bulk conditions in the RCS, not in the CVCS. Assuming all the acetate were converted to bicarbonate and absorbed on the anion-exchange resin, the total anion capacity of many reactors that use zinc acetate would have been consumed. Since the resins functioned normally, EDF and AREVA conclude that little of the acetate results in bicarbonate. Whilst there is no evidence to suggest the figures are wrong, the design and operation of UK EPR will be sufficiently different (more like Konvoi reactors, adding zinc acetate, recycling coolant etc), that the distribution of ^{14}C between the gas, liquid and solid wastes could change.

478 Overall, there appears to be a shortage of conclusive evidence for the fate of the acetate dosed with the zinc. The design features of UK EPR make comparisons with operating plants even more difficult. There is a shortage of definitive evidence for the fate of ^{14}C, partly because it is difficult to measure ^{14}C and plants do not routinely do so, so it is measured infrequently. Despite these deficiencies there appears to be no fundamental nuclear safety concern over the use of acetate; the main outstanding question relates to the influence of this species on the ^{14}C fate in UK EPR. I have shared this information with both the Environment Agency and Radwaste inspectors during Step 4.

4.2.6.1.3 Generation of ^{65}Zn

479 Natural zinc contains 49% ^{64}Zn. In the core, ^{64}Zn is converted to ^{65}Zn which is radioactive. Because ^{65}Zn decays by internal capture and positron emission it can also be difficult to detect. ^{65}Zn has a shorter half-life than ^{60}Co so is less of a concern for long-term disposal. Adding zinc to some reactors has caused an increased short-term radiation and accumulation of radioactive materials on site, even exceeding the activity of ^{60}Co. Consequently, many operators use zinc that has been depleted in ^{64}Zn (< 1%) and EDF and AREVA also recommend the use of such depleted zinc in UK EPR in both the PCSR (Ref. 11) and Environmental Report (Ref. 183). I am content that the use of the depleted form of zinc is appropriate and ALARP for UK EPR.

4.2.6.1.4 Effects on Purification Systems and Wastes

480 Zinc is preferentially absorbed onto the ion-exchange resins in the mixed / cation bed of the CVCS, forcing lithium out and potentially reducing the capacity of the resins for radioactive species. Calculations show that Zn addition at 5 – 15 μg kg^{-1} does adversely affect CVCS resin performance but the overall effect is small in UK EPR, Ref. 154, where the ion exchange beds are large. However the impact of adding more zinc on resin capacity and efficiency would not be trivial and would need assessment if increased zinc concentrations were ever proposed.

481 Zinc addition may decrease radioactive surface contamination on reactor pipework but this may increase radiocobalt release elsewhere (i.e. move the problem rather than prevent it). Addition of zinc does increase the release of other metals from surfaces in some circumstances. These effects have been observed to varying degrees in PWRs and are not hypothetical. There could also be effects on other subsystems such as the main coolant pumps or IRWST. These possible detrimental effects are assessed in this section.

482 The response to RO-UKEPR-45.A1 (Ref. 153) concentrated on relative dose rates and said little about the potential increase in radwaste accumulation and discharges resulting from zinc addition. EDF and AREVA provided quantitative data for waste production of various types from the French Bugey plant in response to TQ-EPR-773 (Ref. 8). The data for liquid effluents, Liquid Waste Processing System (LWPS) concentrates and resins all showed little obvious effect of zinc, although most of the data provided referred to the whole Bugey site, which has two units operating without zinc and two with zinc. A more detailed comparison of resin activities from the Bugey units operating with and without zinc does suggest it potentially doubles the usage of the CVCS resins with zinc addition. However, this is within the annual variability for resin usage, and is overall a small increase at a couple of m^3 per year. EDF and AREVA do claim that zinc reduces radwaste in the longer term as an additional benefit. I do not consider a small short-term increase in radwaste to be problematic from a safety viewpoint, if it occurred, and the Radwaste systems described in Section 4.2.2.3 and 4.5.1 are ‘oversized’ in UK EPR to handle such contingencies.

483 Since iron concentrations increased in the German PWRs following Zn addition (from Alloy 800), and nickel concentrations increased in US reactors following Zn addition (from Inconel 600), some experts believe that adding zinc to a PWR with Inconel 690 SG tubing will release both iron and nickel, for at least the first few cycles. Due to this assumption a ‘fuel crud’ formation penalty was incorporated into the BOA code developed by EPRI. However, no increased iron or nickel release was observed at either Callaway or Vandellòs II immediately following zinc addition. Samples of crud scraped from fuel at

both these stations after adding zinc contained significant amounts of both zinc and ^{51}Cr, but levels of nickel and iron in the coolant at Vandellòs II did not increase, Ref. 148. The reasons for these differences in metal levels in the coolant are not entirely clear and may stem from differences in sampling arrangements or the presence of particulates. EDF and AREVA believe that high iron levels are symptomatic of alloy 800 SGs since Callaway and Vandellòs have Inconel 690 SGs. No safety issues related to additional iron, nickel or chromium release following initial zinc injection have been observed to date. Since even small amounts of these metals in the coolant can give rise to significant fuel crud and radioactivity, their presence should be monitored and targets set. This is related to Assessment Finding **AF-UKEPR-RC-14**.

484 Measurements of the effect of zinc on particulates are rather sparse. Some units have observed increased particulates with consequent increased filter usage in the first cycle following initial zinc addition, but filter usage has returned to normal in the second cycle, Ref. 153. EDF and AREVA cited data from Vandellòs, which indicated that most of the ^{60}Co was dissolved in the coolant, with only 10% as particulate, TQ-EPR-773 (Ref. 8).

485 Enhanced monitoring of particulates and soluble metals should be considered during HFT and the subsequent two cycles, to confirm passivation is having an effect and nothing untoward is taking place.

486 EDF and AREVA do not propose the addition of zinc during Hot Functional Testing of UK EPR. One of the potential benefits of adding zinc during HFT is to ensure any initial surges in soluble metal or particulate release are dealt with when the plant is inactive, see Section 4.2.12 on HFT.

4.2.6.1.5 Other Effects

487 My assessment of some potential further negative impacts of zinc addition follows:

- EDF and AREVA confirmed there would be no impact from zinc on fuel cladding oxidation (TQ-EPR-773 (Ref. 8)). Their evidence was based on data for many thousand fuel elements of various types with zinc at high concentrations, plus specific data for M5® cladding exposed to low to moderate zinc concentrations in France and Germany. All these data indicated no negative effect from zinc addition.
- Zinc may appear in recycled coolant in various boric acid tanks or the IRWST. EDF and AREVA have considered the potential for this type of contamination (in Ref. 154) and concluded that any contamination by zinc would be small and easily cleaned up
- Sudden bursts of particulate release “crud bursts” have been observed occasionally in plants that operate without zinc addition and in a small number of plants operating with zinc. In TQ-EPR-773, I asked EDF and AREVA whether a crud burst could flush zinc out of the reactor, resulting in a requirement to replace it to regain protection. In reply (Ref. 8) EDF and AREVA stated that there does not appear to be a correlation between zinc addition and the frequency of large sudden radiocobalt releases, which seem to relate more to non-routine conditions in the core. I find that the Licensee should consider the possibility that a crud burst might flush zinc out of UK EPR, and hence the need to replenish it. This is part of finding **AF-UKEPR-RC-19.**
- EDF and AREVA confirmed (in TQ-EPR-773, Ref. 8) that peaks in zinc concentration are sometimes observed when changes in reactor load or operations cause zinc to desorb from surfaces. For example, the zinc concentration at Bugey peaked at 600 μg kg^{-1} during the oxygenation phase at the end of the first cycle with zinc injection. EDF and AREVA compared this to typical return peaks of 300 μg kg^{-1} seen subsequently at

Bugey and which are commonplace at other reactors. Since they last a short period of time and can be controlled, I was content that zinc return was not a concern.

- The effect of zinc on components such as motor seals was considered by EDF and AREVA in Ref. 154. This report noted that zinc solubility increases as the temperature decreases, so erosive particulates should not form on motor bearings or seals which are at lower temperatures. EDF and AREVA also referred to observations in French plants, in which various flowrates and temperatures were monitored, with no detectable changes following zinc addition.
- As with any chemical addition, the zinc acetate reagent used may carry with it contaminants such as fluoride. I would expect a licensee to control such impurities as part of their normal business, but an impurity at mg kg^{-1} levels when dosed to achieve μg kg^{-1} levels is not likely to even be detectable.

4.2.6.2 Evidence for Zinc Benefits

488 The key parameters for my assessment of the benefits of zinc were:

- Rates of loss of nickel from Inconel 690, cobalt from Stellite™ and iron from stainless steels.
- Retention of soluble material by all the above surfaces.
- The amount of zinc needed to achieve these effects.

489 The case presented by EDF and AREVA for the effect of zinc in controlling radiation build-up in response to RO-UKEPR-45.A1 (Ref. 153) is largely based on published plant and laboratory data for AISI alloys at high zinc concentrations or from plants where there had been existing problems with radiation control. For instance, laboratory results quoted by EDF and AREVA from Ref. 155 were based on autoclave corrosion tests with Inconel 690, 600, 750, Stellite™ and other alloys which showed:

- Substantial reductions in the rate of corrosion measured by weighing, typically by a factor of around 3 for some metals.
- Surface examinations showed thinner oxide layers with zinc than without zinc, suggesting that zinc was helping to stabilise a passivated surface layer.

490 Similarly, the main PWR plant investigations quoted in Ref. 155 were from Farley 2 and Callaway:

- Spectroscopic examinations of SG tubes from Farley 2 showed zinc concentrating under the oxide layer closest to the metal surface.
- Inspections of Callaway fuel showed decreased crud thicknesses on fuel after SG replacement and zinc addition.
- There may be higher radiocobalt release from surfaces immediately following zinc addition and slower radiocobalt release with extended zinc use, in older plants adding zinc for the first time.

491 The response to RO-UKEPR-45.A1 (Ref. 153) also quoted plant data from outside the US, principally from the Angra, Biblis and Bugey plants. However there were some significant differences between the situations in these plants and that expected for UK EPR. Biblis and Bugey started injection later in life, after radiocobalt levels had built up. Several of the plants had Inconel 600 tubing and Angra used alloy 800 SGs.

492 Nevertheless, the above provided reasonable evidence that adding 20 to 50 μg kg^{-1} zinc is beneficial in PWRs that have trouble with radiation fields or problems with cracking in Inconel 600. This level is much higher than proposed for UK EPR. From Ref. 153 it was clear that evidence for the benefit from lower levels of zinc and Inconel 690 was based on laboratory data from:

- The PETER test loop which showed zinc at 5 μg kg^{-1} significantly reducing nickel release rates of Inconel 690.
- The Nuclear Power Engineering Corporation (NUPEC) test programme which showed a 50% decrease in activity pick up at 10 μg kg^{-1} zinc.

493 Since I expect radiation levels in UK EPR to be low anyway, I believe the above evidence has limited relevance if the reduction in radioactivity is small in absolute terms. Since the effect of zinc is cumulative, I raised TQ-EPR-773 (Ref. 8) to discover how zinc could work at a low concentration and to clarify several of the claims made in Ref. 153.

494 Responding to TQ-EPR-773, EDF and AREVA provided satisfactory details of the tests in the PETER loop and NUPEC. Whilst they could provide evidence for the effectiveness of zinc at 10 μg kg^{-1} with Inconel 690 and 750 and 304 and 316 stainless steels, only data for Inconel 690 exists for zinc at 5 μg kg^{-1}.

495 In the same TQ response, EDF and AREVA provided further information comparing the growth of oxide layer thickness and density with the mass of metal lost from the surfaces of several reactor alloys with and without zinc, data which were missing from their original response to RO-UKEPR-45.A1 (Ref. 153). EDF and AREVA also confirmed that the large reduction in corrosion expected from zinc with Inconel 690 from laboratory tests, should not be expected in a reactor under operating conditions. Generally, EDF and AREVA had no control over the state of passivation of metal surfaces of the laboratory samples cited in evidence, before adding zinc. Therefore it is possible, indeed likely, that most data for zinc benefit relate to surfaces for which an improvement was easily achievable.

496 EDF and AREVA clarified their evidence for the benefit of zinc under plant conditions in the Bugey and Angra plants as follows:

- At Bugey, there had been a 14% reduction in radioactivity in the crossover leg and hot leg after two cycles of zinc injection, the decrease in SG radioactivity was minimal over the same period. Whilst 14% may seem small, it mostly corresponds to natural decay of the cobalt already present with a greatly reduced deposition of additional radiocobalt over the period, behaviour also observed at Diablo Canyon.
- Angra was designed before the significance of Stellite^{TM} on doses was recognised (Ref. 157) and as was common at the time its designers made extensive use of Stellite^{TM}. With zinc addition, Angra-2 has achieved levels of dissolved ^{60}Co in primary coolant in the range 0.1 to 1 MBq t^{-1}, which is comparable with the coolant activity levels of the better Konvoi plants with much lower Stellite^{TM} inventories and with Sizewell B, Ref. 156. Figures for surface activities on the hot and cold legs of Angra 2 also showed similar favourable behaviour.

497 I requested evidence for the passivating effect of zinc in TQ-EPR-773 (Ref. 8). For stainless steel the lab results showed that at high Zn levels, the diffusion of metals through the inner and outer layer decrease to about 50% of their initial value without zinc addition. The only kinetic tests for low zinc concentrations (10 μg kg^{-1}) have been performed under the conditions of a Boiling Water Reactor. These results reveal that the diffusion coefficients of Fe, Cr and Co in the inner oxide layer of steel are between 10 and 50% lower than those obtained without zinc. However, much of this data for Inconel was

based on laboratory testing of Inconel 600. EDF and AREVA also outlined Finnish theories of the action of zinc in passifying surfaces. I find that the Licensee should generate or find data for the effect of low levels of zinc on corrosion release from Inconel and stainless steel, this is part of finding **AF-UKEPR-RC-13**.

498 Overall, the responses to TQ-EPR-773 (Ref. 8) presented complementary published data on the growth of corrosion oxide layers in the presence of zinc and satisfactorily clarified calculation methods, accuracies and assumptions made in the response to RO-UKEPR-45.A1 (Ref. 153).

499 Zinc addition has been claimed by different PWR operators to control stress-corrosion cracking and crud build-up on fuel. EDF and AREVA do not claim zinc is necessary for these purposes in UK EPR.

500 I raised TQ-EPR-1356 requesting recent evidence for nickel and iron corrosion rates, since these are key indicators for the estimate of crud and radiocobalt. EDF and AREVA replied saying that iron and nickel are not routinely monitored on the French fleet, but the 4 analyses that were quoted indicated a lower shutdown nickel release in two 1450 MWe plants (of 0.1 kg and 1.6 kg) than from the 900 and 1300 MWe plants quoted (at 3.1 and 3.0 kg respectively). Their response included various iron concentrations, from which an iron release may be inferred if certain assumptions are made.

501 The response (Ref. 154) to RO-UKEPR-45.A2 (Ref. 9) summarises the status of the evidence for zinc benefits. EDF and AREVA confirmed that there are no data from existing plants with exactly comparable configurations to UK EPR but there are enough data from a variety of plants to expect a modest reduction in radiocobalt accumulation compared to non-zinc levels. Data from SG replacement programmes and from Angra indicate a clear benefit from adding zinc at the earliest stage, including commissioning if possible. The report (Ref. 154) also recommends an assessment of the dose rate reduction for UK EPR should be carried out, taking into account the different enhancements implemented. I consider that such an assessment will be required to support the plant specific safety case in order to limit plant contamination. This is part of assessment finding **AF-UKEPR-RC-13**.

502 Tomari-3 in Japan is the first reactor to commission with zinc from new, in order to control out-of-core radiation fields. In design it is very similar to Tomari-2 and sufficiently similar to UK EPR to allow direct comparison, Ref. 141. I spoke to the commissioning staff at Tomari-3 last October, who said that zinc is having a beneficial effect. Data from Tomari commissioning already suggests some benefits but the picture is far from complete until reports from the core offload in January 2011 are available, later in 2011.

503 Overall, I am content that evidence for the benefit of depleted zinc addition exists and that it should help to control doses near the RCS in UK EPR. Zinc is now being added to many dozens of PWRs world-wide and no safety issues have arisen from its use. I am content that a level of 5 to 15 μg kg^{-1} depleted zinc will not adversely affect UK EPR safety, provided specifications for pH and other solutes including silica and nickel are observed. However, I find that the extent by which doses are reduced by 10 μg kg^{-1} zinc, in comparison with other dose control measures, and the amount of zinc needed is still unclear. The Licensee will need to monitor the application of zinc compared to the benefits claimed by EDF and AREVA for the specified zinc injection profile. This should be used to analyses the performance of the zinc injection programme on a cycle by cycle basis to allow feedback into the plant specific chemistry programme. This is also part of assessment finding **AF-UKEPR-RC-13**.

4.2.6.3 Controlling Zinc Addition

504 The zinc addition system in UK EPR is described in Section 4.2.2.3.

505 After adding zinc for the first time, it would take some time for zinc to coat surfaces evenly and for concentrations in the coolant to become steady. Zinc is so easily absorbed onto metal surfaces and the CVCS resins, that sampling and measuring its presence at μg kg^{-1} levels is difficult. Section 4.2.9 of this report covers the difficulty measuring zinc addition.

506 EDF and AREVA recommends 5 to 15 μg kg^{-1} zinc for UK EPR and has variously advised that the key parameters for planning zinc addition are:

- The zinc concentration multiplied by the number of months of zinc addition, in ppb-months. This parameter is convenient to compare different plants and to assess the efficiency of Zn dosing.
- The total number of kilograms added (about 10 kg for effective passivation of a typical PWR). This is an important parameter, especially for procurement.

507 These specifications are different because the number of kilos needed does not correspond directly to ppb-months due to factors such as the CVCS clean-up rate and the surface area to be treated. Neither parameter is suitable for monitoring zinc addition on a daily or weekly basis.

508 The zinc concentration may seem a more useful parameter, but it would theoretically be possible to keep adding zinc in large quantities, if a significant sink existed, in order to maintain a particular set concentration. The only limitation would be the manual effort of recharging the zinc feed system, which is small. I believe the mass of zinc added and the concentrations of corrosion products could be better comparisons of zinc effectiveness, especially between plants of different design. The ppb-month is plant-specific.

509 Due to changes in the coolant during start-up and shutdown, it is normal practice not to add zinc until after the cycle has started and to stop a day or so before shutdown, Ref. 148.

4.2.6.4 Summary

510 Based upon the evidence presented during GDA, the main conclusions I draw for the zinc assessment are:

- Zinc is now being added to many dozens of PWRs world-wide and no safety issues have arisen from its use. I am content that a level of 10 ± 5 μg kg^{-1} depleted zinc will not adversely affect UK EPR safety provided specifications for pH and other solutes including silica and nickel are observed. I have identified a number of findings for the licensee to ensure that zinc addition and its effects are adequately controlled.
- The addition of zinc has been shown to be beneficial for the reduction of out-of-core radiation fields in many existing PWR and should also be beneficial to UK EPR. Evidence for the precise scale of benefits expected in UK EPR specifically is weak, but clearly any reduction should be beneficial even if lower than expected. The Licensee will need to verify the benefit of low levels of zinc on corrosion release rates from Inconel and stainless steels, and this is part of Finding **AF-UKEPR-RC-13**.
- I am content that negative side-effects of zinc addition can be controlled by the use of depleted zinc. The effect of acetate on the fate of ^{14}C may depend on other chemistry in the reactor and is not a fundamental safety concern with operation of the reactor.
- There are implications for Hot Functional Testing, discussed in Section 4.2.12

511 When taken as a collective answer, the TQ and RO responses under this area add significantly to the UK EPR safety case for zinc addition. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA, but note several areas where further work will be required by a future UK EPR Licensee.

4.2.6.5 Assessment Findings

512 Based upon the assessment of zinc addition in UK EPR described in Section 4.2.6 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as appropriate, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-UKEPR-RC-14*** *– The licensee shall justify limits for silica, iron and nickel in the primary circuit of UK EPR which restrict zinc dosing and include evidence for their adequacy. This Assessment Finding should be completed before zinc is applied to the reactor with nuclear fuel present. Target Milestone – Initial criticality.*

4.2.6.6 GDA Issues

513 Based upon the assessment of zinc addition in UK EPR described in Section 4.2.6 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.7 Assessment – Hydrogen Dosing

514 Most PWRs in operation today dose their primary coolant with hydrogen gas to control corrosion and radiolysis. In normal operation of any PWR, hydrogen is dosed into the primary coolant in small quantities to a) suppress oxidising species production in the core and b) help prevent cracking of Inconel alloys. My assessment of hydrogen addition in UK EPR was supported by TSC contracts, whose reports are in Refs 137, 138, 149 and 150, including a specific review of the UK EPR hydrogen controls and dosing systems.

515 The concentration of hydrogen in the circuit is set by the rates of addition plus any generated by corrosion, minus the rates of hydrogen loss by degassing, diffusion and radiolysis. The minimum RCS hydrogen concentration specified by EDF and for UK EPR is 17 $cm^3\ kg^{-1}$ during normal operation. At the start of Step 4, the upper target figure for hydrogen was 35 $cm^3\ kg^{-1}$ (Ref. 172) but in March 2011, this was reduced to 30 $cm^3\ kg^{-1}$ in Ref. 105.

516 The capability of the UK EPR systems to support the target levels of hydrogen is presented in Section 4.2.2.2.3. I concluded that the design of UK EPR would be capable of maintaining this range of compositions. Section 4.2.2.3.3 of this report assesses systems for physical degasification in UK EPR. The addition of peroxide for chemical degasification is assessed in Section 4.2.11 of this report.

517 The effects of the loss of hydrogen or an incorrect hydrogen level occur over different timescales:

- Hours – a total loss of hydrogen feed will cause the release of a large amount of corroded material (including cobalt) into the coolant circuit. This has been known to result in a core flux anomaly within hours, presumably as a result of solids precipitation. This would necessitate in either restoration of hydrogen or an orderly shutdown by the operators.

- Days – operation with insufficient hydrogen risks formation of an explosive mixture of hydrogen and oxygen in the pressuriser due to radiolysis.
- Years – the timescale over which Inconel 690 may develop cracks is believed to be years or decades, since no cracks of chemical origin have ever been seen in service.

518 This assessment area concerns the justification for the target range, drawing together the effects on radiolysis and integrity.

4.2.7.1 Effects of Radiolysis

519 One of the primary safety functions of hydrogen addition is the suppression of radiolysis, the radiolytic breakdown of water into oxygen and hydrogen that takes place in the core. The addition of extra hydrogen has the effect of promoting the back-reactions that suppress oxygen production. Since oxygen is bad for high-temperature corrosion and the potential creation of flammable mixtures, these are good enough reasons to add hydrogen to the coolant of any PWR. Theoretically a very low concentration of hydrogen is capable of preventing radiolysis ~ 1 $cm^3\ kg^{-1}$, but this would be an inconveniently low level for control and may not account for any boiling in the core. There is also evidence that crud behaviour can be modified once hydrogen gets much below 10 $cm^3\ kg^{-1}$, so for this and other reasons, I consider the absolute minimum practical hydrogen concentration to be 10 $cm^3\ kg^{-1}$ (Refs 137 and 138).

520 In response to RO-UKEPR-44.A1 (Ref. 13) EDF and AREVA present their arguments and evidence for the minimum UK EPR hydrogen concentration of 17 $cm^3\ kg^{-1}$. This value exceeds the minimum required to suppress radiolysis (1 $cm^3\ kg^{-1}$) plus an additional allowance to account for any sub-cooled boiling in the core (to 10 $cm^3\ kg^{-1}$). EDF and AREVA expect that even with 10% void fraction (higher than UK EPR) in the boiling region at least 80% of the dissolved hydrogen remains in the coolant phase. I am content that the minimum level specified for UK EPR is adequate for radiolysis suppression; however the control bands needed for corrosion may well be higher and will need careful consideration by the future Licensee.

4.2.7.2 Effects on Corrosion

521 The primary function of hydrogen in corrosion control, is to help prevent stress corrosion cracking (SCC) of stainless steels. There is a well-known synergy between SCC and dissolved oxygen and chloride levels for sensitised and unsensitised stainless steels, Ref. 30. The addition of hydrogen suppresses oxygen formation and hence cracking.

522 Hydrogen is also beneficial in controlling SCC in nickel alloys, although less significantly than for the stainless steels. It is often quoted, that high levels of hydrogen (> 50 $cm^3\ kg^{-1}$) suppress crack growth rate and lower levels suppress crack initiation. This applies to Inconel 600 and not to Inconel 690. Since Inconel 690 has never been known to crack in nuclear service, there are no reliable data on which to base levels or limits for control of cracking of Inconel 690. There are small quantities of other Inconels in UK EPR, such as X750, for which hydrogen addition would still be beneficial, Ref. 142. At present there is no agreement on the optimum level of hydrogen concentration in PWRs with Inconel 690 steam generators for control of crack growth; although it is known that some hydrogen is beneficial. As a result, EDF and AREVA do not claim hydrogen addition for material integrity (cracking) control in UK EPR and hence the lower normal maximum level of 30 $cm^3\ kg^{-1}$. Recognising the number of reactors (in USA, Europe and Japan) that follow guidelines which allow higher hydrogen levels (up to [redacted] $cm^3\ kg^{-1}$), the action levels for UK EPR will probably remain at the current EPRI limits (Ref. 27).

523 In their response to RO-UKEPR-44.A1 (Refs 172 and 51), EDF and AREVA claim that the material choices for UK EPR (i.e. Inconel 690) means that operation in the specified UK EPR range of 17 to 30 $cm^3 kg^{-1}$ is acceptable from a material integrity point of view.

524 There remains controversy amongst experts as to the exact mechanisms whereby hydrogen controls crack initiation and crack growth in Inconels. Recent work suggests the actual hydrogen concentration used previously has not been optimal in terms of nickel solubility. This has the effect of potentially affecting the degradation rate of nickel based alloys in UK EPR. Therefore many experts now recommend that operating units change either to higher or to lower concentrations of hydrogen, than those used historically. Since reducing the hydrogen concentration to reduce crack growth rates in cooler parts of the reactor is not really feasible, as this may be below the level needed to suppress radiolysis, the US position is that the dissolved hydrogen should be increased to reduce crack growth rates. This is the basis of the EPRI recommendation to operate towards the top of the existing hydrogen band (at [redacted] $cm^3 kg^{-1}$) and for the original US plants to eventually further raise hydrogen concentrations, possibly to 70 to 80 $cm^3 kg^{-1}$ H_2. As discussed in Section 4.2.2.2.3, such high levels are not possible in UK EPR.

525 Recent work implicating hydrogen as a cause of cracking in highly-stressed materials at low temperatures, Low Temperature Crack Propagation (LTCP), is discussed in the Sections on Integrity (4.2.4), Start-up and Shutdown Chemistry (4.2.11.3). In summary, I do not expect LTCP to arise from normal operations, but should be considered as part of shutdown planning. While the upper band of the UK EPR range appears consistent with current plant experience in Inconel 690 plants, experience at the lower end of the UK EPR band is sparse. The main driver for UK EPR in this regard is minimisation of radioactivity, discussed below. There appears little evidence to support moving the lower band from a materials integrity perspective. I consider this to be an Assessment Finding **AF-UKEPR-RC-15**.

526 M5® fuel cladding suffers 60% less corrosion under primary circuit conditions in the presence of hydrogen. However, without hydrogen in the coolant, the corrosion of M5® would be worse than the Zircaloy-4 it supersedes. For cladding, the presence of hydrogen is thus beneficial up to the concentration at which hydriding occurs. At very high hydrogen concentrations, hydrogen is absorbed by zirconium to form a brittle hydride. Higher values (50 – 80 $cm^3 kg^{-1}$) may create more crud and might cause hydriding of the fuel. Since this would damage the fuel, this is the main reason for the upper limit on hydrogen in the coolant. I have not seen evidence for the performance of M5® above 50 $cm^3 kg^{-1}$ hydrogen, although I note that EDF and AREVA currently do not intend to run EPR with this level of hydrogen. EPRI is conducting a series of tests on the possibility of "*cliff edge*" effects from high H_2, Ref. 138. As hydriding occurs mainly by the corrosion reaction this is not anticipated to be a problem in M5® fuel in normal operations. On the basis of current knowledge therefore, the maximum hydrogen level for fuel protection should be less than 50 $cm^3 kg^{-1}$.

4.2.7.3 Effects on Radiation

527 EDF and AREVA believes that a hydrogen level between 17 - 30 $cm^3 kg^{-1}$ is needed to limit general corrosion and nickel release from Inconel 690 for the control of ORE, TQ-EPR-902 (Ref. 8). Higher hydrogen concentrations tend to increase the solubility of nickel ferrite, $NiFe_2O_4 + 6H^+ + H_2 \rightarrow Ni^{2+} + 2Fe^{2+} + 4H_2O$, but decrease the solubility of nickel metal, $Ni + 2H^+ \rightarrow Ni^{2+} + H_2$.

528 It is still not clear which will be the dominating factor for UK EPR but the very limited data in the literature would suggest that lower hydrogen concentrations (25 to 40 $cm^3 kg^{-1}$)

result in decreased ^{58}Co, which would be beneficial. It is this effect that EDF and AREVA claim as the main reason for specifying a low hydrogen level for UK EPR (in response to RO-UKEPR-44.A1 (Refs 172 and 51) and RO-UKEPR-46.A2 (Ref. 161). EDF and AREVA believe it is desirable to limit dissolved hydrogen in the core to below 20 $cm^3\ kg^{-1}$ to minimise transport and deposition of corrosion products, such as nickel. EDF and AREVA cite the apparent rise in soluble ^{58}Co activity with increasing H_2 at the Beznau reactor as evidence that increasing H_2 leads to increased soluble activity. However, the scatter in the data is large and they gave no statistical analysis of the data, which could be well within 'normal' variations. They also cite a reduction from 29 to 26 $cm^3\ kg^{-1}$ at Tsuruga, but the ability to discern a real effect from such a small change is extremely difficult. Whilst some of the published literature suggests that minor adjustments of hydrogen (as little as 5 $cm^3\ kg^{-1}$) have an effect; I do not believe this to be the case when operating at the upper end of the operating band suggested for UK EPR, however the same may not be true at the lower end. The operator of any PWR needs to decide what the band of acceptable operation will be, where that band may vary by up to 15 $cm^3\ kg^{-1}$. Plant and theoretical data do not justify closer control than this.

529 The mechanisms by which hydrogen acts to control the deposition of crud in the core are complex and my TSC questioned some of the arguments put forward by EDF and AREVA regarding the amount of nickel metal dissolved in the coolant in Ref. 161. Theoretically, decreasing the hydrogen concentration should increase the amount of nickel dissolved in the coolant (Ref. 138) and may help to reduce in core deposition of crud as a result, however the evidence for the effect of dissolved hydrogen on nickel deposition within the core is weak below 26 $cm^3\ kg^{-1}$ of dissolved H_2.

530 On the balance of these effects, EDF and AREVA would prefer to operate UK EPR at less than 20 $cm^3\ kg^{-1,}$ but above the minimum required for radiolysis, 10 $cm^3\ kg^{-1}$. However as there is no plant experience at such low value EDF cite the minimum levels recommended by the VGB guidelines (Ref. 29) of [redacted] $cm^3\ kg^{-1}$ and MHI [redacted] $cm^3\ kg^{-1}$, see Section 4.2.4.2. It is notable that these are minimum values, not typical, and the VGB guidelines refer to plants with Alloy 800 not Inconel 690 as in UK EPR. This is part of Assessment Finding **AF-UKEPR-RC-15**.

4.2.7.4 Other Effects

531 Hydrogen should not be deliberately added in such large quantities that it causes other hazards elsewhere in the reactor. In addition to getting hydrogen into the reactor, it is also necessary to get it out and avoid flammable gas mixtures developing at power or during a shutdown, or if too much hydrogen is created by radiolysis. I raised TQ-EPR-086, 491 and 615 (Ref. 8) covering the hazards from excess hydrogen.

532 Whilst there are a number of large vessels and ullage spaces in UK EPR, EDF and AREVA have taken care to specify nitrogen purging systems and hydrogen control technology to minimise flammability risks. These include the following precautions:

- All pipework has a nominal gradient of 2% or greater with a vent at the top.
- The gaseous waste-processing system flushes all vessels in which coolant degasification could occur with nitrogen, to limit the hydrogen concentration to below 4% by volume, see Section 4.5.1.
- There are no gaseous buffer tanks connected directly to the reactor.

- Most of the gaseous waste-processing system works at a slightly reduced pressure to prevent hydrogen leakage into rooms and the allowable leakage is one millionth of an atmosphere-litre per second.
- The inventory of the hydrogenation station in UK EPR is lower than the VCT inventory of earlier designs of PWR and procedures are specified to flood it when not in use.
- The room containing the hydrogenator is equipped with hydrogen gas detectors linked to an automatic supply shut-off.
- The pressuriser has its own gas vent in addition to the on-line degasifier in the CVCS.
- Ventilation of the pressuriser room has a backup ventilation system.
- The VCT is continuously purged with sufficient nitrogen to keep hydrogen below 4% even with maximum ullage.

4.2.7.5 Summary

533 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit hydrogen addition are:

- Hydrogen is an important additive to the coolant of any PWR, maintaining the correct chemistry for controlling corrosion and the build-up of flammable mixtures by radiolysis.
- EDF and AREVA have proposed a low minimum hydrogen concentration of 17 cm^3 kg^{-1}. The low operating band for hydrogen in UK EPR was based mainly upon radioactivity transport concerns. The lower end of this band is outside much of the operating experience of reactors which have Inconel 690 tubing.
- While EDF and AREVA have considered the main impact of hydrogen concentration, at the present time I do not consider there is sufficient evidence to justify a change from the current levels of hydrogen outside known bands. Most reactors with Inconel 690 steam generators operate at lower hydrogen concentrations in the normal range of about 30 - 40 cm^3 kg^{-1}. The debate over optimum hydrogen levels for control of cracking arises from experience with Inconel 600 in older PWRs and should not apply in the UK EPR. At the present time, I do not consider there is sufficient evidence to justify a change from the current levels of hydrogen and I would not support changes from the current operating bands. I have raised this as an Assessment Finding.
- EDF and AREVA have not claimed that hydrogen is necessary to control cracking in Inconel 690, but I do not believe that they have proven that hydrogen (or lack of) does not affect it.

534 When taken as a collective answer, the TQ responses under this area add significantly to the UK EPR safety case for hydrogen. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.7.6 Assessment Findings

535 Based upon the assessment of hydrogen chemistry in UK EPR described in Section 4.2.7 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as

appropriate, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-UKEPR-RC-15*** *– The Licensee shall generate evidence for the optimum band for hydrogen concentration in a reactor with Inconel 690 steam generators. Such reactors normally operate within a narrower band of about 30 to 40* $cm^3\ kg^{-1}$ *and there appears to be little data to justify concentrations below around 25* $cm^3\ kg^{-1}$*. The analysis should include a fuller analysis of the effects of hydrogen levels on Inconel 690 and stainless steels in UK EPR specifically. This Assessment Finding should be completed before hydrogen is first applied to the reactor. Target Milestone – Hot Ops.*

4.2.7.7 GDA Issues

536 Based upon the assessment of hydrogen chemistry in UK EPR described in Section 4.2.7 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.8 Assessment – Control of Safety System Chemistry

537 A number of connected systems are important to the safe operation of the primary circuit. During normal operations and postulated accident scenarios provisions must be made within the reactor design to remove heat and maintain the core inventory and boron concentration. Chemical specifications for all circuits that interface with the primary coolant must be fully compatible with the primary coolant, both in terms of the water chemistry specification and particularly boron and impurity limits.

538 The UK EPR features a number of such systems. The main systems for which boronated coolant must be supplied are (from Ref. 172):

- Boric acid tanks (RBWMS)
- Safety boration system tanks (EBS)
- Primary circuit (RCS) and auxiliary circuits (CVCS and RHRS)
- Safety Injection System (SIS) accumulator
- Fuel pool
- In-Containment Refuelling Water Storage Tank (IRWST)

539 Before starting up the reactor, the RBWMS and EBS tanks would be charged with boron at 7,000 mg kg^{-1} at the expected enrichment for UK EPR. The other vessels listed above would be charged with boron (EBA) of the same enrichment with the concentration specified for cold shutdown and refuelling "C_{RF}". Chemical analysis for enrichment requires special equipment that the Licensee will need to provide for UK EPR. Supplies of boric acid sometimes have high fluoride contents but EDF and AREVA do not normally relax the fluoride specification for these vessels, Ref. 148. The following figure (adapted from Figure 1 in Ref. 172) shows the distribution of boron at start-up:

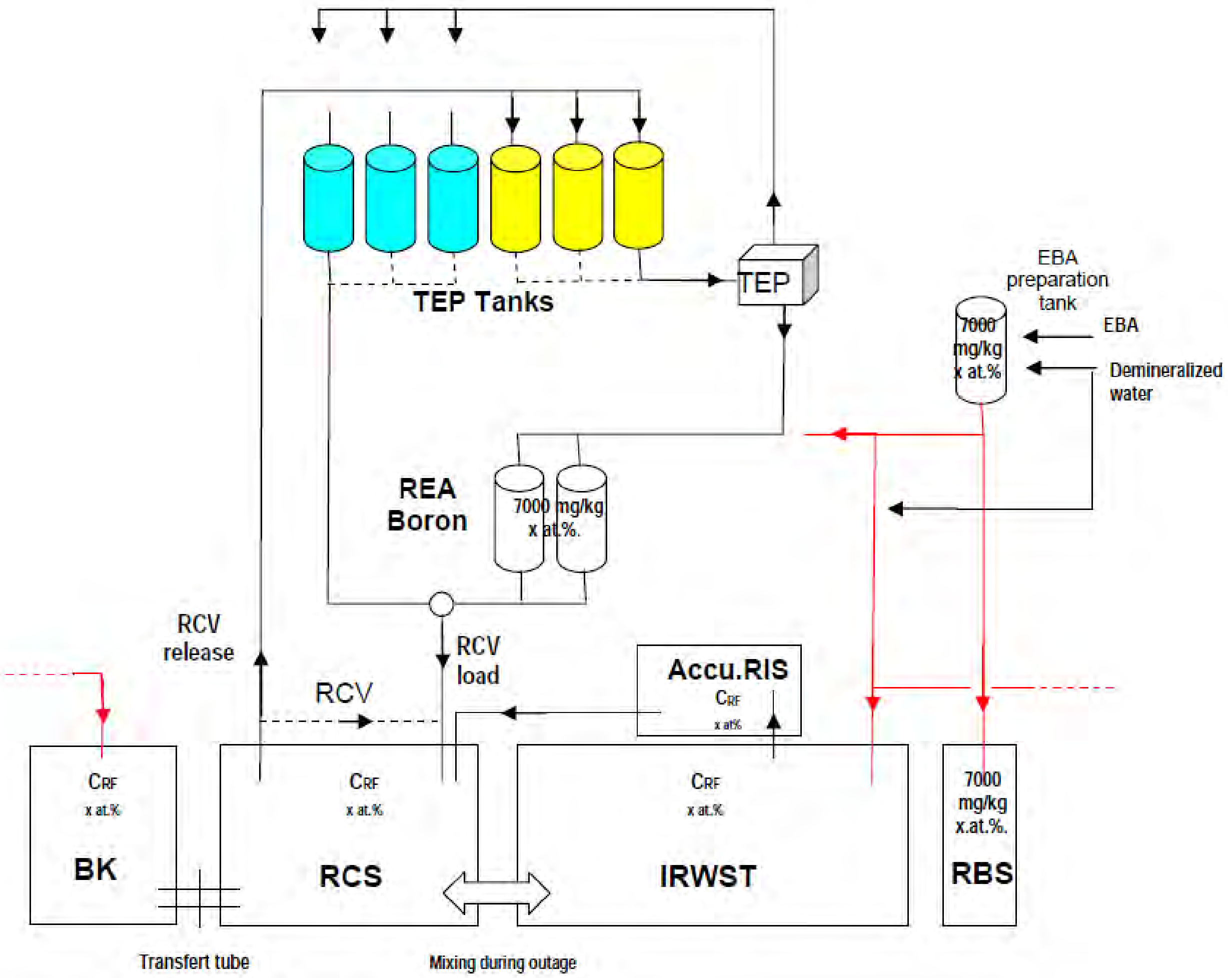


Figure 15: Boron Distribution at Start-up in UK EPR

540 As described in Section 4.2.2, the concentration of boron and enrichment changes in many of the various tanks and vessel during the cycle as coolant volumes are used, recycled and replenished. Notable exceptions to this are the SIS accumulators and EBS tanks which are held at a constant concentration and volume throughout all of the cycle. The control of boron throughout the plant is part of Assessment Finding **AF-UKEPR-RC-04**.

4.2.8.1 SIS/RHRS system

541 The Safety Injection System / Residual Heat Removal System (SIS / RHRS) is described in the PCSR (Ref. 11, Section 6.3). The UK EPR SIS / RHRS is a combined system providing safety injection and removal of residual heat from the reactor. The SIS / RHRS consists of four separate, independent trains, each of these trains being able to inject borated water into the primary circuit by means of an accumulator and pumps via an outlet heat exchanger. The system also provides controlled heat extraction from the primary circuit in shutdown mode through one of the pumps and the heat exchanger. Various alternative configurations of this system are possible to handle a variety of contingencies. The pumps are cooled by the reactor's Component Cooling Water System (CCWS).

542 The accumulators are large volume pressurised tanks containing borated water. These inject into the cold legs of the primary loops.

543 The RHRS pipework should normally be flushed after use to remove any lithium and filled with fresh boronated water, so that they cannot cause a reactivity insertion when switched back on or change the RCS pH during shutdown use.

4.2.8.2 IRWST and Safety Injection System

544 The In-containment Refuelling Water Storage Tank (IRWST) is described in the PCSR (Ref. 11, Section 6.3). The IRWST contains a large quantity of borated water for use during refuelling. It also serves to collect water from the reactor containment in the event of an accident. The IRWST pool acts as a water reserve for the SIS, the Containment Heat Removal System (CHRS) and the CVCS. It also ensures that the area of the containment floor provided for corium spreading is cooled in the event of a severe accident. Filters and anti-clogging devices protect the IRWST and CHRS pumps from transport of debris during postulated accident conditions.

545 In TQ-EPR-162, I asked EDF and AREVA what provision had been made to ensure that boric acid vapours from the IRWST did not cause corrosion in the reactor building. They replied that this had been considered in the design of UK EPR, as follows:

- The potential for condensation was limited by the two-room ventilation concept to certain areas at power. These would be painted with a corrosion-resistant coating and gathered by a system of drains to a stainless lined sump. In shutdown, all areas would be ventilated (by the EVF) so that condensation would not occur.
- There will be three types of protective paint used, one for cool surfaces, one permanent coating for smaller hot components and one temporary coating for large vessels. Condensation on large hot vessels (like the RPV) is not expected by EDF and AREVA.

546 The IRWST can be filled from either the RBWMS system or by blending from the boric acid mixing tank and demineralised water supply.

547 Whilst depletion of the boron enrichment does not occur in the IRWST during power operation, depletion can occur during shutdown when the RCS is re-filled. In this case, EDF and AREVA have made provision to adjust the isotopic ratio at the end of the cycle, prior to RCS filling operations, to avoid boron depletion in the IRWST. EDF and AREVA say this can be achieved either from the RBWMS or directly from the boric acid mixing tank.

548 The IRWST can be affected by natural evaporation, decreasing the level and increasing the boron concentration. In that case, the level can be topped up with demineralised water, after which the boron concentration would be checked, Ref. 172.

549 If the water in the IRWST becomes contaminated, it may be necessary to completely drain the pool. The IRWST can be drained to the extra liquid radwaste discharge system (ExLWDS) tanks either via the purification or bypassing the purification chain. The IRWST then can be refilled in the normal manner. Radioactivity in the IRWST is discussed in Section 4.2.8.

550 The safety injection accumulator SIS will be filled from the IRWST pool.

551 Generally, I find these systems satisfactory from a chemistry perspective. The procedures produced by the Licensee will need to take account for the location of the IRWST being within containment**.**

4.2.8.3 EBS

552 The Extra Borating System (EBS) is described in the PCSR (Ref. 11, Section 6.7). This system consists of two separate independent trains, each able to inject borated water into the primary circuit at high pressure. Each of the EBS trains consists of a borated water tank, a positive displacement pump and two lines of injection into cold legs, via the SIS injection lines. The EBS would be charged with EBA direct from the boron mixing tank, thus avoiding the possibility of introducing depleted boron.

4.2.8.4 Permanent Gases

553 Permanent gases should be excluded from places where they may act as siphon breaks or even create flammable mixtures. Air intrusion occurs normally during refuelling and maintenance activities and can result from interruptions to power midway through liquid transfers. Section 4.2.11 of this report covers activities taken to eliminate air during reactor restart. Radiolysis can also produce flammable mixtures of hydrogen and oxygen and the prevention of flammable gas mixtures is assessed in Section 4.2.2.2.4 of my report.

554 A siphon break could halt some cooling flows and gases could stall the RHRS pumps and for this reason a vent has been provided on the RHRS pump suction leg, TQ-UKEPR-136 (Ref. 8).

4.2.8.5 Summary

555 Based upon the evidence presented during GDA, the main conclusions I draw for the safety systems chemistry assessment are:

- The design of UKEPR incorporates a number of auxiliary and safety systems, all of which need monitoring and appropriate chemical analysis to ensure boron levels are maintained and corrosion is avoided**.**
- The decision to use a single enrichment of boron (EBA) in safety systems and throughout UK EPR is appropriate. The enrichment to be used for UK EPR will be dependent on the eventual core design and is not decided yet.
- The control of boron itself is a finding under the CVCS section of my assessment, because the CVCS performs many of the functions needed to control boron in the safety systems.
- In other parts of my assessment, I have referred to the need to monitor impurities for their corrosion potential (like fluoride or iron) and I this applies to the safety systems also.

556 When taken as a collective answer, the TQ responses under this area add significantly to the UK EPR safety case for safety systems chemistry. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.8.6 Assessment Findings

557 Based upon the assessment of safety systems chemistry in UK EPR described in Section 4.2.8 above, I have identified no Assessment Findings which need to be addressed, as normal regulatory business, either by the designer or by a future Licensee.

4.2.8.7 GDA Issues

558 Based upon the assessment of safety systems chemistry in UK EPR described in Section 4.2.8 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.9 Assessment – Sampling Systems

559 As described in the previous sections, the primary chemistry of UK EPR is important to a number of safety-related aspects of the design. As such, proper control and maintenance of the desired operating chemistry is important and the first step in achieving this is to representatively sample and analyse the coolant. It is clear therefore that any sampling system must be designed, and operated, in a manner consistent with the needs for the safe and reliable operation of the plant. The sampling system must also provide data of the necessary quality and quantity during all modes of reactor operation, including shutdown and accident conditions to enable proper recovery and operator actions. A poorly designed or implemented sampling system could result in at best, delays in or at worst, unrepresentative sampling of important chemical parameters.

560 Assessment of the UK EPR primary sampling capabilities began during Step 3 and continued during Step 4. The overall assessment objective was to demonstrate that the UK EPR has adequate sampling capabilities and capacity to support safe operation of the plant during all modes of operation. Many of the details regarding operation of the system will not be available, and will only become available as operating procedures are developed; hence the focus for GDA was mainly centred on ensuring that there were no fundamental design concerns with the systems. Overall, at the end of Step 3, I was content with the general approach demonstrated for UK EPR in the design of the NSS. Information regarding the intended operation of the system and hence its suitability to provide the chemistry functions was the main focus of the assessment during Step 4.

561 My assessment of sampling systems has been informed by a TSC contract, which specifically reviewed the UK EPR design (Ref. 37). In addition the LCC4 annual report provides information on primary sampling (Ref. 38).

4.2.9.1 NSS Overview

562 The UK EPR includes a comprehensive and systematic sampling system as part of the Nuclear Sampling System (NSS) as described in Section 9.3.1 of the PCSR (Ref. 11). This system is subdivided into those parts which sample the RCS and primary auxiliary systems (NSS) and the Steam Generator secondary side sampling system (RES). As part of the secondary circuit, the RES is assessed in Section 4.4.4. The NSS SDM contains more information on the system design (Refs 39 and 40).

563 The NSS consist of a number of sample locations in the primary and auxiliary circuits, namely the RCS, RHRS, CVCS, SIS (including sampling of the IRWST), CSTS, RBWMS and Fuel Pool Purification System (FPPS), which are routed to a common collection point. The system has the capability of sampling both liquids and gases for a number of reasons including; monitoring of core reactivity, fuel clad integrity, clean-up system performance and chemistry parameters. Systems are in place to condition the sample streams to the required temperatures and pressures for sampling or analysis. The system also provides a number of on-line measurements, including; boron, conductivity (for determination of lithium), hydrogen, oxygen, nitrogen and primary coolant activity. Other parameters are measured as required by manual methods. Provisions are also made to sample from a number of local 'grab' sample locations, including some that require

specific sampling provisions (such as local enclosures) due to activity. EDF and AREVA state that the NSS must be available for monitoring of the primary coolant during all of the plant operating conditions.

564 The entire NSS is fabricated from stainless steel of restricted cobalt content to limit ^{60}Co concentration disturbances in active samples.

565 As the NSS is used to sample during all plant states TQ-EPR-777 (Ref. 8) was raised to understand the expected frequency of sampling in UK EPR. EDF and AREVA claim that the system has been designed considering the representativeness of samples, sampling conditions, ORE, sampling frequency and analysis requirements. The response provides a comprehensive description of the expected (to be confirmed by Licensee in fully developed chemistry specifications) sampling types, frequencies and analysis in relation to the UK EPR NSS design. Significant comfort can be taken from the information presented as this underlines the detailed consideration that has been put into the system design from a chemistry perspective.

4.2.9.2 Reactor Coolant System Sampling

566 The RCS has three main sample lines, which operate continuously:

- RCS loop 1 - hot leg
- RCS loop 3 - cold leg (cross over pipe)
- Pressuriser - liquid phase

567 Lines extracting samples from the primary circuit operate continuously to ensure samples are representative. Sample flow rates are in the order of 300 litres hr^{-1} per line.

568 Each primary sampling line has a solenoid valve plus a check (non-return) valve for isolation. Sample lines from the primary side are cooled by heat exchangers (cooled by CCWS and also Chilled Water System (DER)), initially to temperatures of around 50 °C. The first stage cooler is located within the fuel building, thus minimising sample transit times at high temperatures and the potential for deposition in lines. The second stage of cooling takes place before the on-line meters or prior to grab sampling. Similarly, EDF and AREVA claim that the sample flow rate and routing has been considered to ensure particulate sedimentation in the sample lines is minimised, with Reynolds numbers of >> 2,300 calculated (i.e. turbulent conditions).

569 The RCS NSS samples are directed towards the nuclear sampling room located in the auxiliary building. This room contains the on-line monitors and includes the boron and conductivity meters which are used for automatic control of the primary side pH. The room also includes three separate glove boxes for grab sampling of primary effluents, depending upon their origin and activity level, with the RCS samples passed to the most active “*active primary liquid sample glove box*”. In essence the NSS works by optionally directing a portion of the extracted coolant sample to the on-line meters or to a glove box for grab sampling. The system is configured in such a way that any sample point can be directed to any on-line meter. The glove box is attached to the nuclear ventilation system via permanent iodine filters.

570 The excess sample not analysed or ‘clean’ waste after sampling is recycled by directing it to a separate buffer tank before recycling and re-injecting it as close as possible to the sampling point, thus minimising effluent production. The buffer tank is sized to accept five lines operating continuously at the nominal flow rate. The Primary grade fluids are injected back into the CVCS, upstream of the demineralisers, while contaminated

samples are sent to the chemical drain tanks of the Nuclear Auxiliary Building. The gas phase above the buffer tank is purged by the Gaseous Waste Processing System (GWPS), which is assessed in Section 4.7.1.1. The pumps used to pass the effluent back to the CVCS are canned to avoid leakage. In order to avoid CVCS flow transients the back feed of samples is operated continuously based upon the buffer tank level.

571 The glove box features a system for degassing the coolant in order to analyse separately either the dissolved gases, or the degassed liquid. Dissolved noble gases are the primary dose contributor in liquid RCS samples. Off gas not analysed is directed towards the buffer tank headspace.

572 The main RCS NSS is shown in the figure below, including some of the associated primary auxiliary sample lines (Ref. 39):

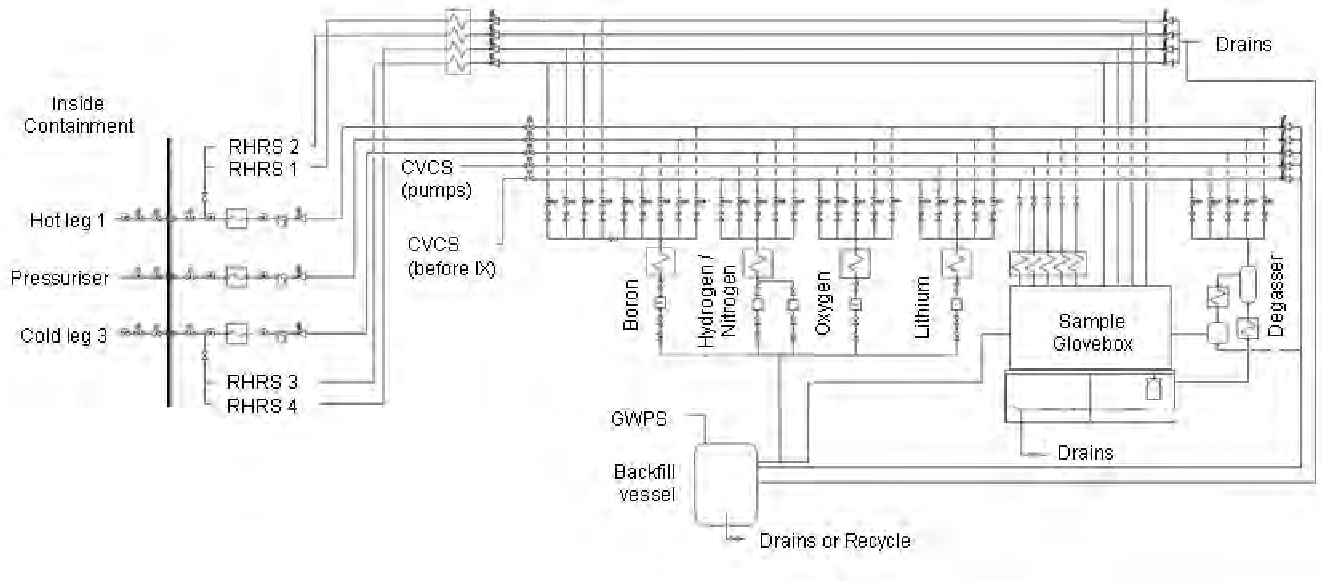


Figure 16:UK EPR Nuclear Sampling System

573 No details are provided on the boron measurement system in the NSS, except that a neutron absorption measurement system will be used (similar to the CVCS meters). The NSS boron meter is used for isotopic control, primary coolant Li-B coordination and during accidents to evaluate the RCS boron concentration (See also Section 4.2.2.2.1, which discusses the use of CVCS boron meters for dilution control). The hydrogen and oxygen meters are common technology which has been used extensively in PWRs. Similarly, the nitrogen meter is standard technology, but its use in UK EPR is novel and results from the use of nitrogen cover gas on a number of tanks and vessels, including the VCT. Dissolved nitrogen is a potential source of ^{14}C (as discussed in Section 4.3.2.4) and of ammonia (see Section 4.2.2 covering the CVCS).

574 The on-line lithium measurement in the NSS uses a conductivity measurement technique, which is novel to the UK. Results from this measurement are used to inform the primary circuit pH control regime and control the automatic injection rate of lithium hydroxide by the CVCS. TQ-EPR-776 (Ref. 8) was raised to request further information and experience of this technique. The response indicated that the use of such measurements to monitor lithium concentration is not uncommon to French PWR operations, especially during load following, and has been validated at the EDF Tricastin 2 plant (900 MW_e). Algorithms in the sensor calculate the lithium hydroxide concentration including the

effects of boric acid dissociations and impurities on the measurement. Back-up measurements can be taken using grab sampling. Based on the evidence presented, I am content that the system should be capable of lithium determination under primary coolant conditions provided stable temperature regulation can be achieved. Further consideration may need to be given to the effects of EBA on the analysis, but this should be straightforward.

575 TQ-EPR-1235 (Ref. 8) queried the potential risks associated with the automatic injection of lithium hydroxide proposed for UK EPR. Based upon the measured concentration of lithium in the NSS the CVCS injects further lithium hydroxide until the difference between measured and required values is reduced (< 0.04 mg kg^{-1}). Control room alarms are triggered when large differences are detected. The main risk is associated with overdosing and the impact of this on fuel cladding, especially at beginning of cycle when lithium is already at its highest concentration. EDF and AREVA calculate an increase in RCS lithium of 0.66 mg kg^{-1} should the CVCS injection continue unabated at maximum flow for 20 minutes, which would be sufficient to trigger the alarms; this indicates that the system could breach an operating limit within 1.5 hours at beginning of cycle. Normal chemistry control procedures for the CVCS can be used to reduce overdosing of lithium. I consider the risks posed by this arrangement to be minimal, and similar to manual dosing, and adequately controlled by the design.

576 The addition of zinc to the UK EPR primary coolant is discussed in Section 4.3.5. An important consideration with any additive made to the primary coolant is the capability to accurately control the addition. TQ-EPR-775 (Ref. 8) specifically requested evidence to support this for UK EPR, particularly considering the low concentrations dosed. The response provided a combination of operational experience and theoretical sampling practice. EDF and AREVA cite EPRI (Ref. 41), IAEA (Ref. 21), EDF and international OEF in the design of the UK EPR sampling systems. Zinc sampling in UK EPR will be undertaken from the CVCS sampling lines, due to variability in results from other sampling locations. Much of the response is related to corrosion product sampling which is not directly relevant to Zinc sampling, however based upon the balance of information presented in this and other TQ responses, I consider that an adequate case has been made to support the claim that accurate zinc management within the RCS of UK EPR is possible.

577 Some PWRs have a sample point which allows collection of the vapour phase in the pressuriser. This allows monitoring of hydrogen, other non-condensable gases and fission products which collect in the gas phase. UK EPR does not have such a sample point as part of the sampling facilities available to the operator. As described in Section 4.2.11, UK EPR will operate with monophasic start-up and has a normal and large flow purge for the pressuriser gas phase. These features should minimise requirements for sampling of the pressuriser gas phase, although a more specific justification for not having the capability to sample the pressuriser vapour space in UK EPR is required, especially given the operation of the CVCS VCT under nitrogen gas purge. I consider this to be an Assessment Finding **AF-UKEPR-RC-16**.

578 Overall, I note that a number of beneficial features have been incorporated into the design, such as effluent recycle provisions, sample isolations and ‘on-line’ measurements for a number of important primary circuit parameters. The UK EPR RCS sampling design makes extensive use of French and German ‘relevant good practice’.

4.2.9.3 Primary Auxiliary System Sampling

579 The NSS allows sampling from a number of locations in the primary auxiliary systems, including the following samples:

- CVCS – upstream of purification and downstream of charging pumps
- RHRS – downstream of each RHRS heat exchanger (4 samples)
- CSTS – sampling of coolant storage tanks (6 samples); downstream of demineraliser,
- SIS – accumulator liquid (4 samples)
- FPPS – reactor building and fuel building purification loops; upstream and downstream of filters

580 The CVCS lines run continuously to ensure representative sampling and operate on the same principles as the main RCS samples lines described above (i.e. they can be directed to the on-line meters and the grab sample glove box).

581 The RHRS samples are also integrated with the RCS samples, although they can only be directed to the boron meter and the grab sample glovebox. Unlike the other samples these are not run continuously in normal operations, but are used during shutdown when the RHRS system is in operation. Via this means the primary coolant is monitored to ensure the correct shutdown margin. Sampling can also be undertaken without the RHRS in operation in order to confirm the correct chemistry before connection; in this case a pump is used to draw the sample.

582 All other samples from the primary auxiliary systems are run on an intermittent basis, when required by operations.

583 Active liquid samples from other primary sampling lines (e.g. certain CVCS or CSTS points) and slightly active samples (from CSTS, CVCS, FPPS or the Fuel Pool Cooling System (FPCS), SIS accumulators or the RBWMS) are directed to two further sampling glove boxes within the nuclear sampling room. As with the RCS samples, these glove boxes include manual degassing devices that allow samples to be obtained in their raw or degassed state and they are attached to the nuclear ventilation system via permanent iodine filters. Samples are sent to the waste drains rather than being recycled to the RCS.

584 The four accumulator samples are merged into a common line inside the reactor building which passes through the containment boundary. The four accumulators are isolated from each other by a valve in each sample line.

585 The measurement of representative corrosion product is difficult due to the interactions of species and the oxide layers of the sample system, and also changes in corrosion product solubility with coolant flow and pH. Within the PCSR, there is reference to corrosion product sampling, albeit limited. Therefore, in light of corrosion product sampling and its evolving practices within the field, further clarification was requested on the systems suitability to monitor accurately corrosion products. TQ-EPR-778 (Ref. 8) requested further information on this capability in UK EPR. TQ-EPR-775 (Ref. 8) also contains information on corrosion product sampling in UK EPR. UK EPR has a specific glove box, dedicated to the sampling of corrosion products in the various purification systems, located in the nuclear auxiliary building. Samples can be taken from both upstream and downstream of the CVCS and FPPS filters. The samples downstream of the filters provide a comparison for the evaluation of the clean-up efficiency of the filters. The desired corrosion product sample can be selected by opening of the appropriate sample solenoid valve to start flow to the glove box. The sample line is purged to the drains system for recycling before a sub-sample is tapped from the main sample line and

passed through a filtering and flow totalising device over the sample drain from the glove box. Effluent from the glove box sub-sample is sent to the chemical drains. The glove box is attached to the nuclear ventilation system via permanent iodine filters. As with other sample glove boxes, the location in the NAB means sample line lengths are minimised.

586 Up to half the corrosion-product in circulation could take the form of particulates in the coolant. It is more difficult to obtain representative samples for particulates, because they tend to flow in streamlines that can avoid sampling apparatus. When sampling corrosion products the ability to isokinetically sample, or more commonly to sample in an isokinetic type regime, should be considered. EDF and AREVA have not yet fully defined such arrangements for UK EPR (TQ-EPR-778, Ref. 8). However, the design of the NSS indicates that such a regime could be implemented relatively easily using the current design, with many of the desired features, such as sub-sampling from a continuous high flow sample, already available. A similar system used at the EDF Penly reactor has been shown to operate satisfactorily (Ref. 41). A justification for the final design choices should be provided, when made. I consider this to be an Assessment Finding **AF-UKEPR-RC-17**.

587 Overall, the UK EPR facilities for corrosion product sampling appear comprehensive and consistent with relevant good practice.

588 As for the primary coolant sampling capabilities, the UK EPR has made extensive use of international OEF and good practice in incorporating a substantial and well developed sampling system. The UK EPR design appears similar to, but often improved on, other primary sampling systems, such as the successful system at Vandellós II in Spain, which also samples from the CVCS letdown line.

4.2.9.4 Post Accident Sampling

589 The NSS also functions as part of the Post Accident Sampling System (PASS) for UK EPR. As described more fully in Section 4.6, in the event of an accident the atmosphere of the containment may include radiolysis products (hydrogen and oxygen), steam, particulates and radioactive fission products (noble gases, radioactive aerosols and iodine). Analysis of the atmosphere can provide an indication of the temperature history of the core during the accident and thereby provide information on the physical state of the core. Early information concerning the extent of the damage and the conditions prevailing in the containment after an accident is important for accident management measures.

590 In a post accident situation, the containment isolation valves of the NSS are automatically closed on a containment isolation signal. These can be re-opened as necessary to sample the primary coolant for boron content, to measure the primary activity and to determine the composition of the primary coolant fission products. Provisions exist for diluting high activity samples ‘on-line’. In the event of an accident highly contaminated samples can be routed back into the containment sump.

591 Generally, the arrangements described for UK EPR appear reasonable, however a number of areas remain where I find that further information is required:

- Sample flow is normally maintained by the back-pressure of the sampled system. In events where the RCS is depressurised, there does not appear to be any provision to draw a sample. The SDM (Ref. 40) states; “*Samples from the RCS can be drawn during PCC 3 and 4 events as long as the primary circuit is pressurized to ensure a sample flow in the NSS sample lines to the NSS rooms in the HNX*”. Where “PCC” is the term used by EDF and AREVA for a Plant Condition Category.

- Whether hydrogen concentration in containment is monitored directly and if not, the justification from an ALARP perspective. This is related to the Combustible Gas Combustion Control System (CGCS), assessed in Section 4.6.3.

592 Overall, while the functionality appears reasonable, further information is needed on the post accident sampling capabilities and procedures in UK EPR, particularly the maintenance of sample flow and hydrogen monitoring listed in the preceding paragraph. I consider this to be an Assessment Finding **AF-UKEPR-RC-18**.

4.2.9.5 Summary

593 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of the UK EPR primary circuit sampling system are:

- UK EPR features a dedicated and sophisticated sampling system for the collection of representative samples for the primary and primary auxiliary circuits. The NSS incorporates much relevant good practice, from both the German KONVOI and French N4 PWR plants, and includes feature specific to the UK EPR design. Thus, the systems for use within UK EPR are based on proven designs with many years operating experience. Some of the positive features of UK EPR include:
  i) Key functions to safeguard operator safety; for example ^{16}N delay coils, thermal cut-off measurements, activity protection, pressure let-down and relief, adequate sample conditioning and use of conditioned and protected glove boxes.
  ii) Consideration given to maximising sample representivity; for example, primary coolers in close proximity to the sample point (this reduces the risk of deposition and chemical reactions within the sample line downstream ensuring maximum sample representivity) and specific features for collection of "*difficult*" samples such as corrosion products and zinc.
  iii) Increased on-line analysis for many important chemical parameters, such as boron, hydrogen and radioactivity, with the ability to readily take off-line measurements including degassed samples.
  iv) Multiple, often redundant, sampling points compatible with all plant operating modes and expected operational transients.
  v) Recycled sample streams to reduce the radwaste associated with continuous flowing samples.
- Only a small number of minor concerns remain with the NSS, relating to sampling from the pressuriser vapour phase, 'isokinetic' type sampling and sampling during post accident states. I have raised findings to support these areas. Although some areas have been identified, for GDA the specific design, system components, sample availability and sample integrity are of greater importance. Overall I believe that EDF and AREVA have considered the sampling requirements for UK EPR in the design of the NSS, which should ensure successful sampling and subsequent ability to control the plant chemistry during all modes of plant operation.

594 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.9.6 Assessment Findings

595 Based upon the assessment of the primary circuit sampling systems in UK EPR described in Section 4.2.9 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-16*** *– The Licensee shall review the provision of a pressuriser vapour space sampling capability. This Assessment Finding should be completed before such facilities would be needed for nuclear safety but certain aspects may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-UKEPR-RC-17*** *– The Licensee shall consider the need for isokinetic type sampling as part of the corrosion product sampling capabilities in the nuclear sampling system. This Assessment Finding should be completed before the sampling system installation is complete. This Assessment Finding should be completed before Hot Functional Testing commences as such capabilities would be needed during these activities, but may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Hot Ops.*
>
> ***AF-UKEPR-RC-18*** *– The Licensee shall demonstrate the adequacy of the post accident sampling capabilities in UK EPR. This Assessment Finding should be completed before such facilities would be needed for nuclear safety but certain aspects could be needed earlier, for example, prior to procurement of the affected equipment. Target milestone – Fuel load.*

4.2.9.7 GDA Issues

596 Based upon the assessment of the primary circuit sampling systems in UK EPR described in Section 4.2.9 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.10 Assessment – Holistic Approach to Normal Operating Chemistry

597 In the preceding sections of this report I have assessed the impact many of the normal operating chemistry parameters would have on fuel integrity, structural integrity, ORE and radwaste in UK EPR including how much is added, how it is added and controlled, the impacts of adding too much or too little and how these risks are mitigated in the design. As has been described, the primary circuit chemistry of all PWRs is dictated by a number of operational factors for which a balance must be struck to give the optimum performance in terms of fuel integrity, structural integrity, ORE and radwaste. Over 50 years of commercial PWR operations have developed and refined these conditions to those that are used today. This means that all (western) PWRs have adopted a primary circuit chemistry regime based upon:

- Coordinated ^{7}LiOH / H_3BO_3 to a desired pH based upon reactivity considerations.
- Maintenance of reducing conditions throughout the circuit.
- Minimisation of impurity ingress.

598 Plus, many operators are also now adding zinc, either for radiation field or integrity concerns.

599 While these overall chemistry controls appear relatively simple, small changes to any of these parameters can have a pronounced effect on the safety performance of the reactor. It is important therefore that the specifications made for one purpose do not negatively impact on another and this section reviews the EDF and AREVA proposals for primary coolant chemistry under normal operations to ensure a holistic approach has been taken. It can be considered as a summation of the preceding more detailed assessments. These parameters are part of a comprehensive chemistry control regime (SAP EKP3, Ref. 4) that helps to minimise corrosion rates and lifetime corrosion losses, addressing SAP EAD1 and EAD2, preventing fuel damage and limiting radioactivity.

600 As detailed earlier in my report, EDF and AREVA have indicated that they expect UK EPR to operate with:

- A constant pH_{300} as early as possible in the fuel cycle, with a target value of pH_{300} = 7.2. A maximum lithium concentration of [redacted] mg kg^{-1} at Beginning of Cycle (BOC) in combination with the use of Enriched Boric Acid (EBA) make this possible. These aspects are assessed in Sections 4.2.2, 4.2.3, 4.2.4 and 4.2.5.
- A minimum hydrogen concentration of 17 cm^3 kg^{-1}, assessed in Section 4.2.7.
- Limitation of impurities to avoid localised RCS and fuel materials corrosion, assessed in Sections 4.2.3, 4.2.4 and 4.2.5.
- Add zinc acetate to achieve 10 ± 5 μg kg^{-1} zinc, assessed in Section 4.2.6.

601 As described in Section 4.1.3, precise values for a number of these parameters are still to be agreed for UK EPR and were not assessed during GDA, but EDF and AREVA are already developing detailed operating plans for FA3 and I would encourage a Licensee of UK EPR to take advantage of experience gained from FA3. Values of the main chemical parameters for the primary circuit of UK EPR are tabulated below, based largely on information provided by EDF and AREVA (in Refs 158, 159, 161 and 172 and the consolidated GDA PCSR, Ref. 105) which were mostly provided originally in the responses to regulatory observation actions RO-EPR-44.A1, A5 and RO-EPR-46.A2. These values are divided into "control" and "diagnostic" parameters and information is given on the expected values and the controlling limit values:

Parameter	Expected Value	Limit Value
Control Parameter		
Total boron, mg kg^{-1}	Function of fuel management	Function of fuel management
^{10}B, mg kg^{-1}	Function of fuel management	Function of fuel management
Lithium, mg kg^{-1}	Lithium is coordinated with total boron to give expected pH_{300} 7.2	≤ [redacted]
Sodium, μg kg^{-1}	< [redacted]	≤ [redacted]
Chloride, μg kg^{-1}	< [redacted]	≤ [redacted]
Fluoride, μg kg^{-1}	< [redacted]	≤ [redacted]
Sulphate, μg kg^{-1}	< [redacted]	≤ [redacted]
Silica, μg kg^{-1}	< [redacted]	≤ [redacted]
Hydrogen, cm^3 kg^{-1}	17 to 30	≥ [redacted] and ≤ [redacted]
Oxygen, μg kg^{-1}	< [redacted]	≤ [redacted]

Parameter	Expected Value	Limit Value
Zinc, µg kg^{-1}	10 ± 5	≤ [redacted]
Nickel, µg kg^{-1}	To be confirmed	≤ [redacted] (with Zn injection)
Diagnostic Parameter		
Boron Enrichment, at. %	Function of fuel management	Function of fuel management
Aluminium, µg kg^{-1}	To be confirmed	To be determined by Licensee
Calcium, µg kg^{-1}	To be confirmed	
Magnesium, µg kg^{-1}	To be confirmed	
Ammonia, µg kg^{-1}	To be confirmed	
Nitrogen, cm^3 kg^{-1}	To be confirmed	

Table 10: UK EPR Primary Circuit Chemistry Controls

602 In line with the Step 4 Assessment Plan for UK EPR, I have not assessed the limit values in detail during GDA but I note that in most cases the preliminary limit values are significantly higher than the expected values, hydrogen being the one exception as has already been described in Section 4.2.7 of my report. These limit values are much more appropriately assessed during the Licensing phase when detailed operating procedures are available; however I am encouraged by the progress made so far in this area by EDF and AREVA. Of particular note are:

- The inclusion of both ‘total boron’ and ‘^{10}B’ as control parameter and ‘boron enrichment’ as a diagnostic parameter. On the basis of the evidence provided during GDA this appears to be a reasonable approach to the added complications of controlling EBA in UK EPR. This does mean there is no direct use of pH_{300} as a control, although as UK EPR is expected to operate at a constant pH_{300} of 7.2 this is easy calculated based on the ‘total boron’ and ‘lithium’ values.
- EDF and AREVA expect UK EPR to operate with additional controls over both sodium and nickel in the primary coolant. Both of these species are not commonly controlled in this manner but the arguments provided for their inclusion are reasonable and demonstrate an ALARP approach by EDF and AREVA.
- The additional diagnostic parameters of ‘ammonia’ and ‘nitrogen’ due to the use of a nitrogen covered VCT and other tank and vessel headspaces are a sensible addition, at least until operating experience is gained with the plant.

603 Whilst the PCSR describes normal operations and principal hazards, it is weaker in presenting analyses of sensitivity to deviations from normal chemistry and justifications for claims made for normal performance. There is also still a need to quantify the impact of chemistry that is not within specification, which could then be used to define corrective actions, see **AF-UKEPR-RC-19**. The operation of a plant with chemistry just within a limit is not greatly better than operating a plant with chemistry slightly outside the limit.

604 It can be seen from these preceding Sections of my report, and the additional assessment above that EDF and AREVA have considered the interplay of each of these main parameters on the consequences of primary circuit chemistry; radioactivity, fuel

integrity and maintenance of pressure boundary materials, as well as the control of boron which is more complicated in UK EPR due to the use of EBA. I am satisfied that EDF and AREVA have demonstrated a holistic approach to the normal operating chemistry to be used in UK EPR. I am satisfied that an adequate case has been made to support GDA and that the Licensee should be able to fully develop the operating chemistry during Licensing for any UK EPR based on this approach, see Assessment Finding **AF-UKEPR-RC-01**.

4.2.10.1 Summary

605 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit holistic chemistry assessment are:

- Balancing the boron and lithium to achieve an expected pH_{300} of 7.2 should provide good control over corrosion and corrosion product transport whilst limiting harmful effects due to high lithium in terms of fuel cladding integrity or tritium production.
- I have not been convinced by the justification presented by EDF and AREVA for reducing dissolved hydrogen level, and this is the subject of a finding in Section 4.2.7 of my report.
- It is noteworthy that levels of control for some impurities in a modern reactor are down at levels of $\mu g\ kg^{-1}$ (parts per billion), levels measurable only with modern analysis techniques. Limit levels for impurities such as nickel and silica need particularly tight controls, especially in relation to boiling. In general, the approach to controlling impurity levels in UK EPR appears sound.
- The design of UK EPR is capable of supporting the primary coolant chemistry specified for normal operations.

606 When taken as a collective answer, the TQ responses under this area add significantly to the UK EPR safety case for primary circuit holistic chemistry. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.10.2 Assessment Findings

607 Based upon the assessment of primary circuit holistic chemistry in UK EPR described in Section 4.2.10 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as appropriate, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-UKEPR-RC-19*** *- The Licensee shall quantify the implications of significant deviations from normal operating chemistry and where necessary specify procedures for managing chemistry that is not within specification, Target Milestone – before raising power when the specified chemistry will be applied for the first time.*

4.2.10.3 GDA Issues

608 Based upon the assessment of primary circuit holistic chemistry in UK EPR described in Section 4.2.10 above, I have identified no GDA Issues in the area of primary circuit holistic chemistry for UK EPR. There is a related GDA Issue, **GI-UKEPR-RC-02**, described in Section 4.2.5.5.

4.2.11 Assessment – Start-up and Shutdown Chemistry

4.2.11.1 Overview

609 At the end of each fuel cycle all PWRs shutdown for refuelling and maintenance and, when this is completed, returned to normal operating conditions during a start-up. Early PWRs operated with virtually no control over the start-up and shutdown chemistry and as a result suffered from very long and dose intensive refuelling outages. Much improvement has been made in this area over recent years, although there is no ‘universal’ approach applied for all PWRs, mostly due to plant differences, economic considerations or subtle differences in the technical basis for the processes.

610 The general progression of steps during a shutdown can be summarised as below, with many steps acting concurrently:

- Boration (to cold shutdown concentration)
- Cooling and depressurisation of the RCS
- Dehydrogenation and oxygenation
- Purification
- RCS opening

Start-up is the opposite of these steps in reverse order, with the exception of purification. Many discrete systems are involved throughout the entire sequence. This assessment topic has concentrated on the chemistry changes and the controls on these, rather than a system by system assessment, however many of the most important systems are assessed earlier in this report.

611 During start-up and shutdown transients a number of significant chemistry changes take place during these periods as the primary circuit is taken from hot reducing alkaline conditions to cold oxidising acidic conditions and back again. These changes cause a number of effects; during shutdown the most important of these is an increase in the concentrations of both soluble and particulate radionuclides (from fuel deposits and soluble corrosion products – 'crud') in the coolant. This change has a pronounced effect not only on the speed and safety of the outage activities but also on future operation of the reactor during the subsequent fuel cycles. A similar (but generally much smaller) event occurs during start-up where the main concern is related to impurity ingress and maintaining adequate chemistry control.

612 The assessment of this area during Step 3 was rather preliminary, mainly due to a lack of information provided by EDF and AREVA. Despite this it was still possible to provide some initial assessment of the UK EPR start-up and shutdown arrangements at Step 3, which can be summarised as:

- A very fast shutdown and start-up are proposed for UK EPR.
- EDF and AREVA recognise the importance of properly controlling start-up and shutdown chemistry for corrosion control, elimination of the potential for hydrogen rich atmospheres and circuit activity in PWRs.
- Fast shutdown will be aided by a period of reduced power operation prior to shutdown followed by forced oxidation with hydrogen peroxide when warm to eliminate hydrogen.
- The proposed regime is based upon EDF experience but includes some features necessary for the EPR design.

613 Overall, I was encouraged by the information available at that time but recognised that further work and evidence would be required during Step 4.

614 Sampling during start-up and shutdown is often of increased frequency, due to the relatively rapid changes in chemistry that are occurring. The assessment of the UK EPR primary sampling system is given in Section 4.3.8, including consideration of the system during such transients.

4.2.11.2 UK EPR Approach to Start-up and Shutdowns

615 During Step 4 a TSC contract was let to review the UK EPR start-up and shutdown arrangements (Ref. 36). An initial review was also undertaken on current ‘relevant good practice’ in start-up and shutdown chemistry (Ref. 35), mainly that presented in chemistry standards such as EPRI (Refs 27 and 28) or VGB guidelines (Ref. 29). The main conclusions of this review are in agreement with the approach adopted by EDF and AREVA for UK EPR and indeed recognise the importance of plant specific optimisations and procedures. In addition an ANT International special topic report provides information on start-up and shutdown chemistry considerations (Ref. 42). The conclusions from the review of UK EPR (Ref. 109) are consistent with the assessment that follows. This review highlighted the following main safety case gaps, relevant to GDA, which I considered further during my assessment:

- The EDF and AREVA documentation does not include a head lift criterion (or equivalent control) for tritium which appears inconsistent with current UK (and much international) practice.
- More definitive information to demonstrate that the risk associated with LTCP in the primary circuit during shutdown is not significant (see Section 4.2.11.3).
- A more detailed description of contingency options if radiochemical specifications are not met at particular stages in the schedule (e.g. purification holds) (see Section 4.2.11.5).
- A more rigorous consideration of the effects of peroxide and hydrazine (including the subsequently formed ammonia) on Ion exchange beds and/or definition of operations to avoid these (see Section 4.2.2.3.1).
- Further justification that the proposed timing of hydrazine injection into CVCS one hour prior to RHRS connection during cool down will be adequate to prevent risks from oxygen introduction, see Section 4.2.11.
- Contingency options for mitigation of tramp fuel in the primary circuit should fuel failures occur.

616 Before discussing the Step 4 assessment in this area, it is relevant to note that EDF and AREVA have proposed a design change to the start-up sequence for UK EPR (CMF (Change Management Form) 28, Ref. 93). This was received late in Step 4, although EDF and AREVA did not respond to many of my queries on start-up and shutdown until similarly late in Step 4, so no changes to responses were necessary. In summary, the original design concept for EPR was to start-up in a bi-phasic mode, as is undertaken on KONVOI and many other PWR plants. This involves creation of the pressuriser steam bubble before operation of the main RCPs. The design change proposal alters the steps of this sequence, instead using the RCPs to heat the RCS to 90 °C before operation of the pressuriser and creation of the steam bubble. This latter, monophasic start-up process allows better homogenisation of the coolant before creating a discontinuity between the RCS and pressuriser volumes. In principal this should offer advantages from

a chemistry perspective. It does, however, introduce other, non-chemistry related considerations such as Low Temperature Over-pressure Protection (LTOP) arrangements. This design change proposal is at an early stage, with EDF and AREVA recognising the need for further study, and will require a fuller assessment post GDA.

617 Numerous TQs (TQ-EPR-835, 156 to 161, 163, 164, 166, 168, 1213, 1217, 1220, 1234 and 1235; Ref. 8) were raised with EDF and AREVA on various aspects of start-up and shutdown chemistry during Step 4. In addition, the responses to RO-UKEPR-44.A1 (Ref. 172 and 51) and RO-UKEPR-46.A2 (Ref. 161), relating to primary circuit chemistry and reduction in primary coolant radioactivity SFAIRP respectively, both contained information of relevance to this part of the assessment. The most relevant of these are discussed further below. The responses to these TQs and ROAs incorporate the design change proposal in some manner, although the underlying chemistry principles in either case should not differ significantly and hence should remain valid.

618 The response most relevant to this part of the assessment is TQ-EPR-166 (Ref. 8). This query requested an overview of the primary circuit start-up and shutdown sequence and the response details EDF and AREVA's expectations and philosophy for controlling UK EPR start-up and shutdowns. Although the response provides details of limits and expected values for many parameters, these were given as indicative only based upon current EDF practices. For the purpose of GDA, and in line with the assessment objectives, this approach is considered reasonable. In this response EDF and AREVA stated their 'main goal' during start-up and shutdown periods as; *"to manage in a consistent way with outage schedule the radionuclide and chemical additives behaviour in order to minimize the consequences (on radiation fields, fuel integrity monitoring,* H_2/O_2 *hazardous mixtures, material performance and effluent/waste production) within a reasonable timeframe".* The response further expands upon each of these points, providing claims, arguments and evidence in support of the main stages of the transients. Overall the response is comprehensive and provides lots of details to support the claims made. As EDF and AREVA indicate the methodology suggested does indeed appear consistent with international practice (and in fact references both the EPRI (Refs 27 and 28) and VGB guidelines (Ref. 29)) and it can be clearly seen where adaptations have been implemented to accommodate UK EPR specifics (for example, the use of a third CVCS demineraliser during shutdown).

619 The overall description of start-up and shutdown chemistry is complex, but is contained in the EDF and AREVA responses so are not repeated here. The summary approach, as described above, is followed. I am content that the approach to start-up and shutdown chemistry in UK EPR seems adequate to support GDA. Post GDA fully developed start-up and shutdown procedures should be developed by the future Licensee for the primary circuit of UK EPR, building upon the sound basis presented for GDA. These should include due consideration of related topics such as limits and conditions, as appropriate, and the assessment that follows. This is related to Assessment Finding **AF-UKEPR-RC-01**.

4.2.11.3 Control of Water Chemistry, Gases and Purification

620 EDF and AREVA make reasonable arguments over the expected pH, redox, radioactivity and purification changes anticipated for UK EPR during both start-up and shutdown periods. Considerable forethought appears to have been given to the complex sequencing during these transients and the effects choices made on timings or durations could have on the consequences. While the majority of points could be considered

complimentary to ‘standard’ PWR practice, some specific points in the suggested sequences are noteworthy:

- Measures taken to control Low Temperature Crack Propagation (LTCP) risks; EDF and AREVA suggest limiting the duration between 150 °C and oxygenation, thus limiting the exposure time in a conducive environment for LTCP. This also has advantages for minimising coolant activities before oxygenation. Despite the very low risk of LTCP in an operating PWR with Inconel 690 SG tubing the additional precautions may still be beneficial. As understanding in this area is still developing I find that the Licensee should review the most up to date knowledge during development of start-up and shutdown procedures for UK EPR. This is part of assessment finding **AF-UKEPR-RC-15**.
- Elevated $pH_{300°C}$ (5.5 - 7.0) during shutdown with fuel clad defects; while not normal practice due to the reduction in corrosion product solubility and potential re-deposition in the RCS, an elevated pH at shutdown has been used previously to reduce iodine volatility and increase removal rates. The recognition of this possibility within the UK EPR approach is encouraging. Further information on corrective actions and operational procedures to safely control and deal with anticipated operational transients during start-up and shutdown periods should be documented in the plant operating procedures. This is related to Assessment Finding **AF-UKEPR-RC-01**.
- Oxygen control practice; the suggested oxygen control practice during start-up and shutdowns (O_2 < [redacted] $\mu g\ kg^{-1}$ when > 120 °C) is consistent with EPRI guidelines, rather than the less restrictive VGB approach. This is reasonable given the SG material choice made for UK EPR.
- No Lithium addition during start-up until just before criticality; typically the decision as to when lithium is added during start-up is a matter of choice. The suggested approach for UK EPR, whilst not identical to many PWRs, is reasonable and the arguments presented for this approach are acceptable. This approach is used at EDF PWRs.

621 A difference in UK EPR from other PWR designs is the use of the IRWST to fill the Residual Heat Removal System (RHRS) prior to connection to the RCS. While this does remove the possibility of lithium contamination causing a pH increase during the shutdown, the IRWST is not maintained under a reducing environment and will thus introduce a quantity of oxygenated boric acid to the RCS. Other PWRs use sources of boric acid which have controlled levels of oxygen, or remove oxygen from the RHRS before connection. The approach taken in UK EPR is to chemically remove this oxygen via hydrazine injection into the RCS, as presented in the response to TQ-EPR-156 (Ref. 8). As the temperature in the RCS is below 120 °C at this point this is consistent with the start-up procedure and should pose minimum risk to the RCS materials. Since thermal decomposition of hydrazine competes with its reaction with oxygen at higher temperatures, hydrazine should be added at an appropriate point in the cool down. The main chemical impact of this may be on the ion exchange resins, which may experience a variation in capacity for impurities due to the ammonia produced from hydrazine thermal decomposition or release of lithium, depending upon the scale and timing of the addition. This effect was discussed in the response to TQ-EPR-903 (Ref. 8) and can be considered negligible if hydrazine is added at an appropriate temperature, although should factor into outage planning.

622 The use of Boron recycle in UK EPR has been assessed previously in my report, both in Section 4.2.2.3.3 (CVCS) and 4.2.3 (Radioactivity). As described there, EDF and AREVA have designed the CSTS of UK EPR to accommodate the flows and changes in boron

needed during start-up and shutdown periods. In essence, while the boron is handled differently outside the primary circuit of UK EPR (i.e. recycled), the RCS changes are unaffected; at shutdown, recycled boric acid is injected via the RBWMS, while at start-up discharged coolant is stored in the CSTS prior to recycling.

623 In addition to the potential for retention of tritium in recycled boric acid and distillates, other in-volatile species could potentially be retained, including lithium and silica.

624 During shutdown, so to not influence the production of acidic conditions, a lithium free dilution source is required. Several instances of inadvertent alkalisation of the RCS have occurred via this mechanism, with resultant difficulties during shutdowns. TQ-EPR-164 (Ref. 8) specifically asked this question for UK EPR. The response provided demonstrated that the multiple purification steps in operation in UK EPR would reduce lithium in recovered boric acid to essentially zero. Maintenance of this is assured by sampling and monitoring prior to use. In addition the shutdown CVCS bed in operation would also act to remove any adventitious lithium added by this method.

625 The potential retention of silica is important in UK EPR due to the use of zinc injection, and this is discussed further in Section 4.3.5.

626 TQ-EPR-157 and 158 (Ref. 8) provide information on the control of gases during start-up and shutdowns in UK EPR. Gases are controlled by the CDS, pressuriser venting or chemical additions of hydrazine to remove dissolved oxygen. Many of the TQ responses in this area highlight the importance of the Coolant Storage and Treatment System (CSTS) degasifier to start-up and shutdown periods. The assessment of the CVCS, including the degasifier, is described in Section 4.2.2.2.4. The degasifier will be used much more during start-up and shutdown periods; to remove hydrogen and fission product gases at shutdown and to remove oxygen at start-up. The CDS degasifier operates in the same manner as described in previously, with changes made to the nitrogen injection and release path depending upon the operating conditions. For shutdowns injection to and releases from the degasifier are handled by the Gaseous Waste Processing System (GWPS) for further abatement, while at start-up the system can operate independently of the GWPS with nitrogen supplied from the plant nitrogen system and discharges to the Heating, Ventilation and Air-Conditioning (HVAC) system as they do not contain fission gases. This later mode controls the input of oxygen to the GWPS, thus maintaining non-flammable conditions. I am content with these arrangements.

627 In response to our queries EDF and AREVA described the expected operation of the CVCS ion exchange demineralisers and filters during shutdown and start-up periods (TQ-EPR-161, Ref. 8). This was an important response in understanding the intended operation of the CVCS system during these operational transients when conditions, in terms of both flow rate and performance requirements, are amongst their most demanding. The current intent for UK EPR is to operate one mixed bed as a de-lithiator (H^+/BO_2^- form) with the second as a purification bed (Li^+/ BO_2^- form). The third vessel is held as a dedicated shutdown purification vessel. The addition of a third, large, CVCS demineraliser in the design offers many potential advantages and options for shutdown activity management including a dedicated shutdown ion exchanger and minimisation of resin and chemical wastes by alternating the operating ion exchangers between de-lithiation and purification duty. The approaches described in the response are consistent with operational ‘good practice’ at many PWRs, where such capabilities exist. It is noted that there is some inconsistency in the documentation over the use of this third ion exchange bed, sometimes implying it is used for shutdown purification and sometimes for de-boration. These two functions are different and would require different resins and

potentially resin changes, potentially producing more waste. This aspect was discussed above.

628 The UK EPR purification flow rate is significantly higher than the latest generation of French PWRs (N4), up to 72 compared to 36 t hr^{-1}. This can only be beneficial for shutdown and start-up chemistry, provided the performance is substantiated. Refer to Section 4.2.2 for assessment of the CVCS systems.

629 The addition of hydrogen peroxide, a strong oxidising agent, during shutdowns has the potential to affect the ion exchange resins which operate during the oxidising phase of the shutdown. EDF and AREVA arguments and evidence in this area are reasonable and support the minimal effect this is expected to have in UK EPR. On the contrary, a much stronger argument is made regarding the need to maintain purification at these times when the activity burden in the coolant is at its highest.

630 Another difference in the approach suggested for UK EPR to ¾ loop working. The RCS is drained to ¾ loop level prior to head lift. EDF and AREVA state (in TQ-EPR-987, Ref. 8) that this will be undertaken during every shutdown and during every plant start up, irrespective of whether maintenance on the SG is required. Reasonable arguments are suggested from a chemistry point of view for this requirement.

631 As indicated elsewhere in this report, UK EPR has been designed to anticipate deviations from ‘standard’ shutdown practices. Restriction of the alkalinity and maintenance of reducing conditions for longer results in increased iodine retention on CVCS resins in case of fuel failures. The design of the CVCS ion exchange system will allow operation with lithiated resins during this period. Similar design improvements, such as the continuous and high capacity Pressuriser (PZR) purge lines, can be used to mitigate increased fission gas releases. I am satisfied that EDF and AREVA have demonstrated a degree of flexibility and resilience in the UK EPR to account for disturbances from normal practices.

4.2.11.4 Control of Radioactivity

632 During a shutdown it is important that the RCS clean-up is progressed to a level where opening of the RCS can be viewed as ALARP. EDF and AREVA have suggested limits for both head lift and criteria for shutdown of the final RCP (to ensure head lift limits are met).

633 After the hydrogen peroxide injection, the activity concentrations in the primary water may increase by several orders of magnitude. Effective mixing of the RCS volume ensures purification efficiency is maximised, however some stagnant bodies (SG-tubes and crossover leg) can be created after the last RCP is stopped creating potential ORE hazards if access is required. The intermediate criteria suggested by EDF and AREVA are aimed at minimising the bulk coolant concentration to an acceptable level such that complete stagnation in these areas results in doses that are ALARP. The inclusion of such criteria is a positive step.

634 The response to RO-UKEPR-46.A2 (Ref. 161) provided details on the consideration given during start-up and shutdown periods to reducing radioactivity SFAIRP. For start-up periods the approach suggested is based upon reducing the quantity of nickel in the RCS prior to power operation, thus limiting the available activatable material during the subsequent fuel cycle. EDF and AREVA suggest an expected value of [redacted] $\mu g\ kg^{-1}$ nickel. This appears a reasonable approach and EDF and AREVA recognise the impact this could potentially have on outage duration. The specification of a nickel criterion

during start-up is an improvement, since many PWRs operate without one including French N4 plants and Sizewell B.

635 As shutdown periods carry a much greater burden of radioactive material release into the RCS the response to RO-UKEPR-46.A2 provided more details on the processes proposed for UK EPR during this transient. The response provided a general justification for timings, sequence and arguments and evidence were presented to describe the influence of the various chemical changes on activity transport, deposition and dissolution. The main chemistry parameters which affect the magnitude of the activity release are the pH and redox potential, with more rapid dissolution favoured by a more acidic and oxidising environment, even before oxygenation. I consider the response provided a suitable description and justification for the steps taken during shutdown to keep radioactivity reduced SFAIRP.

636 UK EPR head lift values are based upon xenon and iodine isotopes. The precise values for these limits have not been assessed, as for all limits and conditions in GDA, however they do not appear impracticable and suggest suitable values could be achievable for UK EPR. This is related to Assessment Finding **AF-UKEPR-RC-02**, with the importance of specific values for head-lift warranting particular attention. Details of likely recovery actions are included (such as increased purification times) and mainly appear to impose time constraint on the schedule rather than additional safety concerns. See also Section 4.3 for the SFP systems.

637 It was notable that no tritium value was included in the listing of chemistry controls during shutdown and TQ-EPR-835 (Ref. 8) had been raised previously on this subject. The response to TQ-EPR-835 indicated that EDF and AREVA felt that no limit, condition or criteria were necessary for tritium in UK EPR. I found this response surprising, given the use of boron recycle and the possible concentration of tritium via this mechanism if not adequately controlled and the non-removal of tritium by UK EPR treatment systems. The overall argument was based upon taking credit for ‘standard’ plant practices to ensure that a high concentration never exists in the RCS prior to head lift. While, generally I can see the logic behind this argument it does not lessen the fundamental safety requirement of maintaining control, especially in this instance as several cases could be postulated where ‘non-standard’ practices result in elevated tritium levels. If these were to occur, and the response indicated there were no controls to stop them, a hazardous level could be reached.

638 This is in contrast to many responses in this area (for example, TQ-EPR-158, 159 and 160 (Ref. 8)) which indicate many controls will be in place for fission product control during shutdowns at various stages such as before power reduction, before RCS oxygenation and before final RCP stop.

639 RO-UKEPR-74.A1 (Ref. 9) was raised to understand the management of tritium in UK EPR. Tritium is produced in all PWRs and cannot be completely eliminated or removed by treatment systems so must be discharged, either as gaseous or aqueous waste. Several reports were provided in response to this ROA.

640 The first response EDF and AREVA provided contained a report detailed the EDF rationale and recommendations for tritium management in its PWR fleet (Ref. 34). This report aimed to demonstrate that no limits or conditions were required for UK EPR. The basis for the arguments presented is that by placing a limit of the Spent Fuel Pool (SFP) tritium concentration, this would implicate management of the RCS activity as these water volumes will eventually mix during a refuelling outage. This seems a reasonable approach but assumes that all shutdowns will include full mixing of the RCS and SFP water volumes. EDF and AREVA claim that no limit is needed on tritium in the RCS

during a cycle and I would agree with this approach for intact circuits. However, opening of the RCS with high levels of tritium potentially introduces an ORE hazard and it is not clear how this relates to the UK EPR discharge predictions.

641 Several examples, both from plant and using calculations (but not for UK EPR) were presented which showed both the high levels achievable in the RCS (> 20,000 MBq t^{-1}) and the increases caused by fuel damage. Average RCS values for the N4 plants are around 8,000 MBq t^{-1} with average maxima of around 15,000 MBq t^{-1}. There is a general trend to decrease these values over the period considered and current values may be lower still. Several operational "*rules*" were suggested to limit the plant tritium inventory and prevent a long term escalation; discharge all the tritium produced, discharge as an aqueous waste in preference to an aerial discharge and discharge all recycled water from the reactor. This general approach seems reasonable and should control the tritium build-up in UK EPR if applied.

642 The second part of the RO-UKEPR-74.A1 response (Ref. 106) provides more details of the general principles from the initial report (Ref. 34), applied to UK EPR. The report introduces a further operational "*rule*" for tritium control aimed at limiting tritium transfer to the secondary side in cases of primary leakage. Further details of the operational strategy for UK EPR are provided; for example, limiting discharges with high boron concentrations due to the economic impact of EBA make-up and boron discharge constraints. The report shows that, while the implementation may be different for UK EPR, the operations considered under the first report can still be functionally achieved in the UK EPR design. A large portion of the report provides information on tritium minimisation; these aspects are assessed under primary coolant radioactivity, Section 4.3.2.3; notably, EDF and AREVA have recognised the contribution secondary neutron sources can potentially make to tritium build in PWRs. Ultimately this report indicates that EDF and AREVA propose "*a preliminary target value for UK EPR of 3,000 MBq t^{-1} for tritium concentration in the Fuel Building Pool and the IRWST pool. Complementary studies are currently in progress to properly assess the different tritium activity limits that should be set in the Fuel Building pool, in the IRWST pool and in the RCS prior to head lift.*" The additional "*rule*" and confidence provided by this response suggest that adequate tritium control should be possible for UK EPR during shutdown periods, provided an adequate set of operating procedures and limits and conditions are developed by the Licensee. The use of a limit on the Spent Fuel Pool activity to control the head-lift criteria seems reasonable, but requires further justification by the Licensee. This is related to Assessment Findings **AF-UKEPR-RC-02**.

643 The final part of the RO-UKEPR-74.A1 response (Ref. 107) provides example tritium calculations for the first two cycles of UK EPR using the newly developed AREVA ABSOLUT-3 tool. These calculations only deal with the RCS and main connected systems and do not consider transfer to the SFP, IRWST evaporation or the GWPS. While many of the assumptions would tend to be optimistic for tritium build-up in the plant (for example, full distillate discharge) they are consistent with the operational "*rules*" described earlier but are highly dependant on operating procedures, while others would tend to be more pessimistic. As such, while the calculations cannot be entirely accurate for an operational UK EPR at this stage where many details are currently unknown, they do show that tritium could be managed adequately and that it can be predicted, dependant upon operational parameters. Various estimates for the RCS tritium concentrations at end of cycle are given, ranging from 4,200 to 12,000 MBq t^{-1}. Such calculations will be needed to support eventual head-lift criteria or other tritium limits or conditions applied for UK EPR. This is related to Assessment Findings **AF-UKEPR-RC-02**.

644 Further assessment of tritium control in the UK EPR Spent Fuel Pool systems is discussed in Section 4.5.1.

645 A number of filters are installed in the UK EPR design for removal of particulate corrosion products, most notably the main CVCS letdown filter and the RCP seal filters (both make-up and letdown). EDF and AREVA do not anticipate changing the filtration efficiency purposefully to account for start-up or shutdown variations. Dose rates or pressure losses may indicate the need to change the filters prior to entering a shutdown and a number of the filters feature monitors and alarms to alert licensee staff to this occurrence. The RCP seal filters do not have installed radiation monitors and reliance is placed on manual measurements.

646 In TQ-EPR-1213 (Ref. 8) I queried the impact of a number of shutdown parameters on release of particulate corrosion products. The response indicates that shutdown rates, around those expected in UK EPR, should have negligible impact on corrosion product release, with the control of RCPs being more important. EDF and AREVA suggest RCP cycling during shutdown should be avoided. The intent for UK EPR is to maintain one RCP operation until the RCS radioactivity limits are met for head lift, thus ensuring minimised transport of corrosion products to low-flow areas. Overall, EDF and AREVA claim such effects are considered in the shutdown procedures suggested for UK EPR.

4.2.11.5 Summary

647 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit start-up and shutdown assessment are:

- Overall, the evidence presented suggests that the primary chemistry during shutdowns in UK EPR should reduce radioactivity SFAIRP and the design has a number of features which should result in improved performance compared to current operating PWRs.
- More definitive information will be required to demonstrate that the risks associated with LTCP in the primary circuit during shutdown are not significant, however based upon the current understanding the risks posed by this mechanism are low.
- The EDF and AREVA documentation does not include a head lift criterion (or equivalent control) for tritium which appears inconsistent with current UK practice. EDF and AREVA have provided detailed information on tritium management in UK EPR, which suggests that tritium management is possible but also that controls are required to ensure an unsafe level is not reached. I am content this can be managed by a competent and experienced Licensee, with adequate procedures and limits and conditions. I have raised Assessment Findings in this area.
- Post GDA, fully detailed chemistry procedures should be developed, building upon the sound basis presented for GDA, and including further detailed information on a number of aspects, including:
- A more detailed description of specified schedule timings, minimum hold times at various stages and/or more detailed description of contingency options if radiochemical specifications are not met at particular points in the schedule (e.g. purification holds). This should include contingency options for mitigation of contamination in the primary circuit should fuel failures occur or occurrence of other anticipated transients.
- Information on principles for managing conflicts between chemistry and outage schedule (or other non-safety criteria).

- The occurrence of unplanned shutdowns, including responses to reactor trips, has not been specifically addressed in the EDF and AREVA documentation provided, although where reference is made, this infers that it would be covered through the refuelling shutdown and start-up procedures but without head-lift occurring.
- A more rigorous consideration of the effects of hydrazine and peroxide on ion exchange resin beds and/or definition of operations to avoid these.
- I have raised a number of Assessment Findings in this area which should support on-going assessment of this important topic.
- EDF and AREVA have proposed a design change to the start-up sequence of UK EPR to operate in a monophasic mode. I do not believe this change will have a significant impact on my assessment undertaken during GDA.

648 When taken as a collective answer, the responses under this area add significantly to the UK EPR safety case for start-up and shutdown periods. EDF and AREVA have presented a well reasoned and justified approach for start-up and shutdown chemistry in UK EPR for GDA. I believe that UK EPR should be capable of well controlled chemistry during these transient periods, with resultant safety benefits.

4.2.11.6 Assessment Findings

649 Based upon the assessment of primary circuit start-up and shutdown chemistry in UK EPR described in Section 4.2.11 above, I have identified no Assessment Findings which need to be addressed by the Licensee in this section of my report. The findings in Sections 4.1.2 and 4.1.3 of my report are clearly as relevant to start-up and shut-down as they are to normal steady operation.

4.2.11.7 GDA Issues

650 Based upon the assessment of primary circuit start-up and shutdown chemistry in UK EPR described in Section 4.2.11 above, I have identified no reactor chemistry GDA Issues in this area.

4.2.12 Assessment – Hot Functional Testing

651 Hot Functional Testing (HFT) was also considered under this topic as this is a unique period of reactor operations which can have a pronounced effect on the subsequent ORE and waste performance of the reactor over many subsequent cycles, if not the lifetime of the plant. However, as this process is very much associated with the later stage of commissioning of a reactor and the understanding of the processes and requirements has evolved over recent years (and will continue to do so), in common with the other sub-topics in this area the assessment has concentrated on the principles and the basis for the approach suggested.

652 In common with other complex industrial facilities, commissioning of a reactor is a lengthy process that involves testing and confirming the operability of each of the reactor systems and components. Chemistry plays an important role in this process; however commissioning was not assessed during GDA as a number of site specific considerations are included. I judge that these aspects can be satisfactorily assessed at a later stage.

653 One aspect of commissioning, in the broadest sense, was assessed during GDA. Hot Functional Testing (HFT) is a unique period in start-up (and shutdown) of the reactor as it

represents the first occasion(s) when the reactor is operated under full temperature and pressure conditions, albeit without the fuel. The chemistry adopted during this period is generally accepted to be important in determining the subsequent behaviour of the reactor, especially the primary circuit, in the ensuing fuel cycles (e.g. shutdown releases and susceptibility to degradation mechanisms).

654 For GDA it is not reasonable to expect EDF and AREVA to have fully developed commissioning and HFT methods and procedures, especially as these are areas where significant international experience is expected to influence the final choices (especially from EPR plant which may commission before any UK plant is licensed).

655 For Step 3 I was encouraged that EDF and AREVA were considering a specific HFT for UK EPR at an early stage. The approach adopted appeared to be broadly consistent with the approach adopted to that used on the most modern French (N4) units, to build up of a protective oxide layer on the surfaces of the RCS and more particularly, on the surfaces of SG tubes. The main steps being:

- A minimum of 300 hours at nominal temperature.
- Alkaline conditions (lithium hydroxide addition).
- Reducing conditions.

656 Some areas of the process were still under consideration:

- EDF and AREVA are working to determine whether or not it would be appropriate to remove the upper layer of the oxide phase formed, by means of acidification followed by forced oxygenation (with hydrogen peroxide) during transition to cold shutdown.
- Examination of the clean-up requirements during this procedure is also being examined to determine if this will have a benefit on subsequent plant operations.

657 RO-UKEPR-46.A2 (Ref. 9) specifically asked for a justification for the expected UK EPR HFT procedure in relation to reduction in primary circuit radioactivity SFAIRP. The response (Ref. 161) states that the approach for UK EPR is targeted at producing a protective inner oxide layer, principally on the SG u-tubes. The response provides further details and justification for the approach suggested, including details of the laboratory and plant experience which EDF and AREVA claim influenced the UK EPR approach.

658 Operational feedback from the early EDF plants which use Inconel 690 TT tubing, as in UK EPR, is that the tubing did not fully passivate during HFT and achieve the low shutdown releases expected, but it seems that the more recent N4 plants have. EDF has experience of this alloy from many of its operating stations. The following table lists reactors with Inconel 690 steam generators in France:

Station	Unit(s)
Bugey	3 and 4
Chooz B	1 and 2
Civaux	1 and 2
Dampierre	1, 2 and 3
Fessenheim	1
Golfech	2
Gravelines	1, 2 and 4

Station	Unit(s)
Penly	2
St. Laurent B	1 and 2
Tricastin	1, 2, 3 and 4

Table 11: French PWRs with Inconel 690 Steam Generator Tubing

659 This may be associated with the surface treatment of the SG tubes used more recently, although other factors may contribute. Conditioning of the SG tubes is discussed further in Section 4.2.12.

660 In general the evidence supplied in RO-UKEPR-46.A2 (Ref. 161) supports the EDF and AREVA approach. The main differences in the evidence tend to centre on the duration and precise concentrations of the procedure (for example, the lithium hydroxide and hydrogen concentrations and the time pre-oxidation is allowed to take), however the fundamental process of hot reducing alkaline pre-oxidation appears well supported and suggests substantial reduction in Corrosion Product (CP) and dose rates are possible. As per the Step 4 assessment objectives, the precise definition of these values were not considered during GDA, however, EDF and AREVA present well reasoned arguments for the expected values and I particularly welcome the addition of hydrogen (as opposed to a reliance on the residual (variable) hydrogen generated by oxidation) and expect this to offer further reward. The exact procedures to be developed for passivation of the surfaces in UK EPR have not yet been completely decided.

661 In addition, those aspects which were still under consideration during Step 3 were discussed further in the response to RO-UKEPR-46.A2 (Ref. 161).

662 The application of a forced acidification step with boric acid, followed by a controlled oxidation during cool down to remove labile outer oxide deposited material are now recognised steps in the EDF and AREVA approach. Removal of the outer layer oxides is an important step before later commissioning stages, which require boric acid addition due to the introduction of fuel. I welcome these additions and believe that an adequate case has been made for their implementation based upon the current knowledge of HFT processes.

663 TQ-EPR-1234 (Ref. 8) asked a number of queries on the response to RO-UKEPR-46.A2. The response to this TQ was satisfactory for answering those relevant to HFT and provided further reassurance of the validity of the EDF and AREVA proposals for UK EPR.

664 EDF and AREVA have specified a primary circuit chemistry for UK EPR which includes the addition of zinc for radiation field control. Primary circuit chemistry and zinc addition are discussed in Section 4.2.6. In the context of HFT the addition of zinc during the process is a recently suggested step (Ref. 148) but is not supported by significant plant experience; for example data from Angra 2 is available but this plant commissioned with zinc after HFT, at first criticality. Results from Angra 2 are encouraging in this respect, with dose rates reported as significantly lower than comparable plants which did not use zinc. Details of this are reported in the EDF and AREVA response (Ref. 154) to RO-UKEPR-45.A2 (Ref. 9). Data from Tomari-3, a reactor in Japan that was commissioned with zinc in 2010, is not yet available.

665 In principle the application of zinc during HFT appears a reasonable addition as the action of zinc primarily affects the inner oxide layer, which is precisely where HFT is aiming to have the greatest effect. However, careful consideration would be required as it is not apparent how much zinc would be needed to fully saturate the RCS surfaces and this may require much higher concentration than during normal operation or greatly increased duration to offer significant benefit. This may also influence complementary procedures such as purification or sampling. EDF and AREVA do not address the possibility of zinc addition during HFT, but have indicated that consideration is being given to this approach. I am content that the justification of whether or not to use zinc during HFT is an aspect that can be addressed during a later stage. I consider this to be an Assessment Finding (**AF-UKEPR-RC-20**).

666 In a similar vain, EDF and AREVA are still considering the possibility of using natural boron during commissioning, instead of EBA. While this has no direct consequence for the HFT process itself, all natural boron must be effectively removed from the plant before operation with nuclear fuel to mitigate any possibility of inadvertent boron dilution. This would be part of Assessment Findings **AF-UKEPR-RC-04**, described in Section 4.2.2, and **AF-UKEPR-RC-21**, described later in this section.

667 EDF and AREVA recognise the importance of purification during HFT. Maximisation of the coolant clean-up rate will influence the benefits gained from any HFT process. The UK EPR approach will use the main CVCS demineralisers operating at maximum throughput of 72 t hr^{-1} for the periods of pre-oxidation and de-lithiation prior to acidification. The capability of the CVCS systems in UK EPR is assessed in Section 4.2.2 and was outside the scope for this assessment area. Even so, recognition of the need to maximise purification is encouraging.

668 A number of support systems will be required during HFT, such as the NSS and CVCS. Capability and availability of these systems was not considered as part of the GDA assessment, and can only be undertaken once fully developed HFT procedures are available, however as the suggested levels fall within the normal operating ranges for these systems no concerns are expected in this area provided availability can be assured. Sampling during HFT may prove an important step and it may be that analysis of chemistry during these periods could be used as a ‘hold point’ and as an indicator of HFT progress. Consideration of this type of control should be justified and included in a fully developed HFT procedure specific to UK EPR. This is related to Assessment Finding **AF-UKEPR-RC-21**.

669 I support development and implementation of a UK EPR HFT process, based upon the fundamental steps outlined by EDF and AREVA for UK EPR. Post GDA a fully developed HFT procedure should be developed for UK EPR, building upon the evidence presented for GDA, including further knowledge and experience particularly from other EPR units commissioned prior to any UK new build. I consider this to be an Assessment Finding **AF-UKEPR-RC-21**.

4.2.12.1 Summary

670 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit HFT assessment are:

- EDF and AREVA have presented a proposed HFT approach for UK EPR, based upon laboratory tests and operational experience and including specifics for UK EPR.
- The approach suggested appears reasonable and consistent with the current state of the art knowledge in this developing area.

- Post GDA, a fully detailed HFT procedure should be developed, building upon the sound basis presented for GDA. I have raised an Assessment Finding in this area which should support on-going assessment of this important topic.

671 Overall, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.2.12.2 Assessment Findings

672 Based upon the assessment of hot functional test chemistry in UK EPR described in Section 4.2.12 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-20*** *– The Licensee shall review whether to add zinc or not during Hot Functional Testing and generate evidence to justify this decision. This Assessment Finding should be completed before HFT procedures are applied to the reactor. Target milestone – Hot Ops.*
>
> ***AF-UKEPR-RC-21*** *– The Licensee shall specify suitable procedures for Hot Functional Testing (HFT), building upon the evidence presented for GDA and including further knowledge and experience particularly from other EPR units commissioned prior to any UK new build. The documentation should justify the controls during HFT of UK EPR, particularly related to hold points, chemistry measurements and target levels. This Assessment Finding should be completed before inactive commissioning activities commence. Target Milestone – Mechanical and Electrical safety system installation complete / commissioning start.*

4.2.12.3 GDA Issues

673 Based upon the assessment of hot functional test chemistry in UK EPR described in Section 4.2.12 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.3 Spent Fuel Pool

674 Operation of any PWR generates a quantity of used fuel during each operating cycle. Fuel discharged from the reactor is transferred to an at-reactor Spent Fuel Pool (SFP) where decay heat is removed and the used fuel is stored. It should be noted that EDF and AREVA claim that UK EPR is an efficient reactor design and should be more efficient at fuel usage than comparable plants. Significant quantities of fuel now reside in wet pool storage throughout the world and the experience in wet storing spent nuclear fuel now spans over 40 years. The benefits provided by this approach are mainly associated with cooling efficiency and shielding and it has been shown that the rates of fuel damage are very low, provided the pool chemistry and temperature is adequately controlled.

675 During Step 3, I started my assessment of the UK EPR SFP and associated systems, mainly concentrating on the chemistry control of the systems and how provisions have been made in the designs to accommodate these requirements. For Reactor Chemistry purposes I consider the fuel pool systems to include the following generic areas and their associated activities and / or equipment:

- Spent Fuel Pool (SFP)

- Transfer facilities between the SFP and the reactor building
- Refuelling cavity
- Ancillaries, such as the IRWST, RHRS, etc. (where not considered elsewhere in the assessment)

676 Overall, I was content with the fundamental design of the SFP cooling and clean-up systems in UK EPR, which are very similar to those currently in use at other PWRs. I noted several positive features in the design which should be beneficial to control of the SFP chemistry. Assessment during Step 4 has concentrated on chemistry control and source terms in the SFP, especially during refuelling activities.

4.3.1 Overview

677 The Spent Fuel Pool (SFP) holds the irradiated fuel while the short-lived high activity fission products decay. The pool consists of a large volume borated water filled tank containing a racking system which is used to accommodate the discharged fuel assemblies. The water in the pool acts as both a personnel dose shield and a cooling medium for the fuel. The cooling system maintains the SFP water at a steady low temperature while the associated clean-up system maintains the activity within the SFP at low levels.

678 EDF and AREVA presented an overview of the UK EPR fuel route and systems to ND in November 2009. Information is provided in the PCSR (Ref. 11, Section 9.1.6). The UK EPR SFP is located within the fuel building and is a determining factor in the design of the reactor building and the fuel building. EDF and AREVA consider the fuel building and reactor building pools as two separate areas:

- This fuel building pool is made up of 3 compartments. The spent fuel pool (SFP), in the centre, is dedicated to the storage of spent fuel whilst its heat decays, as well as some new fuel elements before they are loaded into the core. It is permanently full of borated water, cooled and purified in normal operations. The spent fuel pool is isolated from each of the 2 adjacent compartments by a door and a penstock. The fuel building transfer compartment, between the SFP and the transfer tube, contains the transfer system that enables the fuel assemblies to be moved between the SFP and the reactor pool. The fuel building transfer compartment is not always filled with water, as it is filled alternately with the loading pit; they have the same volume, allowing water to be moved according to requirements. The loading pit, on the side opposite the transfer compartment, is used for loading fuel assemblies into a cask for removal.
- This Reactor pool has 4 compartments. The reactor pit is situated above the RPV and forms a single water volume with the RCS. The set-down compartment for internals is where the upper and lower core internals are stored during refuelling operations. The instrumentation lance compartment is where the instrumentation lances and level measurement probes removed from the core are stored during refuelling. The reactor building transfer compartment is used to transfer fuel to or receive fuel from the fuel building pools. With the exception of the instrumentation lance compartment, which is permanently full, the water source for the remaining reactor building pools is the IRWST. The compartments can be isolated from each other by penstocks.

679 The arrangement of the reactor and spent fuel pools is shown below (Ref. 56):

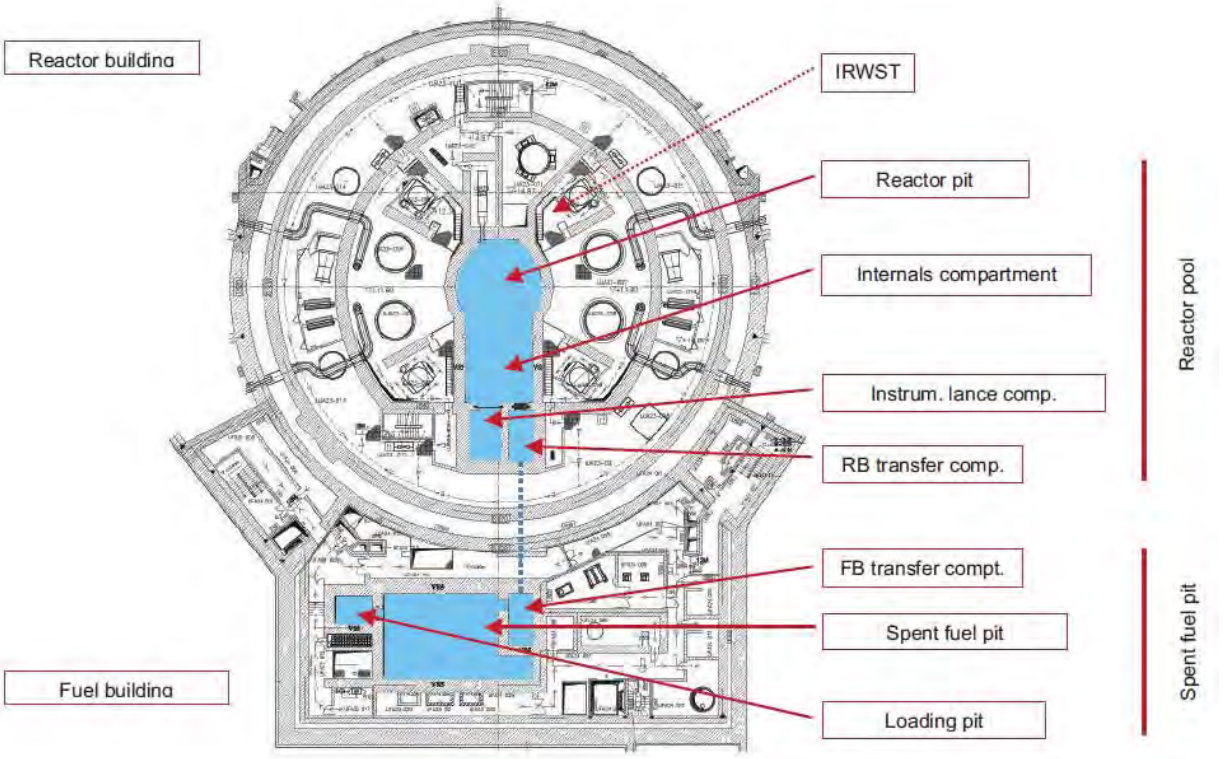


Figure 17: UK EPR Reactor and Spent Fuel Pools

680 The pool liner consists of metal panels welded onto anchors sealed into the concrete walls of the pools. The watertight liner is made of metal panels of austenitic stainless steel sheets free of molybdenum and with a cobalt content of less than 0.2%. Its minimum thickness is 4 mm for the vertical sheets and 6 mm for the bottom of the pools (Ref. 55).

4.3.2 Assessment – Chemical Control, Purification and Source Terms

4.3.2.1 Cooling and Purification Systems

681 In UK EPR the systems for cooling and purifying the SFP water are combined as a single system, the Fuel Pool Cooling System / Fuel Pool Purification System (FPCS / FPPS). Details of the systems are given in Section 9.1.3 of the PCSR (Ref. 11) and the SDM (Ref. 56). The SDM (Ref. 56) provides details on operation of the system when performing its various functions and duties. The overall arrangement of the SFP cooling and purification system is shown in the figure below, with purification loop in red and cooling in blue. Note the third cooling chain is not shown, but is similar to the two that are shown:

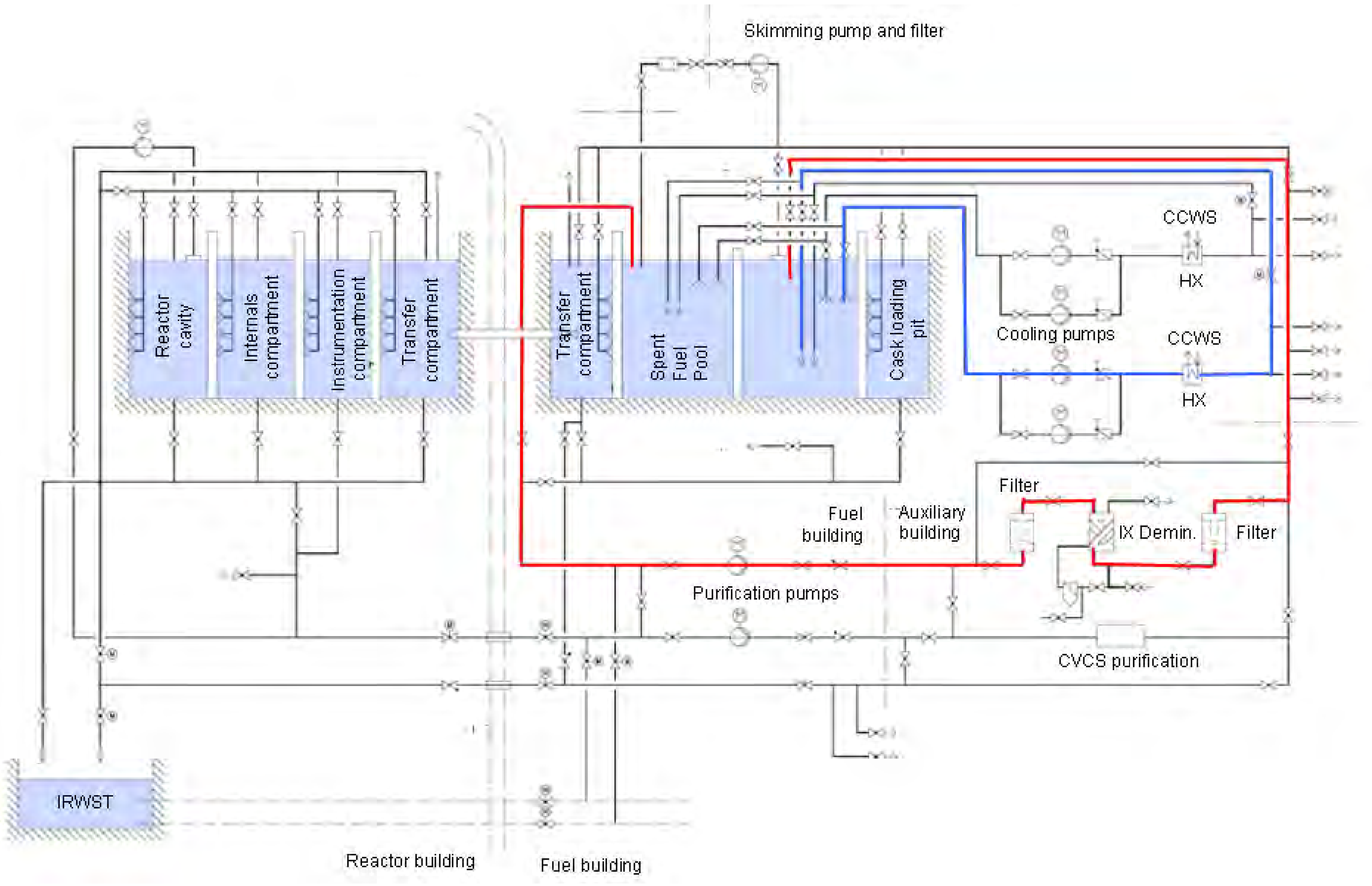


Figure 18:UK EPR Reactor and Spent Fuel Pool Cooling and Purification Systems

4.3.2.1.1 Spent Fuel Pool Cooling System

682 The FPCS is responsible for cooling the SFP. The FPCS extracts water from and returns water to the spent fuel pool and consists of two identical main trains which are independent of one another. Each train consists of two pumps and a heat exchanger (cooled by CCWS). The pool water cooling system also has a third train that provides backup in the event of loss of the two main trains, consisting of a single pump and a heat exchanger, cooled by the Containment Heat Removal System (CHRS). The main pumps and exchangers of the FPCS / FPPS are located in the fuel building. Each cooling train has a connection to the NSS system for sampling water from the SFP in order to monitor its chemistry and radiochemistry.

683 The FPCS design is such that a total loss of cooling is extremely unlikely, however the systems is designed to restart after a boiling event.

684 The addition of a third independent cooling train means that substantially more cooling of the SFP is possible when the decay power of the fuel in the pool is low (e.g. at the end of the fuel cycle). It is conceivable that the water temperature could be lowered to such an extent that soluble boron could precipitate, although this would require temperatures much lower than normal operating conditions and is more likely in the water exiting the heat exchanger rather than the bulk pool due to locally lower temperatures. EDF and AREVA are still considering this effect and may include design changes to mitigate this

risk. This affect needs to be considered in the UK EPR safety case, if appropriate. I consider this to be an Assessment Finding (**AF-UKEPR-RC-22**).

4.3.2.1.2 Spent Fuel Pool Purification System

685 The purification systems for the UK EPR SFP are actually a mixture of existing systems (or sub-systems) and new components. In totality the system performs water transfers / make-up and pool skimming in addition to purification. The FPPS is used to:

- Purify the pools in the reactor building and fuel building and the IRWST.
- Skim the spent fuel pool and reactor pool (two independent systems).
- Fill and empty the fuel building transfer compartment, loading pit, reactor building pool and the IRWST.
- Supply make up water (via RBWMS (borated) or the nuclear island “demineralised water” distribution system (SED).
- Take samples for chemical or radiochemical analysis (via NSS).

686 The FPPS includes two purification pumps that operate in parallel. One pump is generally used for fuel building pool purification and the other pump for reactor building pool purification. Headers are provided upstream and downstream of the purification pumps that allow for the alignment of each pump to either building. There are two purification paths, one is part of the FPPS and the other path utilises the CVCS purification systems (see Section 4.2.2.3).

687 The FPPS purification chain consists of:

- Two front end filters in series, for removing mechanical impurities
- A demineraliser filled with mixed bed resins, for trapping ions
- One back end resin filter, used to trap resins if the strainer inside the demineraliser unit fails

688 The CVCS purification system is assessed in Section 4.2.2.3, so is not discussed in detail here. However, based upon the assessment conducted there is no reason to suggest that this is unreasonable and the CVCS should be adequate to purify the reactor building pools during refuelling.

689 The FPPS is used for the fuel building pools and the reactor building pools when the reactor is at power. The CVCS connection is only used during shutdowns. Either can be used for purification of the IRWST, depending upon the state of the plant and systems. Due to the water chemistry the entire FPPS is made from stainless steel.

690 The FPPS also includes two independent skimming systems, one for the reactor building and one for the fuel building. Both systems consist of a pump and mechanical filter which connect to a suction device.

691 This design of the FPPS is functionally very similar to those currently in use at other PWRs.

692 The IRWST is discussed in Section 4.2.8, so is not assessed here.

4.3.2.2 Operational Chemistry

693 EDF and AREVA propose chemical specifications for the SFP water, such to:

- limit the corrosion risk of fuel cladding (both new and used fuel)
- limit the corrosion risk of the SFP materials
- limit the risk of chemical pollution of the primary circuit

694 This results in limits for boron (both ^{10}B enrichment and total boron), aggressive anions (such as chloride), sodium and zeolite forming elements. These are controlled by sampling of the SFP water using the NSS connections. Despite these concerns and requirements, the Step 4 PCSR (Ref. 11) contained no reference to the expected SFP chemistry for UK EPR. I consider this to be an Assessment Finding (**AF-UKEPR-RC-23**). The Chemistry Chapter in the consolidated PCSR (Ref. 103) identifies most of these requirements but not specifically for the SFP.

695 Water losses and transfers from the various pools require provisions for make-up, both of demineralised water and borated water of the correct enrichment, concentration and purity. Demineralised water is sourced from the Nuclear Island Demineralised Water Distribution system (SED) and borated water is supplied from the Reactor Boron and Water Make-up System (RBWMS), which is assessed in Section 4.2.2. The principal water requirements are:

- Compensation for losses during transfers, for the fuel building transfer compartment, the loading pit or the IRWST; RBWMS
- Compensation for losses due to evaporation; SED
- Compensation for losses of borated water from the SFP; IRWST

696 An important characteristic of the SFP water is that it is part of the reactivity control provisions in the pools during fuel movements and for the reactor pools during refuelling activities. The criticality control aspects of the UK EPR safety case are assessed elsewhere (Ref. 57), as are the potential SFP faults (Ref. 58). However, an important point from a chemistry perspective is that the soluble boron present in the UK EPR SFP is not claimed as being required by EDF and AREVA to maintain sub-criticality for fuel stored correctly in the racks. However it is necessary during refuelling activities to maintain sub-criticality in interim storage accident configurations (for example, an assembly lying on the top of a rack or positioned between the rack and the pool wall). This is common to most SFPs, including in the UK. Due to the connection between the SFP with the reactor vessel (and hence core) during refuelling the soluble boron must be of sufficient concentration to prevent dilution.

697 The spent fuel pool storage racks within the UK EPR SFP utilise borated stainless steel as the neutron absorber material inside a structural framework of stainless steel. This material has been successfully used in such applications for many years, although not extensively in the UK. Historically a number of chemistry problems have been associated with degradation of neutron absorbers within the SFP environment where they can be subjected to intense levels of gamma radiation, releasing large quantities of silica to the SFP water or experiencing corrosion damage that threatened the neutron attenuation properties of the material. A stainless steel base material removes these concerns in UK EPR and minimises the requirements for condition monitoring of the SFP racks, provided adequate temperature and chemistry control is maintained.

698 Although UK EPR uses borated stainless steel for the SFP rack neutron absorbers, EDF and AREVA still specify a silica limit for the SFP water. Silica is difficult to remove by ion exchange processes and would require discharge and make-up if the SFP became contaminated. This requirement is mainly related to the use of zinc in the primary coolant, with high levels resulting in a delay before zinc injection can be initiated. Further design

features in UK EPR, such as stainless steel filters and improved make-up water systems should mean that this limit is rarely approached.

699 The other materials used in the SFP systems should not experience significant degradation, provided the SFP chemistry and cooling are well controlled.

700 TQ-EPR-1235 (Ref. 8) queried the effect of Enriched Boric Acid (EBA) use on the SFP and IRWST concentrations during a cycle. EDF and AREVA claim no depletion of EBA in the SFP during a cycle, due to the low neutron irradiation. Should the enrichment change due to mixing with RCS coolant of lower enrichment (which should be precluded by administrative procedures) this is restored by addition of higher enrichment EBA using the RBWMS. The same process is used for the IRWST.

4.3.2.3 Control of Radioactivity

701 An important function of the FPPS is to minimise the activity within the spent fuel pools and connected systems, influencing both ORE and wastes. The SFP systems will become contaminated with activity either due to water transfers or mixing with other water sources, especially during refuelling, or from activity released into the pool water from stored used fuel. The former will be a quick process leading to spikes in activity, while the latter is expected to be a much more gradual process.

702 An important input to minimising ORE and wastes during refuelling operations is the shutdown chemistry, which is discussed in Section 4.2.11.

703 Irrespective of this, during refuelling a large amount of radioactivity is transported and relocated around the various plant systems. Surface finish and design provisions can have an important impact on the retention of activity in areas where radioactive species have the potential to be accumulated. TQ-EPR-1403 (Ref. 8) was raised to clarify these aspects for the UK EPR design. The response indicated that the stainless steel in the UK EPR SFP systems will be finished to EN 10088-2, with a slightly rougher surface finish allowed on the SFP base. This standard does not specify a particular surface roughness and as such some variability can exist. While this seems appropriate for the SFP and other pools permanently filled with water, consideration should be given to specifying a surface finish for those pools which are routinely filled and drained in order to reduce ORE. Consideration should also be given to the surface finish of the SFP wall which is subject to level oscillations. I consider this to be an Assessment Finding **AF-UKEPR-RC-24**.

704 Much of the emphasis on ensuring activity remaining on pool walls and floors following draining is based on the claimed efficiency of the pool purification systems, skimmers and with manual wash downs. During draining and wash downs active particles held-up on the walls and floors are washed down to the compartment filters. This restricts transfer of activity back to the IRWST or purification and cooling systems, although does create active filters for disposal.

705 Based upon OEF the FPPS flowrates are set such that the full contents of the SFP or reactor pit can be treated at least once every 24 hours. This is claimed to minimise ORE and maximise pool clarity. The provision of dedicated skimming facilities for the pools in both the reactor and fuel buildings will help to minimise dose rates, both during refuelling operations and during clean-up operations. The skimmers contain 1 μm filters which trap active particulate from the pools.

706 In the response (Ref. 59) to RO-UKEPR-73 (Ref. 9) EDF and AREVA provided estimates for the radioactivity within the reactor building and IRWST pools. The activity in these

pools are different from other systems in the reactor in that they generally receive an increase in activity when connected to the RCS (i.e. they do not have a permanent source), but this additional activity is gradually removed during the cycle both by natural decay and purification by the FPPS. This process is very dependant upon operational procedures which determine the timing of the various shutdown steps and the movement of coolant between the various systems, so any estimation is clearly very dependant on the assumptions used. It is apparent that the outage schedule used is very similar to that described in Section 4.2.11 and the estimation features a number of assumptions which should lead to conservative activity estimates, such as reduced purification rates and minimised mixing of water volumes when only limited mixing is expected.

707 The main control that can be applied to limit activity transfer to the SFP is to minimise the activity in the RCS coolant volume before connecting to the SFP. This is commonly achieved through head lift criteria, which are primarily for ORE concerns during refuelling. TQ-EPR-159 (Ref. 8) provided some information on the likely head lift criteria to be applied in UK EPR. As for all limits and conditions these were given as indicative values, to be confirmed by the Licensee, however they did indicate controls on both ^{133}Xe and ^{131}I at various stages of the shutdown (before power reduction, before RCS oxygenation, before last RCP stop and before RPV head lift). These were consistent with the values given in the RO-UKEPR-73 response (Ref. 59, which provides activity levels for FA3) providing comfort that these limits are reasonable and can generally be met when using the "*realistic*" source terms. They are often exceeded when compared to either the "*shielding*" (DPB) or "*effluent*" (DSE) source terms. This arises because the DBP and DSE sources can be more onerous in terms of the effect of some nuclides, which then may translate back to tighter controls, as illustrated in the following paragraphs. This confirms the requirements for the control and the values for these limits should be reviewed at a later stage, when available. This is related to Assessment Finding **AF-UKEPR-RC-02**.

708 The response to RO-UKEPR-73 (Ref. 59) also provides estimates for the IRWST activity, both immediately following refuelling and after 12 months, which is the minimum period between outages considered. The response indicates that the major activity in both cases is associated with the long lived nuclides (corrosion products, caesium isotopes, ^{14}C and tritium) with tritium dominating. The response recognises the need to discharge tritium during the fuel cycle in order to avoid a build-up within the plant; the most penalising case with 100% recycling is calculated to result in a concentration of 28,000 MBq t^{-1} during the outage. Consideration is also given to contamination of the IRWST with a volume of heavily contaminated RHRS coolant.

709 Tritium during shutdowns is discussed in Section 4.2.11, under primary circuit shutdown chemistry. This highlighted the need for tritium controls during a shutdown and discharge of tritiated waste during the cycle. As discussed earlier, EDF and AREVA propose no specific controls for tritium in the RCS during a shutdown, using the SFP activity as the control. This is reflected in the UK EPR source terms (Ref. 60) which suggests a limit value for tritium of 15,000 MBq t^{-1} in the RCS and state that for tritium; "*Since tritium is not involved in the assessment of radiological protection requirements (β emitter), a single envelope value has been set at 37,000 MBq t^{-1}.*" While much higher than the values expected in UK EPR, as suggested in the response to RO-UKEPR-74.A1 (Ref. 34), this means that the estimations provided in RO-UKEPR-73 (Ref. 59) do not reflect the expected concentrations of tritium in the SFP systems and pools. In fact all the sources are taken as being equal to 37,000 MBq t^{-1} at all times. This is reasonable from a direct radiation source viewpoint but neglects both ORE from skin absorption/inhalation and

potential gaseous waste discharges, all of which must be considered elsewhere in the safety case.

710 The second part of the RO-UKEPR-74.A1 response (Ref. 106) however, proposes that "*a preliminary target value for UK EPR of 3,000 MBq t^{-1} for tritium concentration in the Fuel Building Pool and the IRWST pool. Complementary studies are currently in progress to properly assess the different tritium activity limits that should be set in the Fuel Building pool, in the IRWST pool and in the RCS prior to head lift.*" The implications for this on start-up and shutdown chemistry, especially head-lift criteria, are assessed in Section 4.2.11. For the control of radioactivity in the SFP and IRWST this is a positive step proposed by EDF and AREVA and should be beneficial for UK EPR. The 3,000 MBq t^{-1} value proposed is at the lower end of operational experience with SFP tritium activities. The final part of the RO-UKEPR-74.A1 response (Ref. 107) does not consider transfers of tritium to the SFP or IRWST, so does not provide quantitative evidence that such a control or limit is practicable. In this respect the response was inadequate. While I am content that such calculations are possible, and on the basis of the evidence presented to date should not reveal any significant problems, they will be required as part of the evidence supporting the safety case. I consider this to be an Assessment Finding (**AF-UKEPR-RC-25**).

711 Overall, I consider that a reasonable case has been made by EDF and AREVA to demonstrate that tritium control in the UK EPR SFP may be possible; however this is heavily dependant upon tritium controls in the RCS, particularly during shutdowns. This is related to Assessment Finding **AF-UKEPR-RC-02**. Fundamentally this nuclide can be controlled in the SFP and IRWST by discharge and make-up, within acceptable limits. The operation of the boron recycle system therefore become important to minimise accumulation of tritium in the plant, but the "rules" described by EDF and AREVA in the response to RO-UKEPR-74.A1 (Ref. 106), if adequately applied, should minimise this effect. The suggestion of an "*expected value*" and the potential for a limit on tritium in the UK EPR is a positive step by EDF and AREVA. However, I consider that a limit or condition for tritium activity in the SFP, and potentially in the IRWST, is required for UK EPR, both to limit ORE during refuelling activities but also to ensure that BAT and ALARP criteria are demonstrated. I consider this to be an Assessment Finding (**AF-UKEPR-RC-25**).

712 While tritium is unique in not being removed by the FPPS, for the purpose of the estimations for other nuclides in the response (Ref. 59) to RO-UKEPR-73.A1 (Ref. 9), EDF and AREVA assume the FPPS influent concentration is equal to the respective pool concentration, while the outlet is abated by the relevant factor for the demineralisers. The FPPS demineraliser decontamination factors are taken as being equal to the CVCS. This may not be true given the different behaviour of some radionuclides under outage chemical conditions, however the values used are conservative so should account for any changes.

713 RO-UKEPR-74.A2 (Ref. 9) requested evidence that the UK EPR design could adequately control fuel crud throughout the nuclear island systems. Similarly RO-UKEPR-74.A3 (Ref. 9) requested evidence for the control of other radioactive materials throughout the nuclear island. EDF and AREVA chose to combine the response to these actions. At the time of preparing this report, EDF and AREVA had not completed their response to these ROAs, having provided only the first half of a three part response (i.e. two reports out of four).

714 The first part of the response (Ref. 111) is an overview document providing information on how EDF and AREVA have approached the management of activity in UK EPR. Various steps are described including identification, quantification and characterisation of

the source terms, followed by analysis of the performance of the various UK EPR treatment systems. Much of the information is linked to other previously supplied documentation, particularly the responses (Refs 59, 60 and 34) to RO-UKEPR-73 and 74.A1 (Ref. 9). The responses introduces a number of codes and models which have not previously been presented by EDF and AREVA during the Reactor Chemistry assessment, including the Thermal Hydraulic Code (THYC), COCCINEL, DARWIN and CHESS (Ref. 111). As an overview the response is reasonable, providing a degree of confidence that EDF and AREVA have taken a logical and methodical approach to management of the source terms in UK EPR and hence the transfer of activity around the nuclear island systems. However, it does not provide any quantified concentrations or activities, which are expected as part of the latter deliverables under these ROAs.

715 The second part of the response (Ref. 112) provides the EDF and AREVA estimates for fuel crud in UK EPR. This report has been discussed previously, in Sections 4.2.3 and 4.2.5, and provides a bounding estimate for fuel crud production in UK EPR. This analysis is an input to the fuel crud radioactivity likely to be transported to the SFP during refuelling activities.

716 The remaining parts of this ROA response, titled as “*Analysis of UK EPR source term: identification, quantification and characterisation*” and “*Activity management at UK EPR: system performances and control actions*” (in Ref. 111) have not yet been provided. It is these reports which will contain the evidence to support the claim that radioactivity in the UK EPR SFP and IRWST can be adequately managed. Despite these responses not being delivered or assessed, based on the balance of other evidence as presented (mainly from other ROA responses and examining the UK EPR purification systems for the SFP, as outlined in Section 4.5.1.3), I do not consider there should be any fundamental problems with controlling activity in the UK EPR Nuclear Island systems provided a suitable operating and shutdown chemistry regime is defined and maintained and appropriate limits and conditions are enforced by the Licensee. However, such estimates are needed as part of the safety case.

717 Overall, EDF and AREVA have not yet made an adequate and complete case to support the claim that radioactivity can be controlled in the Nuclear Island systems in UK EPR. I am content this could be done, but has not been completed in the Step 4 assessment timescale. I consider this to be a GDA Issue, **GI-UKEPR-RC-02**.

4.3.2.4 Fuel Discharge

718 Once stored for a sufficient period to remove adequate decay heat, EDF and AREVA propose to export used fuel from the SFP dry. It is possible that this fuel may be transferred to a further water cooled storage pond, before long term disposal. TQ-EPR-689 (Ref. 8) was raised to understand the consequences of this process on the fuel, in particular the effect of drying then re-wetting the fuel. The response provided OEF from EDF and AREVA of similar activities carried out in French PWRs over the past 30 years. The risk posed by this operation appears to be small, if adequate controls are in place, which appears to be the case in EDF plants. As many of these controls are administrative and Licensee dependant little information is provided in the response, however as the design of UK EPR follows the same practice there appears no reason to doubt why these cannot be successfully implemented. I consider this to be an Assessment Finding **AF-UKEPR-RC-26.**

4.3.2.5 Summary

719 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of Spent Fuel Pool chemistry in UK EPR are:

- The UK EPR Spent Fuel Pool systems are functionally very similar to current PWRs and the design and material choices are consistent. EDF and AREVA have described the spent fuel pool operational chemistry, mostly in responses and documents outside of the Step 4 PCSR. The chemical requirements for such systems are well known and UK EPR has systems for monitoring, controlling and purifying the pool water which can be considered adequate.
- The control of radioactivity within the large volume spent fuel pool is important from an ORE, waste and discharge perspective. UK EPR should be at least as capable as current PWRs in controlling the activity in the pool, and may be better due to larger, more efficient treatment systems. On the basis of the evidence that was presented, I am content that detailed supporting evidence can be provided during Licensing and the present gaps do not represent a significant unrevealed hazard to the safe operation of the plant for GDA. I have highlighted a number of findings and an Issue in this area where further justification and evidence is still required.
- I consider that limits or conditions will be required on tritium in the UK EPR Spent Fuel Pool, and potentially the IRWST.

720 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.3.2.6 Assessment Findings

721 Based upon the assessment of Spent Fuel Pool chemistry in UK EPR described in Section 4.3.2 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-22*** *– The Licensee shall consider the risks posed by accidental over-cooling of the UK EPR Spent Fuel Pool (SFP). The consequences of this should be documented and recognised in the safety case. Reasonably practicable design changes to mitigate this effect should be considered, if appropriate. This Assessment Finding should be completed before operation of the SFP systems. Target milestone – Cold Ops.*
>
> ***AF-UKEPR-RC-23*** *– The Licensee shall include the safety aspects of the Spent Fuel Pool (SFP) operating chemistry in the safety case. This Assessment Finding should be completed before operation of the SFP systems. Target milestone – Cold Ops.*
>
> ***AF-UKEPR-RC-24*** *– The Licensee shall review the surface finish to be applied to areas of the Spent Fuel Pool (SFP) subject to level oscillations and generate evidence for the suitability of the surface finish chosen. This Assessment Finding should be completed before fuel is delivered to site, but may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Fuel on-site.*
>
> ***AF-UKEPR-RC-25*** *– The Licensee shall specify the acceptable level for tritium in the Spent Fuel Pool and connected systems, including the IRWST. This should include evidence that operator radiation exposure and discharges have been*

considered. This Assessment Finding should be completed before nuclear operations, as this is when tritium will first be generated. Target Milestone – Initial criticality.

AF-UKEPR-RC-26 *– The Licensee shall develop the controls required to ensure that spent fuel can be successfully exported from the UK EPR fuel pool following storage. This Assessment Finding should be completed before nuclear operations, as prior to this the fuel export facilities will not be needed. Target Milestone – Initial criticality.*

4.3.2.7 GDA Issues

722 Based upon the assessment of fuel pool chemistry in UK EPR described in Section 4.3.2 above, I have identified no additional GDA Issues which requires resolution, however this area is strongly linked to the GDA Issue on ex-core radiation described in Section 4.2.5, **GI-UKEPR-RC-02**.

4.4 Secondary Circuit

723 The secondary circuit is actually a collection of individual systems that together form a loop (under normal conditions) for the transfer of thermal energy from the primary circuit to useful kinetic energy for the generation of electricity. All secondary circuits (be they nuclear or conventional plant) function in the same basic manner, namely, converting water to steam in a boiler to drive a turbine, the exhaust from which is then condensed and returned to the boiler where the process is repeated.

724 The design of all of the secondary circuit systems must account for the operations required during start-up, normal operation (including power changes), shutdown, refuelling and during postulated accident scenarios. Each of these systems can act at various times, some of the systems operate continuously, others intermittently, some operate only during accident scenarios while some operate in parallel to others.

725 Assessment of the secondary circuit started in Step 3, but was hindered due to the lack of information presented in the PCSR and supporting documents. A number of areas were further assessed during Step 4.

726 A further complication in the assessment of the UK EPR secondary circuit is the close tie between many of the secondary circuit systems and the site specifics. EDF and AREVA initially stated that the secondary circuit as a whole was outside of the GDA scope for UK EPR; I did not agree with this position and felt that this was significant departure from our requirements and expectations for GDA. Following discussions EDF and AREVA agreed to include a number of secondary circuit systems within the GDA scope. The following table lists the secondary circuit systems within the scope of GDA:

UK EPR Abbreviation	Description
SSS	Start-up and Shutdown Feedwater System
SGBS	Steam Generator Blowdown System
MFWS	Main Feedwater System
EFWS	Emergency Feedwater System
ATD	Start-up Condensate and Feedwater Purification Plant

UK EPR Abbreviation	Description
CEX	Condenser and Condenser Extraction System
CVI	Condenser Vacuum System
CRF	Circulating Water System
MSB	Main Steam By-pass System
RES	Steam Generator Secondary Sampling System
SIR	Chemical Reagent Injection System
SIT	Feedwater Sampling System
SRI	Conventional Island Closed Cooling Water System
MSRT	Main Steam Relief Train
MSSS	Main Steam Supply System

Table 12: UK EPR Secondary Circuit Systems Included in GDA Scope

727 The assessment of secondary circuit chemistry during GDA has sampled a number of interrelated areas which, when taken as a whole, cover a selection of the main chemistry related safety concerns in the secondary circuit. In line with the other assessment areas for Reactor Chemistry in GDA, the approach was to identify the current EDF and AREVA approach and expectations for secondary circuit chemistry in UK EPR. Implicit in this is a determination that the plant can safely support the anticipated chemistry. The areas sampled were:

- Materials, Design and Chemistry
- Materials Integrity and Corrosion
- Sampling Systems
- Start-up and Shutdown Chemistry

Each of these is discussed in detail in the following sections.

4.4.1 Secondary Circuit Overview

728 As the Secondary circuit is a complex arrangement of many systems, a brief discussion of the UK EPR design is given below. A number of the main systems described were subject to more detailed assessment and these are described in more detail in the subsequent sections.

729 The interfaces between the primary and secondary systems are the SGs. Chemically conditioned feedwater is fed to the SGs. A small flow of coolant (<1% of the SG steam output) is extracted by the Steam Generator Blowdown System (SGBD). The SGBS purifies the extracted coolant and returns this to the bulk condenser supply, thus controlling coolant impurity levels. The bulk coolant in the SG is heated to saturation temperature (293°C) by heat transfer from the primary circuit. The resultant two-phase steam flow passes up the steam generator and is dried by the moisture separators and dryers in the top of the steam generator. The dried steam at saturation temperature exits

the steam generator at around 78 bar and passes to the turbine, where it transfers energy to the turbine.

730 The UK EPR also features dedicated Start-up and Shutdown Feedwater System (SSS) and Emergency Feedwater System (EFWS) which supply feedwater to the SGs under certain conditions when the main secondary circuit supply is unavailable. The SSS is assessed in Section 4.2.3.

731 As the temperature and pressure of the steam falls, two-phase flow (steam-water) conditions result within the High Pressure (HP) turbine. As in all PWRs, the formation of wet steam conditions within the HP turbine makes all pipework and components that receive wet steam from the turbine potentially susceptible to corrosion, including Flow Accelerated Corrosion (FAC). Many lines and drains are taken from the turbine to provide steam for feed heating and other purposes, and are exposed to high velocity two-phase flow conditions which again make these systems potentially susceptible to corrosion. Steam from the HP turbine exhaust is dried and reheated in the Moisture Separator Re-heaters (MSRs). While this provides dry steam to the Medium and Low Pressure (MP and LP) turbines the MSRs themselves operate under wet steam conditions and so are again potentially vulnerable to damage. The use of a separate medium pressure turbine stage is not common in PWRs and may introduce additional requirements. Steam from the MP turbine passes on into the LP turbine and low temperature wet steam conditions develop at some stage within the LP turbine, which can lead to a risk of droplet erosion of the turbine blades, and condenser tubes, if the latter are not adequately protected.

732 The detailed design of systems associated with the UK EPR turbine systems are not within the GDA scope and as such no assessment of these systems has been undertaken.

733 Steam exiting the turbines is condensed back to water by passage over cooled condenser tubes fed from the cooling water supply. This interface between the chemically controlled secondary circuit and the cooling water supply, which can be seawater, is a common source of both minor and major impurity ingress. As is common in all PWRs, steam may also be dumped directly from the SGs to the condenser in some circumstances, which can also lead to a risk of condenser tube erosion. Control of oxygen ingress to the condensate is important at this stage.

734 Condensate is collected and stored before extraction through four stages of low pressure (LP) feed heating. During normal operation there is no purification of the condensate at this stage; however the Start-up Condensate and Feedwater Purification Plant (ATD) is used during plant start-ups, as described in Section 4.2.3. This approach is not uncommon for PWRs, and is used in the secondary circuit of existing French PWRs, but it does place much greater reliance on:

- Production of high-purity make-up water
- Purification during reactor start-up
- Removal of any impurities during operation by the Steam Generator Blowdown System (SGBS)
- Condenser tube integrity
- Quick detection of condenser tube leaks

735 Feedwater passes into the feedwater tank, which also serves as a deaerator vessel, where it is sprayed through steam removing non-condensable gases. To minimise the level of oxygen in the feedwater many PWRs, including existing French PWRs, rely on air

extraction in the condenser to fulfil this role. The oxygen concentration in the secondary circuit feedwater is an important parameter that affects corrosion processes within the secondary circuit. The introduction of a deaerator in the UK EPR secondary circuit design can therefore be viewed as a valuable addition to the means available to the licensee for controlling feedwater oxygen concentrations. It also provides a reservoir of treated feedwater that may be valuable under fault conditions.

736 Following deaeration, the feedwater is heated and pressurised by two stages of High Pressure (HP) feed heating before entering the SG. This stage of feed heating uses Direct Contact (DC) heating via extraction steam from the turbines. This is an important feature of PWR secondary circuits as it means that a significant quantity of feedwater does not pass through the full steam system during each pass.

737 The figure below shows the main components of the secondary circuit. The principal water and steam flows are highlighted in blue and red respectively (Ref. 50):

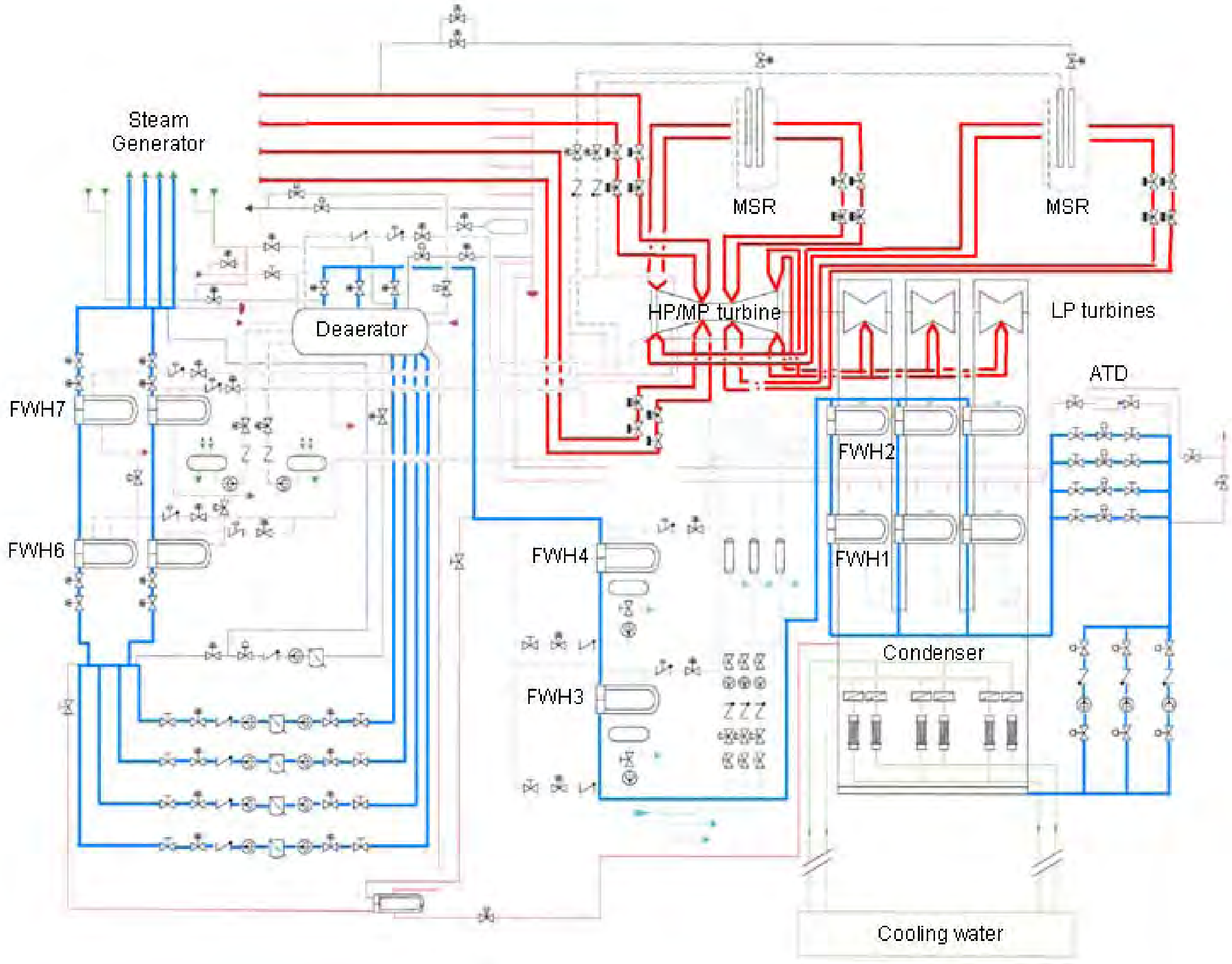


Figure 19: UK EPR Secondary Circuit

4.4.2 Assessment – Materials, Design and Chemistry

738 The main functions of secondary circuit chemistry are to support safe plant operations, in particular:

- Protection of the secondary circuit materials, specifically related to integrity of the system and component failure.
- Avoid sudden large changes effecting plant performance, in particular heat transfer impairment or pressure drops, which may exercise safety systems.
- Support system performance requirements, especially where related to safety.

739 Assessment during Step 4 has concentrated on demonstrating these aims have been realised in the UK EPR safety case. My assessment was supported by a TSC contract which reviewed both relevant good practice in secondary circuit chemistry (Ref. 16) and the UK EPR design specifically (Ref. 15). My assessment that follows is consistent with these reviews.

4.4.2.1 Materials and Design

740 Since all power plants have complex secondary circuits which often contain a wide range of materials, it is necessary to reconcile the often divergent requirements of distinct systems against each other to achieve an overall balance, both for the chemistry and design. In order to define the chemistry a thorough understanding of the system designs and materials is required. The following sections concentrate on the main chemistry related systems in the UK EPR secondary circuit, specifically an assessment of the materials and design choices, which influence the chemistry.

4.4.2.1.1 Steam Generators

741 The UK EPR has four SGs which are similar to EDF N4 plant SGs (model 73 / 19 TE) that are already in service in several plants. These are described in the PCSR (Ref. 11, Section 5.4.2.). Further details are also available in the RCS SDM (Ref. 43). The main differences in comparison to the N4 SGs are an increase in secondary side water volume (normal level increased from 61.5 m^3 on N4 to 82.3 m^3 in UK EPR) and an increased number of SG u-tubes. The Steam Generators (SGs) are the interface between the primary and secondary circuits of a PWR. On the secondary side the outside of the heat transfer u-tubes are in permanent contact with the secondary circuit feed water and this water absorbs the heat and boils creating the steam necessary to drive the secondary circuit turbines. The upper section of each SG is fitted with various moisture separators and driers to improve the steam quality.

742 Many design differences exist between SG designs of different plant lineage. A number of these differences are due to the OEF from earlier SG designs where the materials and design, in combination with the operating chemistry regime, revealed a number of weaknesses causing various degradation issues, including SG tube ‘denting’, wastage, pitting, Stress Corrosion Cracking (SCC), Intergranular attack (IGA) and fouling, amongst others.

743 During Step 3, I was content with the SG features described for UK EPR, which should provide performance at least equivalent, if not better than the latest replacement SGs provided appropriate chemistry controls are adopted. Further assessment was undertaken on a number of these features, and how they influence corrosion performance and plant chemistry in UK EPR, during Step 4. The design of the Steam Generator in UK EPR is shown below (Source - AREVA):

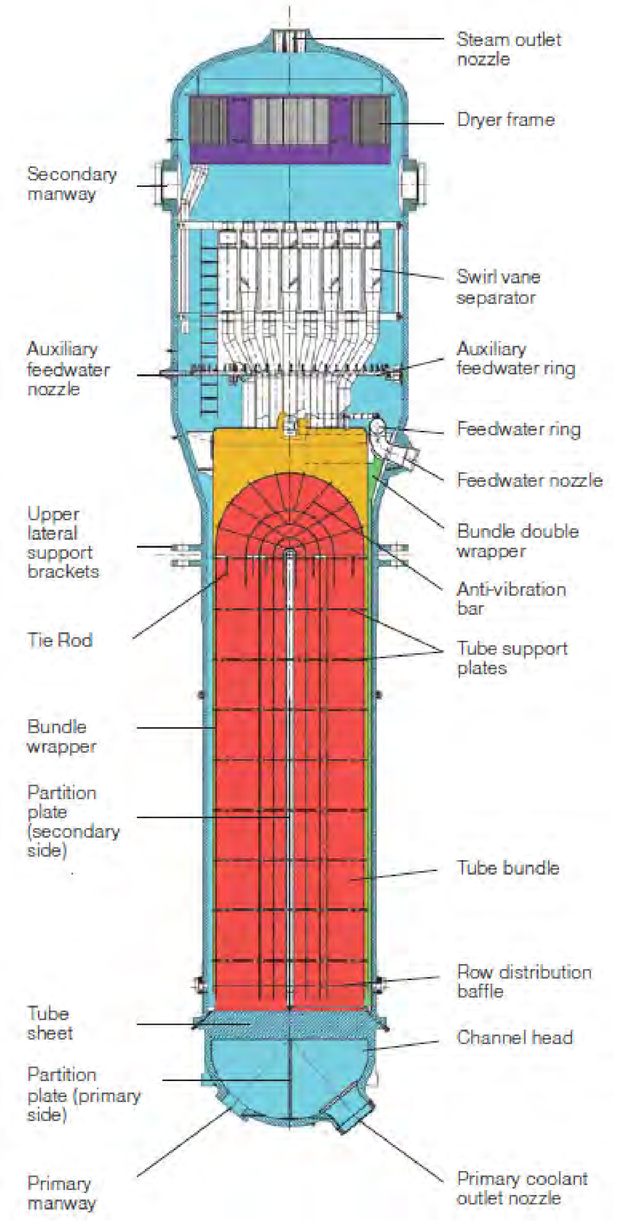


Figure 20: UK EPR Steam Generator

744 The most significant material choice made for the UK EPR SGs is the use of Inconel 690 in the thermally treated condition. This is almost the standard choice for SG tubing material and is consistent with the latest replacement SGs. Protection of this material is a determining factor in any chemistry regime. While it is accepted that, overall, this material has much better corrosion behaviour than Inconel 600, and comparable performance to Alloy 800, EDF and AREVA recognise a number of environments still pose risks to Inconel 690 as defined in the response to RO-UKEPR-44.A2 (Ref. 51). These are environments which contain caustic lead, lower valence sulphur species and acidic solutions that are slightly oxidizing, in addition to the wastage and pitting problems which are common to all SG tube alloys. These are important considerations for the chemistry

regime selected and EDF and AREVA have provided responses to my questions in each of these areas, as described in Section 4.4.2.2.

745 The thermal treatment of the SG u-tubes is important to the corrosion propensity of the material in the secondary side environment. This has been discussed previously in Section 4.2.3.2.

746 The SG tubes are welded to the primary face of the steam generator tubesheet and expanded over the full depth of the tubesheet. This joint is an important area in SG design as a number of SGs have experienced corrosion issues in this area due to the crevices left between the tube and tubesheet. EDF and AREVA claim that an improved process will be used for the UK EPR SGs, resulting in a reduced crevice region (TQ-EPR-1219, Ref. 8). Stress introduced into the SG tubes during this process can cause sensitivity on affected tubes. Again, EDF and AREVA claim that an improved procedure is available for UK EPR, resulting in reduced residual stresses.

747 The UK EPR SG tubes will be hydraulically expanded throughout the entire tubesheet thickness. A 33% reduction in the crevice width is expected in UK EPR compared to N4 SGs due to manufacturing improvements, in line with the more recent replacement SGs manufactured by AREVA. Outside Diameter (OD) residual stresses are low and should not impose additional corrosion concerns with adequate chemistry control.

748 The SG tubes are supported by nine Tube Support Plates (TSP) connected by tie rods, with the TSPs fabricated from a [redacted]. This high chromium steel should provide adequate corrosion resistance except if hostile environments are allowed to develop, although these would damage the more sensitive SG tubes first. Due to the incorporation of an axial economiser in the design the support plates below the divider plate are actually half plates.

749 The UK EPR will have a trefoil-shaped broached TSP. This is claimed to limit the risk of TSP blockage and hide-out phenomena. While it is accepted that the line contact with the steam generator tube in a trefoil design TSP will limit chemical hideout and therefore corrosion damage, similar trefoil-shaped broached tube supports have suffered severe blockage, in both Canadian Deuterium-Uranium (CANDU) reactor recirculating steam generators and Babcock and Wilcox once-through PWR steam generators.

750 TQ-EPR-1219 (Ref. 8) asked for a justification for the selection of trefoil TSP in UK EPR. The response concludes that trefoil supports are required due to the triangular pitch on the SG tubes and that there are no reasons to believe trefoil TSP should be more susceptible to blockage than any other support shape in use. The blockage process is complex and may involve deposition of both particulate and soluble iron, hence depends on many factors. The UK EPR TSP design is the latest evolution and several features may in fact make it less susceptible than current plants.

751 The [redacted] is used for the anti-vibration bars used in the u-bend region of the SGs to minimise tube vibration. Again, these materials should offer suitable corrosion resistance in typical secondary chemistry environments.

752 A flow distribution baffle is used to distribute the flow across the tubesheet. This should minimise local areas of high sludge accumulation on the tube sheet.

753 The UK EPR SG design incorporates an axial economiser. This design feature separates the cold side of the SG tubes from the hot side, via a divider plate from the tubesheet to the sixth TSP. A double wrapper is also included in the SG shell to direct the feedwater flow. These features result in direction of all of the incoming feedwater to the cold side of the tube bundle plus 10% of the recirculated water. The remaining 90% of the recirculated water is directed towards the hot side. EDF and AREVA claim that, in

contrast with other economiser designs, the UK EPR economiser design has overcome two disadvantages seen in earlier designs, namely, no direct cross-cutting flow along the tubes and no reduction in accessibility to the tube bundle for inspection and maintenance.

754 The UK EPR features separate SG feedwater inlets for the main (both normal and start-up and shutdown) and emergency feedwater supplies.

755 Recognising the similarity to the EDF N4 SG design, TQ-EPR-1218 (Ref. 8) requested OEF on the effect of including a number of design features. Based on the N4 feedback it appears that the addition of an economiser does indeed reduce cross flow in the SG and has a positive effect on tube wear in the upper bundle. The feedwater nozzles are different in UK EPR, mainly for the emergency feedwater nozzle which is intended to be used less than in the N4 plant due to the design of the plant. UK EPR retains the inclusion of a thermal sleeve for both the main and emergency feedwater nozzles, as in N4.

756 The original design for the SG shell was for manufacture using [redacted] which contains a maximum of 0.25% chromium. EDF and AREVA included a design change proposal during Step 4 (CMF 17, Ref. 95) to extend the possibilities of material to include the [redacted] grade, in addition to [redacted] grade. Both are currently used in such applications. This proposal has been assessed in the Structural Integrity assessment area (Ref. 116). For a Reactor Chemistry perspective this proposal does not change the chromium content of the alloy, which remains at a maximum of 0.25% (as per RCC-M, Ref. 96).

757 Despite design improvements and chemistry modifications the accumulation of some sludge and deposits within an operating SG is inevitable. An important consideration then becomes the provision in the design for inspection and cleaning (lancing), especially in low flow areas. This has been a recent operational issue with some EDF plants, where deposits in the tube support plate broaches have caused SG pressure losses to rise. TQ-EPR-781 (Ref. 8) queried several points in this area related to quantities, location and provisions for sludge removal in UK EPR.

758 The response provided details of the UK EPR design provisions in this area, which include:

- Optimised Steam Generator Blowdown System (SGBS) nozzles and location.
- Incorporation of a tube lane blocking system to minimise areas of low flow.
- Addition of flow distribution baffle.

759 Supporting these features is an assessment of sludge accumulation in the SG using 3D flow analysis. This indicates that low flow areas in the UK EPR SGs should be minimal, resulting in limited sludge accumulation. OEF from the EDF N4 plants, which have very similar SGs, suggest only a few kg of sludge accumulation occurs in operation. A number of inspection ports are available in the UK EPR SG design to facilitate both tubesheet and tube bundle visual inspection or cleaning. EDF and AREVA claim that the SG shell is manufactured with an allowance for chemical cleaning during its lifetime. The adequacy of this claim is not part of GDA and would require a justification by the Licensee on a case by case basis, but it is encouraging that EDF and AREVA have considered this possibility. It is notable that EDF and AREVA do not anticipate use of a dispersant for chemical sludge mitigation in UK EPR.

4.4.2.1.2 Steam Generator Blowdown System

760 The Steam Generator Blowdown System (SGBS) is used to maintain the quality of the water/steam mixture within the secondary circuit by continuously removing a proportion of the flow from the steam generator. For UK EPR this system is very important to maintaining an adequate water quality in the secondary side.

761 Assessment of this system started during Step 3, although limited information was available at the time. I was content with the proposed functionality of this system during Step 3. Continuing assessment occurred throughout Step 4 focussing on the evidence to support these functions.

762 In UK EPR the nominal SGBS flowrate is expected to be 1% of the main SG flow, which is reasonably high, compared to other PWRs, but can be varied for operational reasons, including operations with higher blowdown rates during impurity increases.

763 The UK EPR SGBS is described in the PCSR (Ref. 11, Section 10.4.7) and the corresponding SDM (Ref. 44). Each SG has a separate blowdown line, extracting from locations close to the tube plate (two nozzles on the hot leg and a third one on the cold leg side of each SG). Two connections to the Nuclear Sampling System (RES) are attached to the blowdown lines, one to the cold leg blowdown line and one to the common hot leg blowdown line. The RES is assessed in Section 4.4.3. The UK EPR SGBS is shown below (Ref. 11):

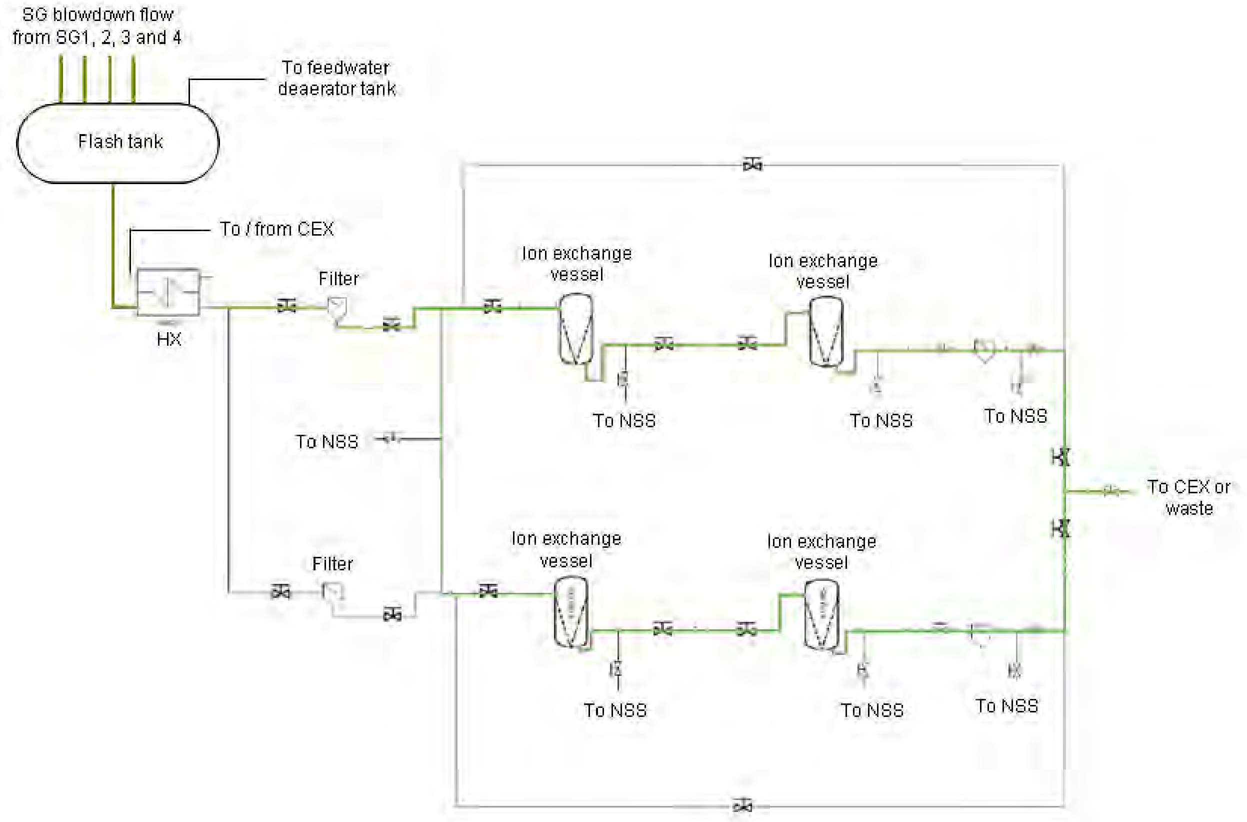


Figure 21: UK EPR Steam Generator Blowdown System

764 The blowdown from each SG is routed via a dedicated flash valve to a single flash tank, which separates the liquid and gaseous phase, with the steam phase extracted to the deaerator tank. The remaining liquid phase is cooled by a regenerative heat exchanger

(blowdown cooler) cooled by the Condensate Extraction System (CEX) before feeding into the demineralisation system which consists of two 50% capacity trains with (2 x 100%) cartridge filters and ion exchange demineralisers. The purified feed is fed back to the condenser, or alternatively can be discharged as waste. By-pass and interconnecting lines exist to transfer blowdown flow to waste without purification or to interconnect the two purification trains. The SGBS is also used to drain, fill and recirculate the SGs during outages as necessary. The RES returns 'clean' secondary samples upstream of the SGBS demineralisers and samples post demineralisation to measure SGBS performance. The blowdown flash vessel and cooler are located within containment. The purification trains are located within the nuclear auxiliary building, which is accessible during operations. Functionally, this system is very similar to SGBS in other PWRs.

765 Radioactivity measurements on the SGBS lines, as part of the 3KRT monitoring system, are used to monitor for primary to secondary leakage and SG tube rupture.

766 Transfer lines linking steam generators 1 and 2 together and generators 3 and 4 together are provided to transfer the water of the affected steam generator towards the unaffected steam generator in case of steam generator tube rupture (SGTR) with loss of offsite power (LOOP) to avoid release of liquid to the environment.

767 A number of important design choices have been made for the UK EPR SGBS, affecting the operating chemistry options:

- The design features no provisions for regeneration of exhausted ion exchange resins. Thus once exhausted resins are removed and replaced. This imposes a number of restrictions on the operating chemistry, as described in Section 4.4.2.2.
- In the Systems Design Manual for the SGBS (Ref. 44) EDF and AREVA claim that the SGBS demineralisers are sized for a lifetime of 24 months before replacement. The influent chemistry to the demineraliser is defined as 0.18 mg kg^{-1} ammonia and 5.8 mg kg^{-1} morpholine (which appears inconsistent with the response to RO-UKEPR-44.A2 described in Section 4.4.2.2 of my report). A description of the replacement procedure for spent resins is included which indicates that on-line resin exchange is possible in the systems such that the 24 month design value is not limiting.
- EDF and AREVA propose the SGBS demineralisers will be arranged as a cation bed followed by an anion resin bed. This arrangement is not unique and other SGBS operate in this manner, including those operated by EDF. In the response to TQ-EPR-779 (Ref. 8) EDF and AREVA claim that this arrangement minimises resin waste when non-regenerated resins are used. There does not appear to be any reason to suggest that the capability to operate in other arrangements is compromised, should the requirement arise (for example an upfront cation followed by a downstream mixed bed), although this would have implications for operations.

768 EDF and AREVA claim material choices in the SGBS are made based upon OEF and corrosion susceptibility. A range of materials are specified in the systems including ferritic steel, ferritic steel with high chromium content or austenitic steel. Reasonable arguments are presented for material choice as a function of location, considering local conditions, with the more resistant materials used in the more potentially susceptible locations. This results in all parts of the demineraliser train being made from austenitic steels due to the pH variations in this part of the plant.

769 The change in coolant temperature and pressure during extraction in the SGBS put parts of this system at risk of Flow Accelerated Corrosion (FAC). A discussion of the UK EPR approach to FAC, including for the SGBS, is given in Section 4.4.3.

4.4.2.1.3 Main Feedwater Systems

770 The feedwater systems transfer condensate from the condenser, through various multiple stages of heating and pressurisation, to the SG inlet. The design and materials used in this system are an important consideration in defining the secondary circuit chemistry regime as they are potentially susceptible to corrosion and contribute a significant input of corrosion products to the SG, if not properly controlled. No details are provided on many of the feedwater systems in UK EPR in the PCSR (Ref. 11); Section 10.4.4 list the low pressure feedwater and feed heating plant (ABP), Feedwater tank (ADG), Main feedwater pump train (MFWPS), High and Medium pressure feedwater and feed heating plant (AHP) and Start-up and shutdown feed pump train (SSS) as "*to follow*". Of these, only the SSS is within the GDA scope and is assessed in Section 4.4.4.

771 Section 10.6 of the PCSR (Ref. 11) provides limited information on the Main Feedwater System (MFWS). Further information is provided by the SDM (Ref. 45). In UK EPR the MFWS is divided into two parts:

- Upstream of the MFWS the feedwater heater is located from the turbine entry up to the water header. This part includes the motor-driven feedwater pump system (APA) and the start-up and shutdown system (SSS), the feedwater tank and various heaters. The first part of the MFWS is located from the feedwater header to the Safeguard Building (SB). It is located within the Conventional Island (CI).
- The second part is located from the entry of the SB up to the SG including the control valve and the measuring devices used for regulating the level of the SG. It is located within the supply boundary of the Nuclear Island (NI).

772 EDF and AREVA only provided details on the NI section of this system for GDA, but this is the less relevant part for Reactor Chemistry. Thus no assessment has been undertaken on the material or design choices for the feedwater heaters, deaerator or other components. These components should be included in the global analysis of the secondary circuit for the selection of an overall secondary circuit chemistry. These aspects are discussed further in Section 4.4.2.2 and are related to Assessment Findings **AF-UKEPR-RC-01** and **AF-UKEPR-RC-27**.

773 The addition of a deaerator tank is a valuable addition to the UK EPR secondary circuit. This feature is not common in many PWRs. Although no details of the design were provided for GDA, I queried the potential impact of this feature in TQ-EPR-1207 (Ref. 8). The deaerator will act to minimise operational chemistry transients associated with air ingress in the condenser, thus minimising associated corrosion product increases and additions of hydrazine for chemical deoxygenation. The tank also provides a useful store of feedwater for transient and accident conditions.

774 The remaining sections of the MFWS inside the NI do not fulfil any chemistry functions, and as such are not described further, except for the following points which are relevant to the interaction of the system materials with chemistry:

- The MFWS System Design Manual (Ref. 45) indicates that a $pH_{25°C}$ greater than 9.8 is expected for this system during operation (which appears inconsistent with the response to RO-UKEPR-44.A2 described in Section 4.4.2.2 of my report).
- All components in the MFWS are made from ferritic steel
- EDF and AREVA recognise the requirement to protect the main feedwater lines from FAC damage and claim appropriate design (valves and pipe routing), stable conditions (water velocity) and materials as the primary means of achieving

protection. Additional corrosion allowance has been added to the required design thickness. FAC is discussed further in Section 4.4.3

4.4.2.1.4 Emergency Feedwater System

775 A stable flow of feedwater is important to ensure transients in the primary circuit are minimised. During unavailability or failure of the MFWS (and SSS), feedwater can be supplied to the SGs in UK EPR via a dedicated Emergency Feedwater System (EFWS) as described in Section 6.6 of the PCSR (Ref. 11) and the EFWS SDM (Ref. 18). The UK EPR features a four train EFWS with four identical trains comprising a water storage tank, pump, four separate injection lines (one to each SG) and manual interconnections between the four trains which allow draining, filling or injection of any tank to any SG. Connections exist to allow other additional water sources to be injected by this method in the long term. The EFWS is not used during normal operations of the plant. However, it may be used to fill the SGs during plant start-up or for wet lay-up.

776 The EFWS is an important secondary circuit safety system and it is notable that EDF and AREVA have applied the same diversity and redundancy logic to this system as with other plant safety systems. EDF and AREVA claim that the use of the EFWS will be minimised in UK EPR.

777 The storage tanks are supplied with feedwater from the conventional island water distribution system (SER at $pH_{25°C} > 8.8$, see Sections 4.4.2.1.9 and 4.4.5.4). Sufficient storage capacity for at least 24 hours feed supply following station black-out or loss of ultimate heat sink is provided, including make-up provisions from other system (such as the fire fighting supplies (JAC)). This SER system supplies demineralised water that has been treated to $pH_{25°C} > 8.8$ and controlled impurities. However, the SER water is fully aerated hence may contain elevated levels (up to 10 mg kg^{-1}) of dissolved oxygen. EDF and AREVA state that the EFWS is not deaerated before use as an emergency feed supply. When used for SG filling a connection exists to the Chemical Reagent Injection System (SIR) for the addition of chemical treatments. Due to the use of aerated feedwater, the EFWS is made entirely of stainless steel which is a reasonable position.

778 However, the real corrosion risk for aerated feedwater is within the SGs themselves, where oxygen could cause considerable corrosion damage, especially at temperatures above 120°C. For this reason, loss of SIR during SG filling is not considered as a significant risk due to the low temperatures (discussed elsewhere in this report). It appears contradictory that EDF and AREVA have recognised the necessity for chemical treatment of the EFWS supply during its use in SG start-up and wet lay-up, but have ruled out chemically treatment of the EFWS supply during accident conditions. This means that significant quantities of oxygen could enter the UK EPR SGs during actuation of the system, when the temperature is significantly higher, although the frequency of such actuations is claimed to be low by EDF and AREVA. Comparable systems in other PWRs use stored condensate as a source of emergency feedwater, often with reduced dissolved oxygen content. This is achieved by a number of means including nitrogen blanketing or covering the water surface with an impermeable membrane, however these tanks are initially fed with condensate which meets (or is close to) the feedwater oxygen content limit (< 10 μg kg-1) and hence the aim is to minimise any pick-up. With the current UK EPR design, an additional step of deaeration would be required to remove the oxygen before or during storage. As described in Section 4.2.2.3.3, the degasser in the Coolant Degasification System (CDS) can be used to produce deaerated demineralised water, however it is unclear if this could be used to feed the EFWS. I understand that

EDF and AREVA are considering hydrazine for this eventuality, but this is not described in their Safety Case, Ref. 105.

779 I recognise that the main aim for the EFWS is to supply sufficient water to the SG to enable adequate decay heat removal and achieve a safe shutdown of the reactor. Assessment of the adequacy of this claim is not within the Reactor Chemistry remit. However, no consideration appears to have been given to the introduction of oxygenated EFWS feedwater into the SG in UK EPR. A fuller justification for this design choice, including consideration of mitigations if appropriate, should be provided. I consider this to be an Assessment Finding **AF-UKEPR-RC-28**.

4.4.2.1.5 Condensate Systems

780 The condensate systems in UK EPR act to condense steam discharge from the final (LP) stages of the turbine, by-pass steam or other steam sources. The systems contribute to a number of chemistry related functions including deaeration and removal of non-condensable gases from the secondary coolant. In addition the condensate systems store a bulk supply of feedwater that is available to supply the feedwater systems and a number of auxiliary systems, mainly for cooling.

781 The Condensate Extraction (CEX) system in UK EPR is split into two sub-systems covering the condenser and extraction functions respectively. Neither of these systems is included in the Step 4 PCSR (Ref. 11). Some details were provided as part of the response to RO-UKEPR-44.A2 (Ref. 9) in Ref. 46. As much of the first of these is related to site specific characteristics, such as cooling water supply, many details regarding the precise condenser design are not available during GDA. Leakage of the condenser heat exchanger tubes can be a principal cause of both minor and gross impurity ingress to the secondary circuit. EDF and AREVA claim that the UK EPR design will use a ‘leak tight’ approach, similar to that at the EDF Penly reactors, with [redacted] tubing fixed (welded and rolled) to [redacted] tube sheets. The tubes are split into six tube bundles (two per LP turbine cylinder). A number of the tubes (7%) are of greater wall thickness to account for impact and erosion damage caused by the wet steam entry. I am content that the use of [redacted] tubing is an appropriate choice for UK EPR and should provide reliable condenser performance.

782 The use of a ‘leak tight’ condenser is an important part of the overall UK EPR secondary chemistry systems. As suggested in TQ-EPR-1207 (Ref. 8), this feature is an important part of the justification for not including a condensate polishing plant (or similar) in UK EPR. This is discussed further in Section 4.4.2.2.1.

783 A number of sampling points are included in CEX to detect impurity ingress. These samples are part of the Feedwater Chemical Sampling System (SIT). This system is assessed in Section 4.4.4.3.

784 The CEX extraction function takes condensate from the condenser hotwell and transfers it to the LP feed heaters and deaerator tank, via three 50% pumps. In addition the CEX provides condensate to a number of other systems as a medium for heat exchanger cooling. The CEX supply to the feed system is subject to “*magnetic filtration*” although no details are available on this feature at present. Secondary coolant losses are made up in the CEX system from the conventional island water distribution system (SER).

785 EDF and AREVA also claim that the UK EPR condenser contributes to deaeration of the secondary circuit with an expected condensate oxygen concentration of 5 $\mu g\ kg^{-1}$ during normal operations. During normal operations the Condenser Vacuum System (CVI)

maintains a vacuum on the condenser systems, removing non-condensable gases to the NAB ventilation system (DWN) and minimising air ingress into the condenser (Ref. 46).

4.4.2.1.6 Steam Systems

786 Steam generated in the SGs needs to be transferred to the turbines. The Main Steam Supply System (MSSS) is designed to ensure the supply of steam to the turbine and to various steam consumers in the turbine hall during power operation, as described in Section 10.3 of the PCSR (Ref. 11) and the associated SDM (Ref. 47).

787 In UK EPR the MSSS is divided into four Main Steam Lines (MSL), one connected to each SG outlet. The MSL are made from ferritic steel which, under normal SG outlet conditions ($< 0.25\%$ moisture) and with appropriate chemical conditioning, should result in minimal corrosion risks. The MSSS is connected to the Main Steam Relief Train (MSRT). This system allows direct discharge of SG outlet steam to the atmosphere for operational reasons such as unavailability of the condenser. Again, ferritic steel is used for this system.

788 UK EPR also incorporates a steam by-pass system for direct discharge of SG steam to the condenser. The role of the Main Steam By-pass (MSB) is to regulate the steam flow from the steam generator by counteracting changes in the amount of steam consumed by the turbine, and its associated parts, and hence prevent a reactor trip or any discharge from the atmospheric relief valves (MSRT). Without the MSB the steam generator safety valves would be activated during rapid transient conditions or power variations at low load. The by-pass redirects steam from the turbine inlet to the condenser via the de-superheating pressure reduction boxes. The system is designed to deal with approximately 60% of the nominal steam flow produced by the reactor. The MSB pipework is fabricated from carbon steel.

789 A important consideration for any secondary chemistry regime is the partitioning of the volatile pH additive into the steam phase. The extent to which this occurs is a fundamental property of the chosen amine(s) and determines the resultant pH_T and hence the protection or otherwise offered to the system. This can be further exacerbated by additional amine partitioning into condensation produced in the steam systems, especially in drain lines. The material choices are an important aspect of this process. No information has been made available on material choices in such systems as part of GDA. Information on material choices, in combination with chemistry at these locations under operating conditions, should be included in an overall assessment of corrosion susceptibility for the UK EPR secondary circuit. This is related to an Assessment Finding **AF-UKEPR-RC-27**.

4.4.2.1.7 Chemical Dosing Systems

790 Chemical additions must be made to the secondary circuit in order to maintain the coolant chemistry within the required bands. The UK EPR design features a Chemical Treatment and Injection of Reagents System (SIR) which injects chemical reagents to ensure that the water in the secondary systems and in the auxiliary systems has the required chemical properties. This system is not described in the PCSR (Ref. 11), but there are SDMs available (Ref. 48 and 49).

791 The system is subdivided into a number of sub-systems which deliver the various chemical additives to the discreet systems. For example; the SIR6 sub-system supplies systems within the Nuclear Island (NI), including the EFWS, Component Cooling Water System (CCWS) and Containment Heat Removal System (CHRS), amongst others.

Isolation from treated systems is provided by a motor operated valve and a check valve, but these are parts of the served systems not the SIR itself. The SIR SDMs (Ref. 48 and 49) provides details of the system functions and proposed chemical additives; ammonia, ethanolamine, morpholine, hydrazine and trisodium phosphate which will be used for conditioning of the water/steam systems, auxiliary systems and SGs during wet lay-up and start-up. Further information on reagent injection points was provided in letter EPR00807N (Ref. 50). The most relevant SIR sub-systems to the secondary circuit are discussed below.

792 SIR2, 3 and 4 sub-systems provide hydrazine, pH additive mixtures (normal operations) and hydrazine/ammonia for shutdown respectively. These systems serve the Feedwater tank (ADG), HP and MP Feedwater plant (AHP) and CEX. Three tanks, containing ammonia, morpholine (or ethanolamine) and hydrazine are used to feed mixing tanks, where the station chemist can manually prepare the required dilute solution (by adding demineralised water from SED) for injection into the secondary system. TSP is added directly to the mixing tank in powder form. The chemicals suggested for each tank are taken as preliminary until a precise secondary chemistry regime is defined. The TSP mixing tank is maintained at elevated temperature by an installed heater system in order to minimise the risk of TSP crystallisation at low temperatures. The mixing tanks are sized for a seven day supply under normal operating conditions.

793 Hydrazine injection is automatic and constant based upon measurement from the hydrazine meter in the AHP sample taken by the Feedwater Sampling System (SIT). The pH additive mixture is added manually to the CEX, when necessary to maintain the target pH, with the flowrate set based upon grab sampling pH measurements from the SIT. Other chemical additions (for example, during start-up) are manually implemented based upon measurements in the served systems.

794 The SIR6 sub-system features three separate injection lines, two to the EFWS and one to the CCWS, all inside the NI. Details are provided in the SDM (Refs 48 and 49) on the anticipated chemical treatments to be applied; however these are taken as preliminary until the final secondary chemistry (and auxiliary system) regimes are decided and should not prevent other reagents or combination of reagents from being added by this system. Rinsing provisions are included in the design.

795 No information is available on the exact injection locations, but the following preliminary locations are notable:

- Deaerator feed
- Downstream of HP feed heaters
- CEX pump discharge

796 Due to the corrosive nature of the strong chemical stored and delivered by the SIR, all equipment subjected to the action of chemical products (pipework, vents, valves, etc.) are made of stainless steel of an appropriate grade (304L or 316L). The potential use of morpholine requires the use of Teflon seals (rather than Viton or similar) due to the degrading nature of morpholine for these materials. It is noted that some of the concentrated chemicals used in the SIR are potentially flammable. If this requirement is retained when the final chemistry regimes are defined, I find that a justification and analysis for this approach should be undertaken as part of assessment findings **AF-UKEPR-RC-29** and **AF-UKEPR-RC-02**.

797 The design of the SIR appears reasonable, consisting of a simple set of storage and mixing tanks, pumps and injection lines. The All Volatile Treatment (AVT) chemical tanks appear segregated from the TSP dosing tank which should prevent inadvertent addition

of phosphates to the secondary side systems. There are many interconnections between the various AVT chemical mixing tanks, however the inadvertent addition of these to the secondary circuit should not be an issue as they are all used in the secondary circuit and higher than expected levels will cause a control to be breached with resulting rectifying actions. Overall, the design of the SIR appears satisfactory, but should be reviewed to ensure compatibility with the defined secondary chemistry regime, once available.

4.4.2.1.8 Circulating Water System

798 The circulating water system (CRF) provides cooling water as the heat sink to the inside of the condenser tubes. The main impact of this system on secondary circuit chemistry is that this cooling water is the potential source of impurities if a condenser leak occurs. Despite EDF and AREVA including this system in the scope for GDA, very little information is available as this is very much a site specific system. No details are provided in the PCSR (Section 10.4.4, Ref. 11), nor is an SDM available. As such no assessment of this system has been undertaken in GDA.

4.4.2.1.9 Demineralised Water Systems

799 Demineralised water is required for a significant number of nuclear and conventional systems in any PWR. Generally this is produced on site using a water treatment plant to filter and purify the raw water to a condition suitable for use by the plant systems. This is the first step in ensuring impurity levels are met. The UK EPR demineralised water systems (SDA (demineralised water production system), SDS (demineralised seawater production system), SED (nuclear island demineralised water distribution system) and SER (conventional island demineralised water distribution system)) are described in limited detail in the PCSR (Ref. 11, Section 9.2.3). The system ordinarily processes seawater via filtration, reverse osmosis, degasification and ion exchange. Alternatively, towns-water can be used. Typical outlet figures are given as 0.2 μS cm^{-1}, 10 μg kg^{-1} silica and 2 μg kg^{-1}sodium.

800 Demineralised water treatment systems can often be site specific due to the different feedwater supply compositions. As such no detailed assessment of this system has been included in GDA, although I note that the outlet figures appear reasonable and there should be no reason to suggest that a suitable system could not be specified on a site specific basis.

4.4.2.2 Chemistry

801 Definition of a secondary circuit chemistry operating regime is a difficult task in a PWR. Many factors may be considered including material compatibility, corrosion control, environmental impact and economic viability. The complex nature of secondary circuits, involving many systems and components and a range of thermo-hydraulic conditions, further complicates the decision as a given chemistry is often not ideal for all parts of the circuit. The nominally non-active nature of the secondary circuit means that options are not restricted by the consequences of contamination. Even with these complications, it is almost certain that the most likely regime will involve an All Volatile Treatment (AVT), which consists of:

- Addition of a volatile pH raising additive.
- Addition of a reducing agent.

- Minimisation of impurities.

802 The Step 4 PCSR (Ref. 11) presents little substantive information on the proposed secondary circuit chemistry regime or how it has been determined. The information that is presented is given in Section 5.4.2. This states that the principle adopted for feedwater and steam generator water chemical treatment is an All Volatile Treatment (AVT) utilising hydrazine as a deoxygenating agent and an amine (morpholine, ethanolamine or ammonia) for pH control.

803 The UK EPR secondary circuit chemistry was described and justified in the response to RO-UKEPR-44.A2 (Ref. 51). Overall, this response provides a reasonable description of the rationale and logic behind the proposed UK EPR secondary chemistry regimes and appears to include the main considerations which should form part of the resolution. However, as a final specification has not yet been made for UK EPR, the response is inconclusive in a number of areas and further justification and evidence will be required as the project progresses and as designs for UK EPR become more developed. A number of more detailed Assessment Findings appear in the following sections, where each principal aspect of the proposed regimes is discussed.

804 EDF and AREVA specify three potential secondary chemistry regimes for UK EPR, which differ only by the volatile pH raising additive combination and all feature hydrazine redox control and minimisation of impurities. These are:

- Ammonia/Morpholine at pH_{25} of 9.5 to 9.6
- Ethanolamine at pH_{25} of 9.4 to 9.6
- Ammonia/Ethanolamine at pH_{25} of 9.6 to 9.7

805 These potential regimes do not agree with statements made in the system design documents for the SGBS and MFWS, described in Sections 4.4.2.1.2 and 4.4.2.1.3 of my report. These documents should consistently reflect the actual secondary chemistry, once defined. I consider this to be an Assessment Finding **AF-UKEPR-RC-29**.

806 At a high level, these suggested regimes are reasonable and are in alignment with all other operating commercial PWRs worldwide (possibly apart from one which does not operate an AVT for specific reasons) and are consistent with the recommendations made in international guidelines (Refs 28 and 29). However, as implied elsewhere in this section, specification of a secondary chemistry is highly plant design and Licensee (due to economic impact) dependant. The response to RO-UKEPR-44.A2 (Ref. 51) restricts the chemistry choices for UK EPR based upon three important considerations, namely, regulatory limits, design specifics and identified potential corrosion threats to the plant.

807 A significant ‘regulatory’ limitation on the proposed UK EPR secondary circuit chemistry, as described in the response to RO-UKEPR-44.A2, is via a limit placed on nitrogen containing liquid wastes discharge to the environment. This appears to be based upon French regulations applicable to FA3 and hence may not be applicable to any UK EPR.

808 An immediate consequence of this limitation is that a secondary chemistry regime with a high ammonia AVT secondary chemistry regime with a feedwater pH_{25} of around 10 would be discounted. This approach is not uncommon and has been successfully applied in several PWRs; this change could result in a final feedwater iron concentration of $< 1\ \mu g\ kg^{-1}$ (typically around $0.5\ \mu g\ kg^{-1}$), which is substantially lower than that expected for UK EPR ($< 2\ \mu g\ kg^{-1}$).

809 This would suggest a wider range of options may be possible for UK EPR. The nitrogen limitation should be reviewed during later stages of the project, following consultation with

the Environment Agency, and may result in previously unfavoured operational regimes being permitted, potentially requiring a revision to the results of the optimisation performed for GDA. I consider this to be an Assessment Finding **AF-UKEPR-RC-30**.

810 A number of design features described in Section 4.4.1 will influence the chemistry that will and can be operated on UK EPR and the response to RO-UKEPR-44.A2 is influenced by these.

811 The main design choices affecting the UK EPR is the omission of a Condensate Polishing Plant (CPP) (or similar) for normal operations and the SGBS design in which the cation resin is operated in amine form, without regeneration, at a relatively high flow rate of 1%. While not uncommon these design choices do influence the secondary chemistry regimes proposed. The SGBS has a finite purification capacity and once exhausted the ion exchange resins will no longer remove impurities. Unavoidably the pH control amines will also exchange with the cation resin in the system meaning that higher amine concentrations (hence higher pH_{25}) will reduce the frequency of replacement. In essence the decision of when and how to replace resins in the SGBS is an economic decision for the Licensee, but these decisions do have implications on the secondary circuit chemistry possible for UK EPR.

812 EDF and AREVA have indicated that the SGBS resins in UK EPR will operate in the amine form. The response to RO-UKEPR-44.A2 (Ref. 51) provides estimates for the lifetime of the SGBS resins, which range from 7 to 22 months, depending upon the regime and precise pH_{25}. For the lower pH_{25} values suggested the lifetime is reasonably constant between 19 and 22 months, while at the higher end Ammonia/Morpholine gives lifetimes around twice as long as the other two regimes at 16 months. Thus it is likely that some replacement of SGBS resins will be required during a fuel cycle.

813 This mode of operation allows much longer lifetimes between replacements but does have implications for the system performance. EDF and AREVA claim that it possible to operate with up to a limit of 2 $\mu g\ kg^{-1}$ sodium in the blowdown returned to the condenser. As there is no other mechanism for impurity removal in an operating UK EPR (apart from letdown and make-up) this suggests that the plant could end up with a similar level in the feedwater, given enough time. Due to the concentration factor that occurs in SGs this could result in unfavourable concentrations in the SG water. Other PWRs operating amine form resins under similar circumstances appear to operate to lower limits for sodium in the blowdown return. Whilst EDF and AREVA have subsequently advised a sodium limit of 3 $\mu g\ kg^{-1}$ in SGBD and claim that increases in feedwater sodium would be detectable in the SGBD at these levels, this is not stated in their Safety Case, Ref. 105.

814 EDF and AREVA suggest a SGBD limit for sodium in UK EPR of 20 $\mu g\ kg^{-1}$, as opposed to 10 $\mu g\ kg^{-1}$ applied to the French fleet and 5 $\mu g\ kg^{-1}$ in the EPRI guidelines (Ref. 28). This is based upon OEF from German plants which operate with up to 50 $\mu g\ kg^{-1}$. As noted in several sections of this report including Section 4.3.2.1, the UK EPR SG tube alloy is different to that used in Germany (Alloy 800), which has experienced some very limited degradation problems in recent years potentially due in part to less restrictive impurity controls. This was queried in TQ-EPR-1221 (Ref. 8) and the response indicates the main driver is to allow “*flexibility*” in operations, with OEF suggesting the actual value will be much lower than this limit. While I am content that UK EPR could meet the more restrictive specifications, further justification may be needed once precise procedures are developed for UK EPR. Not operating beyond amine breakthrough would markedly shorten the operational life of the blowdown resins, to between 7 and 2 months, which for the UK EPR are not intended to be regenerated, although replacement is possible.

815 Without the design provisions to regenerate used resins, the available options for the UK EPR secondary chemistry regime are largely dictated by the lifetime considered acceptable for the ion-exchange resins in the SGBS, which is largely an economic decision. Nevertheless, even given the current design constraints several possibilities exist for extending the resin lifetime and/or increasing the desired pH_{25}:

- The blowdown flow could be reduced, although this may have an impact upon removal of impurities.
- Higher capacity resins might be used, if available, rather than those currently specified.
- Larger quantities of resin would offer a similar benefit, although at the cost of modifying the blowdown vessels.

816 I queried the optioneering undertaken on the UK EPR SGBS arrangement in TQ-EPR-779 (Ref. 8). The argument made by EDF and AREVA against on-site resin regeneration is the possibility of impurity ingress to the secondary circuit from traces of the strong acid and alkali regenerant chemicals used during the process or resin degradation products from repeated regenerations. This is a reasonable argument, but should be balanced against the overall plant design. Insufficient justification has been provided relating to the initial assumptions regarding blowdown flow, resin capacity, vessel capacities and the blowdown resin life required and how they relate to the eventual secondary circuit chemistry regime adopted. I consider this to be an Assessment Finding, **AF-UKEPR-RC-31,** since this is largely site-specific. An inefficient SGBS would result in a greater risk of SG tubing damage.

817 All of the suggested chemistries for UK EPR include an organic amine component. During operation these will degrade under the thermal conditions to produce small chain organic breakdown products such as formic or acetic acid. These species are inefficiently removed on ion exchange resins and as such will tend to accumulate within the secondary circuit over time, although they themselves are unstable and will eventually decompose to CO_2 which will be discharged at the condenser, leading to an equilibrium level in the circuit. This also potentially affects after cation conductivity measurements by obscuring anionic ingress. This is discussed further in Section 4.4.4. Organic acids can also depress the pH within the secondary circuit in certain locations, although less so with amines than ammonia, and is relevant to the discussion of FAC that follows in Section 4.4.3.3.

818 A further consideration in defining a suitable chemistry regime is to counter potential corrosion threats to the secondary circuit materials. In the response to RO-UKER-44.A2 (Ref. 51), EDF and AREVA suggest a pH range of between 9 and 12 is needed to minimise general corrosion in carbon and low alloy steels. Studies have shown that both the solubility and corrosion rates of iron alloys is very much pH dependant and passes through a minimum at or close to pH_T 7.0. Very similar behaviour is seen for other transition metals such as chromium and nickel due to their similar chemistry. Therefore the arguments presented by EDF and AREVA are reasonable.

819 As described in Section 4.4.3.3, chemistry is an important parameter in FAC susceptibility. EDF and AREVA suggest a minimum pH for the feedwater in UK EPR of pH_{175} 6.63. This is based upon two phase conditions with 36% liquid mass and is attributed to the results presented in an EPRI report (Ref. 52). Calculations on this basis result in the lower pH_{25} limits suggested by EDF and AREVA for UK EPR. Chemistry impacts on FAC are considered further in Section 4.4.3.3.2, as these must be weighed in conjunction with comparable improvements made in material choices.

820 An aim of secondary circuit chemistry, as acknowledged by EDF and AREVA is the prevention of localised corrosion phenomena, such as Intergranular Attack (IGA) or Stress Corrosion Cracking (SCC). Both nickel alloys and stainless steels are susceptible to these modes of corrosion given a conducive environment. The risks of these mechanisms can be diminished by controlling the pH_T. In the response to RO-UKEPR-44.A2 EDF and AREVA suggest a pH_{25} of 10, with a limit of 10.2. This is based upon both nickel alloy and stainless steel susceptibility in a reducing environment and on OEF from German plants which have operated a high pH ammonia based AVT regime without observed damage (with Alloy 800).

821 In principle this argument is reasonable; however the actual parameter that is important is pH_T not pH_{25}, although in reality it is indeed pH_{25} that will be controlled. This minor discrepancy does potentially influence the justification for the secondary chemistry regimes suggested for UK EPR. Due to the differing properties of the amines suggested for UK EPR (compared to ammonia) a different pH_{25} would result for the same pH_T under the SG conditions. Calculations on this basis result in the upper pH_{25} limits suggested by EDF and AREVA for UK EPR.

822 It is worth noting that I am not aware of any cases of IGA/SCC in nickel alloys resulting purely from amines. The volatility of these species means that the high pH values needed (generally $pH_T > 10$) cannot be reached under normal conditions. It is commonly accepted that other, non volatile, species are needed that drive the pH higher. See my assessment of sodium in the SGBD above.

823 The data presented does indicate a potential for SCC at lower pH_T in nickel alloys when reduced sulphur species or lead contamination is present. EDF and AREVA claim that the uses of materials containing these species are strictly controlled during operations and more likely during construction, commissioning or maintenance.

824 TQ-EPR-1214 (Ref. 8) queried several points related to lead contamination in UK EPR. EDF and AREVA agree that lead is potentially deleterious to Inconel 690 alloys, although the precise concentration or conditions (pH, redox potential, superheat, deposit films, existence and properties of liquid films etc.) are still subject to uncertainty and much laboratory testing. Concentrations as low as 100 $\mu g\ kg^{-1}$ have been suggested. Data presented from current EDF plants demonstrate the high uncertainties that still exist in this area, although the measured feedwater concentrations were extremely low (< 0.1 $\mu g\ kg^{-1}$). I am satisfied that, provided comparable controls are put in place by the Licensee of UK EPR during construction, commissioning, maintenance and operations, there is no reason to suggest that this should be a risk for UK EPR. This is related to an Assessment Finding **AF-UKEPR-RC-03**.

825 A similar TQ was raised on reduced sulphur contamination. The response to TQ-EPR-1215 (Ref. 8) provides information on laboratory studies, EDF practices for measuring sulphate as an indicator to reduced sulphur and likely implications for UK EPR. The response suggests no reason why UK EPR should be more prone to this form of degradation than current operating PWRs. I am content this is the case, provided adequate chemistry controls are maintained.

826 Despite improvements in the design of the SG internals or secondary feed systems, transport of iron to the SG is inevitable. This can be reduced by maintaining a high pH. EDF and AREVA recommend that as high a pH as possible (within the allowed range) is maintained. A particular consequence of this iron transport can be sludge pile accumulation on the Tube-Sheet and blockage of TSPs, both of which can result in corrosion or flow restrictions. A number of current French plants have experienced

particular problems with TSP blockage. A low pH seems to be a contributory factor. Experience form other PWRs reinforces this position.

827 EDF and AREVA have taken the positive step of removing copper sources from the UK EPR secondary circuit. The exclusion of copper and copper alloys, as well as being consistent with OEF, means that restrictions on high pH regimes which would be needed to mitigate copper alloy corrosion are not necessary in UK EPR.

828 UK EPR will operate with hydrazine addition to produce a reductive environment in the secondary circuit. EDF and AREVA propose to operate with hydrazine addition in the range of 50 to 100 μg kg^{-1}, with higher concentrations possible to deal with conditions of higher oxygen ingress resulting in a N_2H_4:O_2 ratio of between 5 and 10. Arguments are made based upon the effect of hydrazine on iron release, transport and reactivity in the SGs and corrosion mechanisms. Hydrazine is universally used in commercial PWRs and the values suggested appear reasonable, albeit potentially higher than may be necessary in reality for UK EPR with a deaerator. I am satisfied with the arguments and evidence presented in this area.

829 In addition to the controls on sodium and iron discussed previously in this section, EDF and AREVA also propose controls on chloride, sulphate, silica and oxygen in UK EPR. The arguments and evidence presented for these species are reasonable and are consistent with operating plant experience.

830 Overall, while I am satisfied that the chemistries suggested can be safely operated in UK EPR and may lead to adequate protection, based upon the evidence presented I do not consider that an adequate justification has yet been provided for the overall secondary chemistry considering material choices, corrosion threats and plant design amongst others. I am content that this can be completed as further details of the secondary circuit systems become available. I consider this to be an Assessment Finding **AF-UKEPR-RC-27**. This is also strongly linked to Assessment Finding **AF-UKEPR-RC-01**.

4.4.2.2.1 Fault conditions

831 An important consideration for secondary circuit chemistry is the behaviour of the systems during fault conditions. It is possible to consider a number of potential faulted chemistry conditions in the secondary circuit, however due to the omission of a condensate polishing plant (or similar) in UK EPR the behaviour during a condenser leak can be considered a representative case. As stated in Section 4.4.5.4, the Start-up Condensate and Feedwater Purification Plant (ATD) system is not designed for use at power so cannot provide any short-term purification during condenser leakage.

832 TQ-EPR-1204 (Ref. 8) was raised to understand the process for determining, monitoring and rectifying a condenser leak. The response indicates that the general steps are:

- Monitoring continuously the chemical quality of SG Blowdown.
- Determination of defective tube bundle by the chemical sampling system (SIT).
- Dependant upon the size of the leak, either; reducing the load to a level compatible with the shutdown of a condenser seawater pump (CRF) so as to isolate the defective bundle or reducing load to hot stand-by conditions.
- Opening the water box to find the leaking tube(s) and affecting repairs.
- Back to expected chemical criteria by flushing the secondary system water.

833 In a case of an increasing pollution in the secondary side water or in case of an unavailability of the condenser, the blowdown can be directed to waste after the mechanical filtration via bypass and, if desired, also after the demineralisation. This provides time to detect and repair the source of the pollution. The response to TQ-EPR-1204 did not provide evidence to support these claims, using a leak rate of 1 litre per hour to determine if a reduced load or hot-standby is required (which is assumed to be the smallest detectable leak). As described above, I am content these arrangements are adequate, provided a rigorous system of operating limits and conditions is enforced which would restrict operation with elevated impurity levels.

834 It is notable that there are no 'automatic' actions associated with impurity ingress from a condenser leak. The UK Advanced Gas Cooled (AGR) reactors feature a Chloride Ingress Protection System which trips the reactor if a high level of impurity ingress is detected in the boiler feedwater. This is due to the different boiler design which could suffer rapid corrosion under such circumstances. This type of system was retained for the UK PWR at Sizewell B, although it is understood not to have been used. TQ-EPR-1430 (Ref. 8) was raised on this point. A response was provided on 5 May 2011, too late for assessment. As such, the arrangement in this regard should be reviewed on a site specific basis once full details of the plant chemistry and design are known. I consider this to be an Assessment Finding **AF-UKEPR-RC-32**.

4.4.2.3 Summary

835 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of secondary circuit materials, design and chemistry in UK EPR are:

- The design of the UK EPR secondary systems and components incorporate a number of features and design provisions which have been derived based upon the latest generation of PWRs in both France and Germany and international feedback. Positive features include the addition of a deaerator, [redacted] tubed "*leak tight*" condenser, absence of copper alloys and improved material choices. These should reduce the potential for chemistry related operational problems in the secondary circuit and help to alleviate the risks posed by historical degradation and safety concerns.
- The basic approach suggested by EDF and AREVA for UK EPR secondary water chemistry and corrosion control is acceptable although the detailed design, operation and operational chemistry regimes of the UK EPR secondary circuit are not yet fully defined. However, the information currently available does not suggest there should be any fundamental problems that would prevent safe operation of the secondary circuit of a UK EPR. As the design and chemistry choices are as yet incomplete, it is possible that specific deficiencies may exist in the currently suggested chemistry optimisation and limits placed on some impurities. The foremost shortfall in this area for UK EPR is the lack of a complete and cohesive secondary circuit analysis and optimisation which considers the operating regime, material choices, corrosion threats and plant design amongst others. This will form an important part of the safety case moving forward, but I am content this can be addressed at a later stage.
- The importance of the SGBS in the secondary circuit of UK EPR is apparent and the optimisation of this feature will be important, as this will dictate many of the available operating chemistry choices. The currently presented information for this system needs to be integrated into the overall analysis described above.

- On-going work would benefit from the production of comprehensive chemistry documentation that addresses the relationship of the secondary circuit design and operation to the secondary circuit chemistry and corrosion risks. This will assume consistency across the many secondary circuit SSCs as the safety case develops.

836 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.4.2.4 Assessment Findings

837 Based upon the assessment of secondary circuit materials, design and chemistry in UK EPR described in Section 4.4.2 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-27*** *– The Licensee shall conduct a design review, justification and analysis for the secondary circuit considering the operating regime, material choices, corrosion threats and plant design amongst others. This will input into the secondary chemistry optimisation. This should consider all of the major secondary circuit systems, including many of those not included within the GDA scope. This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-UKEPR-RC-28*** *– The Licensee shall generate an assessment of the consequences of introducing Emergency Feedwater into the SG with elevated dissolved oxygen levels. This Assessment Finding should be completed before operation of the steam generators at temperatures above 120°C, as risks below this temperature are low. Target milestone – Hot Ops.*
>
> ***AF-UKEPR-RC-29*** *– The licensee shall update the safety case documentation to reflect the defined secondary chemistry regime. This Assessment Finding should be completed before initial plant operations. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-UKEPR-RC-30*** *– The Licensee shall review and justify the limitation on nitrogenous discharges from UK EPR on a site specific basis in consultation with the relevant regulatory bodies. This information should feed into the site specific secondary chemistry optimisation and analysis. This Assessment Finding should be completed before initial plant operations. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-UKEPR-RC-31*** *– The Licensee shall review and justify the plant specific technical strategy for the Steam Generator Blowdown System ion exchange resin beds, in conjunction with the plant specific chemistry optimisation and analysis. This Assessment Finding should be completed before initial plant operations. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-UKEPR-RC-32*** *– The Licensee shall review the requirements for automatic actions in case of significant ingress of impurities that could damage Steam Generator tubing or other components needed for nuclear safety. Documentation of the review should include evidence that the adopted site-specific strategy is appropriate. This*

Assessment Finding should be completed before plant operations commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.

4.4.2.5 GDA Issues

838 Based upon the assessment of secondary circuit materials, design and chemistry in UK EPR described in Section 4.4.2 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.4.3 Assessment – Material Integrity and Corrosion

839 Integrity of the secondary system is an important consideration for secondary circuit chemistry; for many components an inadequate chemistry regime would result in, at worst, rapid deterioration and potential for failure or, at best, increased corrosion product transport. This section details the assessment of how the material, design and chemistry choices described in Section 4.4.2 affect the integrity of secondary circuit components, particularly those related to pressure boundary integrity.

840 The assessment during Step 4 sampled two main areas of the secondary circuit to assess the impact of chemistry and materials on integrity; steam generator tubing and main secondary pipework in addition to assessing the principal material choices throughout the main circuit for the major components.

4.4.3.1 Overview of Secondary Circuit Material Choices

841 In addition to detailed information in individual system SDMs, EDF and AREVA provided an overview of material selection for the UK EPR secondary systems in Ref. 50.

842 The following table provides a summary of the principal materials used for the Secondary Circuits in UK EPR. Note that a number of these systems are outside of the GDA scope (*italicised* below) and the corresponding material choices are therefore provided for information only and subject to change;

Component	**UK EPR Specified Material (Ref. 50)**	**EPRI URD Recommended Material (Ref. 53)**
SG tubes	Thermally treated Inconel 690	
TSPs	[redacted]	
AVBs	[redacted]	
SG shell	[redacted]	
MSR tubes	[redacted]	[redacted]
MSR chevrons	[redacted]	[redacted]
MSR shell	[redacted]	[redacted]
Condenser tubes	[redacted]	[redacted]
Condenser shell	[redacted]	[redacted]

Component	**UK EPR Specified Material (Ref. 50)**	**EPRI URD Recommended Material (Ref. 53)**
Condenser tubesheets	[redacted]	[redacted]
FW heater tubes	[redacted]	[redacted]
FW heater shells	[redacted]	
FW heater tubesheets	[redacted]	[redacted]
Deaerator shell	[redacted]	
Deaerator internals	[redacted]	
Piping	[redacted]	[redacted]
Steam lines	[redacted]	

Table 13: UK EPR Secondary Circuit Component Material Choices

843 Such material choices are often plant and Licensee dependant with the degree of protection, or otherwise, offered by the chemistry in these locations being an important factor in such decisions. Thus there is no 'standard' design for such systems but there exists a wealth of experience and knowledge from operating plants to suggest which material may perform better than others in specific applications. A useful compendium of such experience is represented by the EPRI Utility Requirements Document (URD) (Ref. 53) which recommends materials for a number of secondary components. The UK EPR materials are compatible with these recommendations and in some cases may exceed them, as shown in the Table above. The only notable difference from the recommendations made in the URD is the use of ferritic stainless steel for the HP FW heater tubes. Although out of scope for GDA, this choice could be demonstrated to be reasonable from a Reactor Chemistry perspective given the increased resistance to erosion-corrosion and hardness compared to austenitic steels. The use of the same material in the MSR tubes gives further confidence.

844 Overall, the main material choices appear consistent with industry experience and OEF. However, a number of decisions still need to be taken regarding specifics for certain components where choices are still available. This is related to an Assessment Finding **AF-UKEPR-RC-27**.

4.4.3.2 Steam Generator Tube Integrity

845 Maintenance of integrity of the SG tubes is important as these thin walled tubes are the main barrier between the active primary and inactive secondary circuits. Activity released to the secondary circuit is potentially available for release to the atmosphere. The main chemistry related threats to integrity are assessed further below.

4.4.3.2.1 Denting Corrosion

846 Denting is a particular corrosion phenomenon related to the inability of AVT chemistry regimes to maintain a buffering capacity, especially in the case of ingress of aggressive species. In early SG designs this leads to general corrosion of the carbon steel TSP's and tube sheet. Aside from the fact that this process causes damage to the carbon steel components the main impact is that the oxide generated in the process accumulates in crevice areas (i.e. the annular gap between the tubes and TSP and the gap between the tube plate and tubes). The volume of this oxide is much larger than the original metal hence this exerts a pressure on the tubes as the oxide grows. This causes denting in the thin walled SG tubes leading to other issues such as increased stresses and inspection difficulties. In extreme cases cracking has been observed in between the tube support holes and the secondary flow distribution holes causing distortions in the tube bundle to occur.

847 Based on the UK EPR design, this type of corrosion should be ruled out, due to:

- Replacement of carbon steel components in the TSP with more resistant alloys.
- Maintenance of secondary chemistry purity to limit contaminant ingress.
- Removal of copper components.
- Design changes to the TSPs and tube plate expansion process.

848 I am content risks posed by this type of corrosion in UK EPR are ALARP.

4.4.3.2.2 Pitting Corrosion

849 Pitting corrosion occurs due to a localised breakdown in the surface passivity which creates a concentrated area for corrosion. It is generally accepted that pitting requires an aggressive impurity, low pH, an oxidant (usually copper) and is accelerated by increasing temperature, Ref. 192. The presence of sludge or scale is an important factor as these act as concentrators for the various factors required for pitting. The primary focus to inhibit this phenomenon has been a drive towards improved secondary circuit chemistry to minimise both corrosive species and sludge within the SG.

850 Based on the UK EPR design, this type of corrosion should be minimised, due to:

- Use of Inconel 690 SG tube alloy
- Maintenance of secondary chemistry purity to limit contaminant ingress
- Removal of copper components
- Optimisation of sludge mitigation provisions

851 I am content risks posed by this type of corrosion in UK EPR can be adequately controlled, provided impurity control is maintained and a suitable chemistry regime is selected which minimises iron transport to the SGs.

4.4.3.2.3 Intergranular Attack / Stress Corrosion Cracking

852 Outer Diameter (OD) Intergranular Attack / Stress Corrosion Cracking (IGA/SCC) has been known to affect SG u-tubes under certain circumstances, in particular the presence of chemical impurities. Based upon the description of the relevant chemistry parameters given in Section 4.4.2, and the materials and design choice described in Section 4.3, I am content that UK EPR should be as resistant to these types of corrosion as current PWRs, provided an appropriate chemistry regime is maintained.

4.4.3.3 Flow Accelerated Corrosion

853 Flow Accelerated Corrosion (FAC) is a potential area of concern throughout the entire secondary circuit. Numerous instances of FAC have been reported in the secondary circuit of power plants. It is a corrosion process that arises as a consequence of dissolution of the normally protective oxide film which forms on carbon and low alloy steel pipework. As the mechanism is a physico-chemical process, dissolution of the protective oxide layer and the transfer of dissolved iron from the surface control the rates of damage. FAC can occur under both single and two-phase flow conditions, and can be particularly prevalent under the conditions that can occur around the secondary circuit. Not only can FAC lead to rapid failures of components, it is also implicated as a significant source of Corrosion Product (CP) transport around the secondary circuit.

854 In reality, FAC susceptibility can be reduced using (or a combination of):

- Flow conditions
- Materials selection (especially chromium content)
- Water chemistry

855 During Step 3, EDF and AREVA provided some limited information on consideration given to FAC in UK EPR. This suggested that consideration had been given to this degradation mechanism in the UK EPR secondary circuit in terms of each of the main mitigation routes detailed above. I was content with this argument during Step 3. During Step 4 I requested further detailed evidence to support these arguments, especially related to material selection and chemistry protection.

856 TQ-EPR-780 (Ref. 8) provides a general overview of the approach taken by EDF and AREVA to combat FAC in UK EPR, including a description of the BRT-CICERO model which is currently used by EDF at their existing reactors. This response provides a synopsis of the FAC mitigation measures applied to UK EPR during the design stage, including consideration of both material and chemistry choices. The arguments made regarding chemistry and materials are all reasonable and consistent with my expectations for a new reactor design.

857 An important consideration for FAC mitigation at any reactor in operation is the definition of a suitable monitoring/surveillance programme. This requires full details of the local chemistry and material choices and as such is not expected during GDA. However, based upon the information presented in TQ-EPR-780 (Ref. 8) it is apparent that EDF and AREVA have the experience and capabilities to develop one at a later stage. However, it is clear that, at the current stage of development, no formal consideration had been given to such a scheme in UK EPR, in terms of accessibility and practicality. This will need to be defined and assessed once full details of the plant chemistry and materials are available and a subsequent analysis is complete. I consider this to be an Assessment Finding **AF-UKEPR-RC-33**.

4.4.3.3.1 Material Mitigation

858 The material mitigation approach to FAC is to use an alloy with elevated chromium content. Chromium, even at low levels around 0.1%, can significantly reduce the rates of damage caused by FAC by altering the protective film formed on the material to one that is more resistant. This approach is used widely, both for replacement components in existing reactors and during the construction of new reactors elsewhere.

859 TQ-EPR-1208 (Ref. 8) queried the OEF basis for the design and material choices EDF and AREVA have implemented in UK EPR. The response contains a useful summary of FAC incidences in EDF plants, from the earliest in the 1970's to the present day. Description of mitigating actions both on the affected plants (chemistry) and descendant designs (materials) provide a good basis for claiming lessons learned have been applied to UK EPR. It would not have been appropriate to provide a full and complete justification for all materials in this response, however several examples were provided where choices have been made based upon FAC concerns and EDF and AREVA chose alloys with sufficient Cr content to mitigate, or even to eliminate FAC degradations, including:

- "*choice of* [redacted] *for sensitive pipes and of stainless steel for highly sensitive pipes will eliminate the risks of FAC degradations of hall turbine pipes*."
- "*choice of* [redacted] *guarantee a 60 years lifetime of main water pipes*."
- HP feedwater heater materials including [redacted] tube bundle and [redacted] impingement baffles.
- [redacted] tube bundle, [redacted] drains and nozzles and [redacted] internal shields in Moisture Separator Reheaters (MSR).

860 All of these are very desirable measures from a FAC perspective aimed at mitigating the risk of damage. This suggests many of the main components will be afforded a degree of protection from FAC based purely on material choices.

861 Further details were provided in the response to TQ-EPR-1210 (Ref. 8) on the classification of pipes in UK EPR to FAC susceptibility. EDF use a simplified classification system based upon the service conditions of the pipe and the perceived risk of FAC this carries. Each class of piping carries a material choice for the affected pipeline, with chromium contents increasing with the perceived FAC risk. Carbon steel would be specified for pipework insensitive to FAC and stainless steel for pipework that was highly sensitive to FAC. The table below summarises the approach taken by EDF and AREVA to controlling FAC;

Pipe class	FAC Risk	Typical Conditions	Example UK EPR Locations	Material Mitigation
Insensitive	No risk of notable thickness loss	Dry or superheated steam; water at < 75 °C	Steam line drain system (VPU) Main steam by-pass (MSB) MSR to generator Dry steam lines	[redacted]
Sensitive	Risk of notable thickness loss	Wet steam; water at > 75 °C with flow singularities and non-optimised chemistry	Steam line drains (VPU) MSR drains Feedwater lines at > 75 °C	[redacted]

Pipe class	FAC Risk	Typical Conditions	Example UK EPR Locations	Material Mitigation
Highly Sensitive	Notable thickness loss expected	Biphasic fluids	Turbine extract lines Drain lines Pressure relief lines	[redacted]

Table 14: UK EPR Material Selection Approach for Flow Accelerated Corrosion Mitigation

862 The material choice for each category is based upon a technical and financial assessment performed by EDF in 2005 and as described in the response to TQ-EPR-1211 (Ref. 8). There are two options for pipework of intermediate sensitivity; use an alloy steel with good intrinsic resistance or a higher grade of carbon steel with an extra corrosion allowance. Three materials were considered; [redacted] and ‘doped’ or ‘standard’ [redacted]. BRT-CICERO calculations demonstrated the relative benefit of the chromium content to FAC rates. Economic (and other, non FAC related, technical) decisions led to the adoption of [redacted] for FAC sensitive areas in UK EPR. Purely from a FAC mitigation perspective this is entirely reasonable, with [redacted] chromium content. While simplified and not considering the interplay of material, local chemistry, geometry or flow, the EDF approach does provide a basis on which a plant specific optimisation could be performed. It is likely that this approach would allocate most pipes to the ‘correct’ category, with further refinement of a smaller sub-set of locations on the border between categories requiring individual analysis and optimisation. I am satisfied with this approach at a high level. The responses to TQ-EPR-1210 and TQ-EPR-1211 (Ref. 8) suggest that EDF have indeed reduced the risks of FAC in the secondary circuit in UK EPR by appropriate material selection, for the insensitive and highly sensitive areas.

863 It is notable that the AREVA policy related to FAC mitigation is slightly different from the EDF requirements described above. This means that the small part of the secondary circuit located in the nuclear island will use a carbon steel ([redacted] with a minimum of [redacted] chromium) and “*additional thicknesses*” to ensure a 60 years lifetime. AREVA claim that this departure is justified due to the optimised secondary water chemistry for UK EPR. Unlike the EDF approach there is a clear claim here on the chemistry regime in providing mitigation. The use of a carbon steel for regions of intermediate sensitivity would place a demand on the water chemistry to help protect the surface from FAC. It is desirable to provide ‘passive’ means of protection if reasonably practicable and the use of low alloy steel up to the NI boundary appears a better solution in this regard. This discrepancy should be reviewed for UK EPR. I consider this to be an Assessment Finding **AF-UKEPR-RC-27**.

864 While reviewing the detailed design documents provided it is apparent that consideration has indeed been given to individual systems, however it is not clear how consistent, detailed or comprehensive this analysis was. It is also not universal across each of the systems and hence may have been undertaken on a piecemeal basis. For example the SGBS SDM (Ref. 44) states that; *“Considering the materials and the water chemistry and based on the field experience with other plants there are no erosion corrosion problems expected with the chosen material. The material of the flash tank steam line and the line between flash tank and blowdown cooler is chosen on basis of FAC calculations. An additional wall thickness is necessary for the ferritic main line downstream the flash tank considering erosion corrosion because of possible low pH-value.”* While this may be a

reflection of the status of the detailed design at the time of the Step 4 design freeze (December 2009), it will need to be addressed as the design is finalised. The production of a comprehensive analysis for the secondary circuit is an important part of this approach. This is related to Assessment Finding **AF-UKEPR-RC-27**.

865 As described in Sections 4.4.1, 4.4.3 and contained within Assessment Finding **AF-UK-EPR-RC-29** overall, much of the detailed information on the choice and location of materials used in UK EPR that are resistant to FAC is not currently available, nor has an assessment for FAC around the UK EPR secondary circuit been undertaken. The information provided as part of the GDA assessment is sufficient to suggest that the main choices taken by EDF and AREVA are reasonable and provides a degree of confidence that such an undertaking is possible and should not reveal significant shortfalls in the UK EPR design. While this is not surprising given the current incomplete status of the design and corresponding chemistry regime for UK EPR, it will need to be addressed at a later stage. The responses provided in this area give confidence that this can be satisfactorily done.

4.4.3.3.2 Chemistry Mitigation

866 As described in Section 4.4.2.2, chemistry is an important parameter in FAC susceptibility. EDF and AREVA suggest a minimum pH for the feedwater in UK EPR of $pH_{175°C}$ 6.63. This is based upon two phase conditions with 36% liquid mass and is attributed to the results presented in an EPRI report (Ref. 52). EDF and AREVA claim that this is a conservative assumption, but no results were presented for the actual pH expected around the UK EPR secondary circuit. Underlying this basis appears to be an assumption that the FAC rate will be maximum at the location in the plant where these conditions exist. Due to the complexity of the secondary circuit, this is potentially untrue and may in fact neglect other areas of the plant where sensitivities exist, due to materials or the resulting environment.

867 The validity and effect of this assumption was queried in TQ-EPR-1203 (Ref. 8). In this response EDF and AREVA agree that a single pH value is not uniquely suited to all of the secondary circuit. Several example calculations with the BRT-CICERO code are described, for non UK EPR plants, which demonstrate the variations in FAC damage rates with varying pH_T, chromium content and temperature. It is interesting to note that these calculations indicated a need for “*additional* [pipe] *thicknesses in specific areas*”. Further calculations were also provided for UK EPR feed system conditions, which showed that the pH_T in these systems depends upon which of the suggested secondary chemistry regimes was implemented. This analysis suggested some FAC sensitivity was possible in these systems, depending upon the precise materials used. This appears to have been recognised by EDF and AREVA who stated that “*The pH required in different parts of the secondary circuit will be optimised following the materials choice*”. In fact, this is an iterative process, with material choices intimately linked to operating chemistry and hence system design. As described above, detailed information on the choice and location of materials used in UK EPR that are resistant to FAC is not currently available, an assessment for FAC around the FA3 EPR secondary circuit been undertaken by EDF and AREVA but large parts of the secondary circuit are site-dependent. The effects of amine degradation on pH_T also need to be considered in the assessment.

868 Ultimately, this may mean that the minimum pH_T should be defined for alternative locations around the secondary circuit that are more susceptible to FAC. Working back from this analysis may lead to a different requirement for pH_{25}, which in turn could affect the whole basis for the secondary chemistry and associated system designs and

operation. I consider this to be an unlikely occurrence as ‘adequate’ in this context is subjective and inadequacy does not mean the plant is unsafe, rather further attention may be needed on the balance struck between monitoring/surveillance and mitigation in these areas. This is related to an Assessment Finding **AF-UKEPR-RC-27**.

869 EDF and AREVA expect UK EPR to operate with high levels of hydrazine in the feedwater to remove residual dissolved oxygen. It can be shown that a small residual feedwater oxygen concentration is beneficial in reducing FAC, although this must be balanced with the risk of oxygen induced corrosion in the SGs. EDF and AREVA suggest that such a regime is not justified instead preferring to remove as much oxygen as possible from the feedwater. This is consistent with current operating plant chemistry.

870 Overall, EDF and AREVA have suggested an approach for chemical mitigation of FAC in UK EPR. There is nothing to suggest this approach is unreasonable, and I believe that the chemistry regime suggested for UK EPR should offer some degree of protection from FAC, however as indicated previously a more detailed assessment of the UK EPR specifically will be needed as the project progresses, both to demonstrate control of the FAC risks and as an input into the development of a monitoring/surveillance scheme for UK EPR. This is related to Assessment Findings **AF-UKEPR-RC-01**, **AF-UKEPR-RC-27** and **AF-UKEPR-RC-33**.

4.4.3.4 Summary

871 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of secondary circuit integrity in UK EPR are:

- While many of the detailed material choices for UK EPR have yet to be made, EDF and AREVA have provided information on the principal material choices for the secondary circuit which is in contact with the coolant. These appear reasonable and consistent with operating experience from the latest generation of PWRs.
- For the specific areas sampled during GDA, SG tube integrity and FAC, EDF and AREVA have provided reasonable arguments to support UK EPR for GDA. Many of the historically encountered integrity problems will be eliminated or reduced in UK EPR. As indicated previously, the foremost shortfall in this area is the lack of a complete and cohesive secondary circuit assessment and optimisation which considers the operating regime, material choices, corrosion threats and plant design amongst others. This will form an important part of the safety case moving forward, but I am content this can be addressed at a later stage. I have raised Assessment Findings in these areas.

872 The information currently available does not suggest there should be any fundamental chemistry related integrity concerns that would prevent safe operation of the secondary circuit of a UK EPR. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.4.3.5 Assessment Findings

873 Based upon the assessment of secondary circuit integrity in UK EPR described in Section 4.4.3 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-33** – The Licensee shall generate evidence that the monitoring and surveillance programme for flow accelerated corrosion around the secondary circuit will be adequate. This Assessment Finding should be completed before plant operations at elevated temperatures, but certain aspects may need consideration earlier, for example, to facilitate inspection provisions in the design. Target Milestone – Hot Operations.*
>
> ***AF-UKEPR-RC-34** – The Licensee shall review the case for using a different material for the Nuclear Island (NI) sections of the feedwater piping and generate evidence for the suitability of the material used. This Assessment Finding should be completed before such components are delivered to site, to ensure appropriate design choices are made. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

4.4.3.6 GDA Issues

874 Based upon the assessment of secondary circuit integrity in UK EPR described in Section 4.4.3 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.4.4 Assessment – Sampling Systems

875 For very similar reasons to those given elsewhere in this report, sampling of the secondary coolant in UK EPR is an important part of maintaining control of the plant chemistry and helps to determine deviations and faults, often long before they become a serious safety concern. For these reasons the secondary circuit sampling systems in UK EPR were selected as an area for assessment during GDA.

876 Assessment of the UK EPR secondary sampling capabilities began during Step 3 and continued during Step 4. The overall assessment objective was to demonstrate that the UK EPR has adequate sampling capabilities and capacity to support safe operation of the plant during all modes of operation. Information regarding the detailed operation of the system and hence its suitability to provide the chemistry functions was the main focus of the assessment during Step 4.

877 During Step 3 I noted a number of beneficial features had been incorporated into the design, such as effluent recycle provisions, sample isolations and ‘on-line’ measurements for a number of important secondary circuit parameters. Overall, at the end of Step 3, I were content with the general approach demonstrated for UK EPR in the design of the secondary sampling systems. However, I had not fully considered the overall suitability of the UK EPR secondary sampling system, but did recognise the effort that appeared to have been put into the design of the systems. I expected further details would be required in a number of areas such as the capability of the system to deliver representative samples and sampling locations.

878 As for the primary side sampling systems, my assessment has been informed by a TSC contract, which specifically reviewed the UK EPR design in this area (Ref. 37).

4.4.4.1 Secondary Sampling Overview

879 The sampling system for the UK EPR is a collection of discrete systems that collectively provide the licensee with the capability to sample the secondary circuit systems. Together these systems deliver representative samples of fluids from secondary systems to on-line monitors which are used to detect impurity ingress and provide information on deviations in plant performance, in addition to providing a number of local grab sample locations.

880 As a number of secondary systems are defined as out of scope for the GDA assessment a complete review of all secondary system sampling is not possible. However, in response to my request, EDF and AREVA provided information in sampling locations in UK EPR (Ref. 54).

881 These UK EPR secondary side sampling systems are described in detail below and are composed of:

- The SG secondary side sampling system (RES), part of the nuclear island sampling system.
- The Feedwater Chemical Sampling System (SIT).

4.4.4.2 Steam Generator Sampling

882 The RES is described in the PCSR (Ref. 11, Section 9.3.1) and in the corresponding SDM (Ref. 54). This system receives samples from the secondary side of the each SG and liquid samples from the SGBS treatment lines and directs them towards the sampling room located in the auxiliary building. Grab samples for chemical analysis are taken over a sink. In addition, each sampling line is permanently connected to on-line monitors (conductivity, after cation conductivity and sodium) and is thermally conditioned (using a heat exchanger cooled by CCWS followed by a common finishing heat exchanger cooled by the Chilled Water System (DER)). On-line instrumentation is protected by magnetic filters to ensure magnetite deposition or clogging does not affect the meters. This is commonly used in conventional power stations and is suggested by EDF based on OEF from previous French nuclear plants. Where a dedicated instrument is not used for each line, cross connections allow the various meters to cover all sample lines. A permanent measurement of activity, using the Permanent Radiation Monitoring System (PRMS) is also performed on-line on each of the four SGs, helping to determine normal primary to secondary leakage and allow quick detection of SGTR using on-line activity monitoring including Containment Isolation Valves (CIVs) which are activated on high activity levels. The entire RES system is made from austenitic steel, apart from the heat exchanger pipes which are made of ferritic steel.

883 The RES consists of the following samples:

- One line per SG, taken from either the hot leg, cold leg.
- Five sampling lines from the SGBS; downstream of the mechanical filters, two samples downstream of the cation demineraliser of trains 1 and 2 and two samples downstream of the anion demineraliser and final resin filter of trains 1 and 2.

884 As described in Section 4.4.2.11, each SG has a separate blowdown line, extracting from locations close to the tube plate and comprising of two nozzles on the hot leg (which join to a common line) and a third one on the cold leg side of each SG. In normal operation, the SG sampling lines are connected at the hot leg side of each SG as most impurities collect there. Sample flows are in the order of 250 litres hr^{-1} per line and run continuously. The cold leg side of the SG are usually closed, being used if necessary during start-up. Sampling lines monitoring the effectiveness of the SGBS operate at around 150 litres hr^{-1} per line and are operated as required to monitor the SGBS performance, typically monitoring the SGBS demineraliser outlets. The sample lines are designed so that turbulent flow conditions ensure representative sampling. Sample flow is driven by the system operating pressure, which is sufficient in all plant states requiring RES sampling. Each line is fitted with the required control, isolation and pressure relief valves. The sample lines include a motorised valve which closes quickly when activated by a

containment isolation signal, and a programmed slow-opening valve for use when the line is put back into service; this prevents thermal shocks to the head heat exchangers.

885 Effluent from the conductivity and PRMS activity measurement outlets is directed to a buffer tank (at atmospheric pressure) whose level is controlled by a motor-driven discharge pump which returns the coolant upstream of the SGBS, unless chemically or radiologically contaminated, in which case it is directed to waste via the Nuclear Vent and Drain System (NVDS). The buffer tank is sized to be sufficient to receive, continuously and permanently, all the flow from the in-service RES lines.

886 The radioactivity monitors in the secondary system (i.e. the main steam monitoring system, the Nuclear Sampling System (RES) of the SGBS and the condenser air removal system) are installed to monitor any primary-to-secondary transfer of radioactivity, most likely due to SG tube leakage or rupture. The defective steam generator is identified by continuous monitoring of the SGBS in conjunction with the online activity monitoring (KRT) and grab sampling analysis. Secondary fluid is extracted from the SGBS sampling lines and routed via gamma activity measurement equipment (KRT) such that each SG is monitored separately and continuously for radioactivity carryover to the secondary side. The main safety-classified main stream line monitors are the primary means of measurements, with the RES as a diverse means to verify that affected SG. Grab sampling using the RES is possible under these conditions, within radioactivity limits.

887 On a functional level the design adopted within the RES is consistent with industry experience and good practices from the KONVOI and EDF plants. Specific features adopted that may increase sample consistency and accuracy include temperature conditioning in close proximity to the sample point and the use of short sampling lines where practicable, both of which reduce the length of sample line at high temperature and reduced the risk of deposition and line effects.

888 As described in Section 4.4.2.2, the build up of organic degradation products in the secondary coolant due to use of an organic amine conditioning agent leads to higher after cation conductivity values that obscure detection of any ingress of strong acid anions, such as chloride and sulphate. In UK EPR the anion resins are to be replaced when the effluent from the blowdown resins has an after-cation conductivity > 0.2 μS cm^{-1}, which probably reflects the expected levels of organic acids in the effluent stream. In principle this could obscure the presence of low levels of strong anions such as chloride and sulphate (0.2 μS cm^{-1} is equivalent to around 15 μg kg^{-1} chloride), which will be returned to the steam generator, as in the case of sodium discussed previously. I queried the consideration given to this in TQ-EPR-1205 (Ref. 8). The response provided feedback from EDF plants which dose a range of secondary chemistry additives, including ammonia, morpholine and ethanolamine as suggested for UK EPR, although none operate a secondary chemistry identical to those suggested for UK EPR. EDF and AREVA suggest a similar approach to existing EDF plants could be used, whereby increases over the ‘baseline’ SGBS cation conductivity will be investigated by sampling to determine the cause of the increase. Furthermore, EDF and AREVA claim that the addition of a deaerator to UK EPR should further reduce any effects of this phenomenon due to limiting the dissolved oxygen available for degradation of the amines. I am content that this effect can be adequately managed in UK EPR but should be further considered once a final chemistry regime is defined and when defining limits and conditions specific to the plant. I consider this to be an Assessment Finding **AF-UKEPR-RC-35**. Since the conductivity method ceases to be straightforward if amines are employed there will be a need to define and document the actions necessary to minimise and control impurity levels.

889 As described in Section 4.4.2, control of particulate and soluble iron is important. TQ-EPR-1404 (Ref. 8) queried how this would be achieved in UK EPR. The response provides a description of those features in the RES which should allow accurate samples to be taken including, large number of sampling points, flow, temperature and pressure regulation, reduced sample line length, turbulent and constant sample flow and the use of specific devices for filtering the sample for analysis. All of the features described are consistent with OEF from existing plants and should provide capabilities at least equivalent to current plants, noting that representative iron sampling is difficult in any plant. In the response (Ref. 51) to RO-UKEPR-44.A2 (Ref. 9) EDF and AREVA suggest that the feedwater iron level will be measured regularly to estimate deposit build-up in the SGs, which is a positive proactive approach.

890 Overall, the RES design is considered to be satisfactory for the sampling of the SG secondary side and incorporates a number of beneficial features which should offer advantages for control and monitoring of secondary chemistry.

4.4.4.3 Feedwater Sampling

891 Sampling of the secondary systems outside of the SGs is undertaken by the Feedwater Chemical Sampling System (SIT). The SIT is not described in the PCSR (Ref. 11), but a description was provided in response to RO-UKEPR-44.A2 (Ref. 46). The SIT is the equivalent of the RES for the feedwater system, providing both on-line and grab sample locations throughout the secondary circuit. The system samples various locations which are grouped into four categories based on the frequency and location of analysis, namely:

- Continuous centralised measurements of CEX, deaerator, Moisture Separator Reheaters (MSR), HP feedwater heaters (AHP) and the Steam Line Drain System (VPU) (6 lines in total).
- Continuous local measurements of the six condenser pressure tanks and the CEX in order to detect leaks in the various tube bundles (6 lines in total).
- Discontinuous measurements of suspended solids, total iron and dissolved oxygen in the AHP system.
- Manual discontinuous measurements in a number of secondary systems including; LP and HP feedwater heaters (ABP and AHP), deaerator, MSR, Turbine Steam and Drains System (GPV), Conventional Island Closed Cooling Water System (SRI), Condenser Vacuum System (CVI), Start-up Condensate and Feedwater Purification Plant (ATD) and CEX.

892 The SIT is fabricated in stainless steel (304L or 316L) dependant upon the corrosiveness of the sampled liquid.

893 Samples are directed towards a number of “*panels*” located within the turbine hall, generally as close as possible to the sample points to minimise delay and response times. The continuous centralised measurements are directed towards a SIT sampling room in the turbine hall; other panels are arranged locally. On-line measurements are available to the operators in the control room, especially for CEX samples to determine impurity ingress. Samples are cooled by a primary (Conventional Island Closed Cooling Water System (SRI)) and secondary (Chilled Water System (DER)) cooler; with the exception of the CEX samples which are cool enough not to need the primary cooler. The primary cooler is located in the turbine hall close to the sampling location. The CEX, MSR, AHP and VPU sampling lines have an electric heater located downstream of the

secondary coolant in order to control the temperature of the samples to 25 ± 1°C at a flowrate of 250 litres hr^{-1}.

894 The continuous centralised sample lines are equipped with various on-line meters for dissolved oxygen, hydrazine, sodium, conductivity and pH. Excess sample and uncontaminated meter effluent is returned to the CEX. Grab sample waste and contaminated meter effluents are sent to waste via the Secondary System Wastewater Removal (SEK). The continuous CEX samples are directed through after cation conductivity meters to determine cooling water ingress; once detected more local sampling is undertaken to determine and isolate the location of the leak before repair. Detection of impurity ingress has been discussed previously, Section 4.4.2.2.1.

895 Overall, the SIT appears to have taken much OEF and experience from current plants including the use of multiple manual sampling points, local sampling temperature reduction and two heat exchangers fitted in series to accurately condition sample temperature. The use of on-line instrumentation allows rapid detection of potential chemistry faults and is consistent with many of the more modern plants. Specific improvements to the SIT for UK EPR which are beneficial, compared to the latest French (N4) plants, include:

- Doubling of general Secondary Condensers (CEX) conductivity measurements.
- Sodium and pH measurement on CEX.
- Addition of protective by-passable magnetic filters and installed 'Johnson mesh' mechanical filters upstream of control systems.

4.4.4.4 Summary

896 Based upon the evidence presented during GDA, the main conclusion I draw for the secondary circuit sampling assessment of UK EPR is:

- The UK EPR secondary circuit sampling systems, the RES and the SIT, have both taken due account of operating experience and relevant good practice in their design. Many of the incorporated design features, as described above, will provide improvements to the sampling capabilities and chemistry control.

897 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.4.4.5 Assessment Findings

898 Based upon the assessment of the secondary circuit sampling in UK EPR described in Section 4.4.4 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-35*** *– The Licensee shall review the implications for organic acid impurities in the secondary circuit based upon the operating chemistry and document their justification for any limits specified. This Assessment Finding should be completed before hot operation of the secondary side of the plant. Target Milestone – Hot operations.*

4.4.4.6 GDA Issues

899 Based upon the assessment of secondary circuit sampling in UK EPR described in Section 4.4.4 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.4.5 Assessment – Start-up and Shutdown Chemistry

4.4.5.1 Overview

900 As for the primary circuit, during any shutdown the secondary circuit will be taken from normal operating conditions of high temperature and pressure to almost ambient conditions. As the secondary circuit is nominally non-active, there is no radioactive ‘crud’ burst although a significant increase in iron in the coolant is expected and as such the concern is more with maintaining adequate chemistry control during the transient. Similarly start-up periods can pose similar challenges and the main difficulty is with establishing and maintaining the correct chemistry.

901 No details were provided in the safety case on this topic during Step 3, so all assessment has been undertaken during Step 4.

902 TSC support was also provided in this area during Step 4, including a specific review of UK EPR (Ref. 109).

903 A number of TQs and ROA responses provided information on the UK EPR start-up and shutdown chemistry in the secondary circuit. TQ-EPR-167 (Ref. 8) provides a general overview of the steps during such transients and the response to RO-UKEPR-44.A2 (Ref. 9) provides an overview of the chemistry (Ref. 51). These are the main responses in this area.

904 Several phases were identified in the shutdown sequence; from hot shutdown, where primary side heat is removed first by the SGs and subsequently by the RHRS once connected to the primary circuit, to cold shutdown. During this transition the heat removal duty of the SG diminishes and thus the steam generation slows which alters both the feedwater flow and the partitioning of the pH additive between the steam and water phase. Under low flow conditions (< 4% power) the SG feedwater is supplied via the Start-up and Shutdown Feedwater System (SSS). During long shutdown periods this may introduce higher levels of oxygen than desirable, but can be managed by maintaining an excess of hydrazine at a low temperature. In addition to the deoxygenation function during normal operations the addition of a deaerator to the UK EPR secondary circuit is advantageous for such transient periods, providing a reservoir of conditioned feedwater. The SSS pipework is specified as 13CrMo4-5 low alloy steel which should provide adequate protection from Flow Accelerated Corrosion (FAC) risks. This alloy is used in EDF plants with positive OEF.

905 Chemical dosing of the various systems is fulfilled by the Chemical Reagents Injection System (SIR). During start-up and shutdown the SIR controls the chemistry in the CEX, ADG and ATD systems. Further assessment of the SIR is described in Section 4.4.

906 The assessment of the UK EPR secondary sampling system is given in Section 4.4.4, including consideration of the suitability and operability of the system during start-up and shutdowns.

4.4.5.2 Control of Chemistry during Shutdowns

907 Similar to normal operations, the only system available to clean-up the secondary coolant in UK EPR during a shutdown is the Steam Generator Blowdown System (SGBS), which

is operated at full capacity during the cool down (1 % of main feed flow). The SGBS is assessed in more detail in Section 4.4.2.1.2. Even though control of impurity levels is important to ensure optimum start-up conditions, the risks from impurity ingress are less during a hot shutdown phase compared to normal operation, due to the lower temperatures. As a consequence, the hot shutdown chemical specification is focused on oxygen concentration limitation and cationic conductivity in the steam generator feedwater.

908 EDF and AREVA described the UK EPR approach in response to TQ-EPR-167 (Ref. 8). During a shutdown the heat transfer between the primary side and the secondary side is smaller than during power generation, hence this leads to limited steam production. During this transition phase EDF and AREVA assume that no steam is produced so as to establish conservative chemistry specifications of the SGBS. Amines added will remain in the liquid phase during a hot shutdown and consequently, the expected pH (in the feedwater and SG blowdown) will be maintained between 9.4 and 9.7 at 25 °C, dependent on the selected amine. According to TQ-EPR-167 the expected feedwater dissolved oxygen concentration of during hot shutdown is below 20 µg kg^{-1}. This target is more rigorous than that specified by EPRI (Ref. 28). Feedwater required as the coolant contracts is provided from the feedwater deaerator tank.

909 During the shutdown transient the changes in temperature, pressure and chemistry in the SG causes any impurities which have concentrated in crevice regions to be released into the SG water; the 'hide out return' (HOR). While not a decontamination technique as such, measurement of the concentrations during these periods is an indicator of general secondary circuit performance over the previous cycle and may indicate a requirement for maintenance or more aggressive cleaning methods during the shutdown. In the response to RO-UKEPR-44.A2 (Ref. 51), EDF and AREVA describe a process for such determinations in UK EPR which appears reasonable.

4.4.5.3 Storage and Lay-up

910 Once cooled and stabilised the secondary circuit needs to be placed into a suitable storage condition which, with the exception of the SGs, means a dry lay-up. For the SGs the nature of this storage depends on the duration of the lay-up required and the activities to be performed (for example, maintenance). In the EDF and AREVA approach dry lay-up involves the establishment and maintenance of a controlled humidity environment while wet lay-up involves conditioning with high pH and hydrazine. While both approaches could be shown to be acceptable, I queried a number of detailed points.

911 For dry lay-up the underlying assumption is that by controlling the relative humidity (RH) no condensation will occur in the components. Condensation can be very detrimental due to pollution from airborne contaminants which can lead to the generation of very high impurity levels locally. EDF and AREVA suggest a limit value of 40% RH at 20 °C will be used for UK EPR. I queried these effects in TQ-EPR-1405 (Ref. 8). The response from EDF and AREVA provided general data, but not for magnesium salts which have been found to be prevalent in the UK marine environment (Ref. 108). The response also appears to take credit for the HVAC systems to maintain low levels of impurities during dry lay-up operations. I am not content that an adequate case has been made in this area, although this is largely an operational matter and will require management by the Licensee. There is no reason to consider UK EPR could not operate to lower RH levels if required. I consider this to be an Assessment Finding **AF-UKEPR-RC-36**.

912 For wet lay-up no concentrations were specified for anionic impurities. The current EPRI practice is to have levels less than [redacted] mg kg^{-1}. The response to TQ-EPR-1209 (Ref. 8)

indicated that although current EDF practice is to control the levels by using the influent water source which may not be suitable if leaching of SG internals occurs; the approach for UK EPR will be based upon a limit of 0.5 mg kg^{-1} each of sodium, chloride and sulphate. I agree that the approach suggested for UK EPR seems reasonable.

913 The addition of hydrazine during wet lay-up was also queried (in TQ-EPR-1209), as the calculated minimum amount of hydrazine appears to rely on a formula which would allow ever increasing amounts to be added, with no maximum. This might not cause difficulties for lay-up requirements but could create a disposal hazard if significant quantities are generated. EDF and AREVA suggest the addition of copper sulphate to react with excess hydrazine prior to disposal. This approach has not been justified when aeration would generate less waste, but I consider that a Licensee could specify a suitable mode of operation.

4.4.5.4 Start-up Chemistry Control

914 During a start-up the impurities (especially oxidising species) within the secondary circuit are often much higher than during normal operations. Refilling of the secondary circuit during a start-up is undertaken from the water distribution system (SER within nuclear island) at pH 9. The condenser vacuum and deaerator systems are used to remove oxygen and non-condensable gases during heat up, with limiting values for oxygen before rising above 120 °C of 100 $\mu g\ kg^{-1}$ and a target Steam Generator Blowdown system (SGBS) hydrazine concentration of $> 100\ \mu g\ kg^{-1}$.

915 During Step 3 EDF and AREVA provided some information on the Start-up Condensate and Feedwater Purification Plant (ATD) although it was not clear if this was included in the UK EPR design. I have confirmed that this is indeed part of the design, but was not included in the Step 4 PCSR (Ref. 11). The ATD is used to fill the secondary circuit and purify and heat the SG feedwater during start-up phases and consists of filtration, ion exchange, chemical dosing connected to the SIR and a regenerative heat exchanger. The system will be used to treat approximately 1,800 m^3 of secondary coolant at a flow rate of around 300 $m^3\ hr^{-1}$ to produce the start-up feedwater specifications. As the UK EPR ATD media is not regenerated on site this reduces the potential for secondary circuit contamination by regenerant chemicals. The ATD system has no operational role during normal power operations or in fault conditions.

916 The ATD system is a new plant feature for UK EPR; it does not have an equivalent in previous French or German plants. In the N4 series the same functions are performed by feedwater tank heating by auxiliary steam and via condenser discharge and make-up. Some 900 MW_e plants use a mobile purification station, similar to the UK EPR ATD system, to chemically condition the feedwater plant. The basis for the ATD system is consistent with the approach suggested by EDF and AREVA and I believe that the functional requirements of the system can be met. However, the detailed system design has not been considered during GDA. I am encouraged by the introduction of the ATD into the UK EPR design and believe that it will offer advantages for impurity control during start-up periods; additionally I am content that failure or unavailability of the ATD will not result in safety issues, merely delays to the start-up duration. In cases of complete unavailability of the ATD, UK EPR could still operate in the same manner as the N4 plants.

917 I asked various queries on the ATD system in TQ-EPR-1406, 1407 and 1408 (Ref. 8), regarding design features and operating performance. The responses provided greater clarity on the operational intent for start-up in UK EPR using the ATD system to control the chemistry. Based on the responses it appears that the intent is to operate the ATD

with standard ion exchange resins on a non-regenerable basis, with an expected lifetime of 100 hours at the nominal flowrate and outlet concentrations. Some of the operational details are currently lacking, but these can be developed as the safety case is progressed. This is related to Assessment finding **AF-UKEPR-RC-01**.

918 In the response to RO-UKEPR-44.A2 (Ref. 51), EDF and AREVA suggest that the start-up impurity specifications will be based upon German plant feedback. This will allow higher concentrations of impurities in the SGBD for 5 days following start-up. This is a specific difference seen in VGB (Ref. 29) guidelines as opposed to EDF or EPRI (Ref. 28), which suggests a staggered approach with a further diminution of impurities before raising power above 25 or 30%, minimising risk of impurity hide-out. This aspect was queried in TQ-EPR-1221 (Ref. 8). The response confirmed the absence of a hold point before power raise in UK EPR. It is interesting that this hold point is retained in EDF plants, which also contain Inconel 690 tubing. EDF and AREVA provided OEF suggesting that the values likely to be experienced should be an order of magnitude lower, but the driver for the proposed change appears to be an allowance for "*operating flexibility*". I am not convinced of the validity of this approach for UK EPR, where the SG tube alloy is different to that used in Germany (Alloy 800), which has experienced some very limited degradation problems in recent years for which the more relaxed secondary control has been suggested as a contributing factor. While I am content that UK EPR could meet the more restrictive specifications this may impact upon outage duration and further justification may be needed once precise procedures are developed for UK EPR.

4.4.5.5 Summary

919 The overall approach suggested by EDF and AREVA for secondary circuit shutdown, lay-up and start-up appears reasonable. Many details of the precise arrangements need to be finalised, and there may need to be further justification for some of the parameters, but this can be done as the project progresses. I am content that an adequate case has been made for GDA in this area.

920 Based upon the evidence presented during GDA, the main conclusions I draw for the secondary circuit start-up and shutdown assessment are:

- EDF and AREVA have presented an approach for start-up and shutdown chemistry in the secondary circuit of UK EPR. A number of features of the UK EPR design, such as the ATD system, provide positive improvements to the control of plant chemistry during such periods.
- Post GDA, fully detailed chemistry procedures should be developed, building upon the sound basis presented for GDA. I note a number of areas where further justification may be required. I have raised an Assessment Finding in this area which should support on-going assessment of this important topic.
- Post GDA fully developed start-up and shutdown procedures should be developed for the secondary circuit of UK EPR, building upon the basis presented for GDA. These should include due consideration of related topics such as limits and conditions, as appropriate. This is related to Assessment Finding **AF-UKEPR-RC-02**.

921 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.4.5.6 Assessment Findings

922 Based upon the assessment of secondary circuit start-up and shutdown chemistry in UK EPR described in Section 4.4.5 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-36*** *– The Licensee shall specify the dry lay-up chemistry requirements for the secondary circuit of UK EPR. This should include all stages of installation, commissioning and operations with evidence of their suitability. This Assessment Finding should be completed before delivery to site of the secondary circuit equipment, but certain aspects may need consideration earlier, for example, during component manufacture. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

4.4.5.7 GDA Issues

923 Based upon the assessment of secondary circuit start-up and shutdown chemistry in UK EPR described in Section 4.4.5 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.5 Ancillary Systems

924 In addition to the main primary and secondary circuits, a number of ancillary systems are required in order to support safe reactor operations. These systems are relevant because they fulfil a safety function and either they provide or support chemistry control functions or they are chemically controlled for reasons related to Safety. Those system sampled during GDA are discussed further in the following sections.

4.5.1 Assessment – Radwaste Systems

925 The design of UK EPR includes a number of provisions in order to reduce off-site releases in normal operation when compared to existing PWR plant. An assessment of the UK EPR source terms and provisions to reduce activity SFAIRP is given in Section 4.2.3. Assessment of the chemical aspects of the systems used to treat these wastes before discharge started during Step 3, although limited time was available to completely asses these complex systems. It was noted that UK EPR had included:

- Improved segregation of floor / chemical drains thus reducing the volumes of liquids discharged from the effluent treatment systems.
- Improved filtration, demineralisation and evaporation techniques used for treatment of radioactive liquid effluents.
- Hold up tanks which increase radioactive decay of short lived nuclides before discharge of liquid effluents.
- Specific consideration of the Gaseous Waste Process System (GWPS) to reduce aerial discharges during normal operations.

926 Due to the close links with other assessment areas for these systems, I have supported colleagues in ND and the Environment Agency in their assessments during Step 4.

4.5.1.1 Gaseous Waste Processing Systems

927 Radioactive fission gases, among them xenon and krypton, are generated in the reactor core during normal operations. A higher portion of these gases are released to the reactor coolant if fuel cladding defects occur. Additionally, hydrogen is added to the reactor coolant by the CVCS. Since these gases are dissolved in the reactor coolant, they are transported to various systems in the plant as a result of process fluid interchange during operations. To prevent flammable mixtures developing and other problems, there is a requirement to control these gases and condition them for release.

928 The UK EPR features a Gaseous Waste Processing System (GWPS), as detailed in the PCSR (Ref. 11, Section 11.4.3) and the associated SDM (Ref. 78). The GWPS limits the hydrogen concentration in the connected systems in order to prevent the formation of explosive mixtures and it processes radioactive gaseous wastes so as to minimise personnel exposure to radiation, and to control their release to the environment. In order to do this the GWPS:

- Maintains the majority of the connected components at a slight vacuum.
- Flushes the vessels in which coolant degasification occurs with nitrogen.
- Controls the hydrogen content in the system and in the flushed vessels to less than 4% (with an expected value of 0.3% after the recombiner) and an oxygen content of lower than 2% (with an expected value of 0.1% after the recombiner).
- Delay release of noble gases to the environment until sufficient decay has occurred.

929 The GWPS is shown schematically below (Ref. 78):

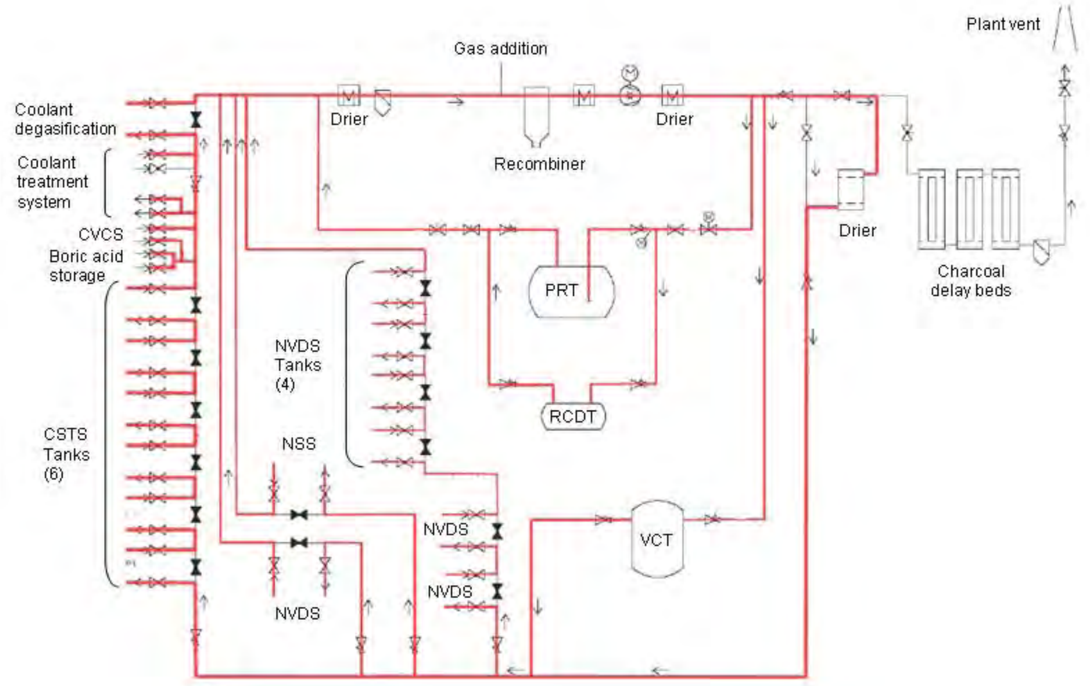


Figure 22: UK EPR Gaseous Waste Processing System

930 The GWPS consists of pipe connections to the various vessels, a catalytic recombiner, drying equipment, gas analysis sensors and three carbon bed delay columns arranged in

series. Vessels served include the VCT, the CVCS degasser, the CSTS coolant storage tanks, the NSS sample tank and various drains and hold-up tanks connected to the primary system. Coolant storage tanks are connected in activity order, preventing transfer of activity to lower contaminated parts of the plant. All components of the GWPS are made of austenitic stainless steel.

931 The GWPS has two distinct operational modes termed "*steady state*" and "*surge gas*" mode. In steady state mode the system is operated as a semi-closed loop. Released gases (hydrogen, oxygen and active noble gases) in the connected vessels are flushed out by the nitrogen purge gas stream. After recombination in the recombiner and subsequent drying the purge gas is reused, thus minimising gas releases from the plant. Only a small fraction of the purge gas is passed to the delay bed system for discharge to the plant stack. During large liquid transfer into the connected vessel (i.e. at start-up and shutdown) the GWPS reverts to surge gas mode. In this condition a much greater fraction of the purge gas is passed to the delay bed system for discharge to the plant vent.

932 The first function of the GWPS, namely control of flammable hazards, is primarily achieved by the recombiner, which is the means of recombining hydrogen purged from the connected systems. The recombiner is a heated vessel containing catalytic spheres. During operation the hydrogen and the oxygen concentration in the purge gas are measured upstream of the recombiner and are used to automatically inject additional hydrogen and oxygen as required in order to maintain a near stoichiometric ratio (slight excess of hydrogen) at the recombiner inlet. Further measurement downstream of the recombiner monitor for effectiveness. Failure of the recombiner or loss of the upstream monitoring causes the recombiner to be bypassed. Nitrogen is injected up-stream of the recombiner to reduce the hydrogen concentration by dilution (nitrogen can also be injected to help maintain the required vacuum with the recombiner in operation).

933 EDF and AREVA have calculated the size of the system on the basis of a primary coolant dissolved hydrogen concentration of 4.5 mg kg^{-1} (around 50 cm^3 kg^{-1}), which is more than twice the intended operational band for UK EPR, and on full removal in the connected vessels. The highest concentration calculated in the GWPS treated systems is 3.8% hydrogen from the CVCS degasifier.

934 Some of the coolant in the CSTS may be purified and recycled via the RBWMS. Coolant stored in the CSTS tanks which is not routed this way can still be reused in the primary circuit of UK EPR without further purification. An important function of the GWPS is therefore to prevent contamination of these latter sources with dissolved oxygen. EDF and AREVA claim that based upon the maximum design value in the GWPS of 0.1% oxygen (after the recombiner), the resulting dissolved oxygen content will be around 50% of the required value to allow direct injection of the coolant. During shutdown oxygenation, the addition of hydrogen peroxide changes the primary coolant to oxygenated conditions. The degassifier and Pressuriser Relief Tank (PRT) are connected downstream or on separate braches of the GWPS, thus minimising risk of higher influent concentrations during transients, however a potential route to the VCT exists should the degasifier not function as efficiently as expected. EDF and AREVA calculations show this may increase the coolant storage tank concentrations, but still below the limit needed for injection. It is noted that these calculations assume a temperature of 50 °C; a lower temperature would result in increased transfer to the liquid phase and higher concentrations than those calculated.

935 The second main function of the GWPS, conditioning of the gaseous waste before discharge is fulfilled by the carbon delay bed system. The UK EPR delay beds are sized to allow for a minimum of 40 days decay for xenon isotopes and 40 hours for krypton isotopes. The underlying physical retention process of the delay function does not

consume the carbon and is based on a reversible dynamic absorption process, controlled by the operational parameters of the gas stream such as moisture content, pressure and temperature. This type of system is used on many PWRs and the requirements are well understood.

936 EDF and AREVA consider both the steady state and surge gas modes in the design of the GWPS delay beds. Steady state calculations use the small release rate to the delay beds, based on the KONVOI designs and OEF, with the purge gas state considers start-up and shutdown operations, with an additional margin of 400 m^3 added during start-up events. The total mass of carbon in the delay beds in UK EPR is around 7,000 kg. The most important fission products for delay on the beds are xenon and krypton, which effectively determine the mass of charcoal required. Calculations by EDF and AREVA show that this mass of charcoal is sufficient to meet the delay time requirements for the system, with significant margin. Water entrainment to the delay beds would impair the function of the system. However, this process is reversible by drying the beds and is avoided during operations by the dryers installed in the GWPS, including the gel dryer immediately before the beds. The NVDS is used to drain any condensate formed inside the GWPS.

937 As part of the response to RO-UKEPR-73 (Refs 79 and 176) EDF and AREVA provided estimates for the activity within the GWPS. The UK EPR GWPS design will operate in a semi closed-loop mode for most of an operating cycle. This means that gaseous activity will accumulate within the system with the only means of removing activity being through the small discharge flow and by natural decay of the radionuclides. This means that long lived isotopes (^{85}Kr) will accumulate in the system over time. EDF and AREVA provide estimates for the activity in the GWPS for normal operations, shutdown and on completion of an 18 month cycle. These values are subject to much uncertainty due to details on plant operations, but can be considered conservative.

938 This may mean that discharges are lower, but doses to operators may be higher (although only marginally in both cases). It is notable that no limits or conditions have been suggested for the maximum activities allowable in the GWPS, or for operational limits which might instigate a transfer to surge gas mode. This may be more important during operations with fuel failures when activity released to the coolant will be higher. I consider this to be an Assessment Finding **AF-UKEPR-RC-37**.

939 Overall, the calculations for the GWPS appear conservative and EDF and AREVA have considered operational transients in the design. The design is based on well proven and mature technologies with many years of experience in PWRs. I am content that an adequate case has been made for the GWPS as part of GDA.

4.5.1.2 Liquid Waste Processing Systems

940 The UK EPR systems for the treatment of liquid wastes are complex. Together, they are used to store, process and monitor spent, non-reusable liquid waste before it is discharged to the environment. The Liquid Waste Processing System (LWPS) in UK EPR is designed with sufficient capacity to process spent radioactive liquid waste from two UK EPR reactors and is described in the PCSR (Ref. 11, Section 11.4.2.2) and the SDM (Ref. 80). The LWPS is installed in the Effluent Treatment Building (ETB). The main systems served by the LWPS are:

- Nuclear Vent and Drain System (NVDS) for the Nuclear Island and ETB
- CSTS distillates

- Site effluents coming from the liquid waste discharge systems

941 Following treatment the liquid waste is stored in the Liquid Radwaste Monitoring and Discharge System (LRMDS or ExLWDS) for final monitoring before discharge. The liquid wastes are sampled (for chemical and radiochemical properties) by a dedicated sampling system, the ETB sampling system (TEN). The base material used for all equipment is 304L stainless steel, except for the reagent injection system and parts of the evaporator which are made from 316L stainless steel, due to corrosion risks.

942 The main processes which are used to condition the waste stream prior to discharge are filtration, evaporation and demineralisation. Four main classes of waste are treated by the LWPS, each with a different chemical and radiochemical properties; floor drains, process drains (mainly minor polluted primary coolant), chemical drains (significantly polluted primary coolant and other chemical wastes) and CSTS distillates. Each waste class has two separate tanks in the LWPS, one for storage and collection while the other is being treated, with design features to minimise deposition or dead legs. The tank volumes are based on predicted effluent levels, from 75 to 160 m^3 per tank. Details of the volume of effluents expected to be treated by the LWPS are subject to uncertainty as they depend heavily on plant operating parameters. EDF and AREVA have used OEF from the latest N4 French PWRs as an input to the design, with the exception that some of the waste categories are altered in UK EPR (for example, water used to transfer ion exchange resins is classed as chemical drains in UK EPR and process drains in N4). The volume of CSTS distillates is currently uncertain, depending upon the extent of boron recycle. Tank volumes are based on 1300 MW_e and N4 with additional margins (but are sufficient for a two reactor site).

943 The LWPS allows each waste stream to be processed using any of the conditioning treatments although it is assumed that the following will generally apply:

- Floor drains – filtration only
- Process drains – filtration and demineralisation
- Chemical drains – evaporation; but highly dependant upon waste properties
- CSTS distillates – filtration only

944 The LWPS has a total of six filters; one 25 µm filter for each waste effluent (floor, process and chemical drains), a 5 µm filter before the demineralisers, a final 25 µm filter downstream of the demineralisers to capture any resin fines and a final 5 µm filter before transfer to the LRMDS tanks. All filters are monitored for dose rate and pressure drop, with increase in each initiating change out.

945 The three demineraliser vessels (3.3 m^3 each) can be filled with any type of ion exchange resin required for treatment of the wastes. Demineralisation is undertaken on a particular tank contents in a closed loop mode until the required discharge concentrations are met. Provisions for resin exchange and transfer are provided in the design.

946 A particular chemical concern with boric acid solutions is the potential for crystallisation and precipitation. This is generally controlled by maintaining an upper limit in the boron concentration at a given temperature. The UK EPR LWPS maintains the temperature of potentially affected vessel and pipes at 30°C. EDF and AREVA also propose to control the ratio of sodium hydroxide to boric acid within a defined band to allow solutions of up to 40,000 mg kg^{-1} boron. This is particularly relevant for the evaporator where boron concentrations will increase. Other effects such as the accumulation of radioactivity in the evaporator and the generation of other precipitates should also be considered when

details of the evaporator design and operations are available, I consider this to be an Assessment Finding (**AF-UKEPR-RC-38**).

947 The RO-UKEPR-73 response (Ref. 79) provides information on the expected activities in the LWPS, which depends on the treatment applied:

- Demineralisation is undertaken until discharge targets are met, thus limiting the treated effluent activities.
- Upstream of the LWPS evaporator the radioactivity is set as the highest of the feed streams. Downstream of the evaporator the activity is divided between concentrates and distillates, based on the evaporator performance characteristics. As described in the paragraph above, the evaporator design is unknown at present, hence estimates are based on EDF 900 MW$_e$ and N4 plant feedback. EDF and AREVA recognise that the distillate will contain the vast majority of the influent tritium.
- CSTS distillates activities are determined by the efficiency of the CSTS boron recycle evaporator and degasser efficiencies.

948 As described in Section 4.3.2.3, EDF and AREVA have taken a limiting value of 37,000 MBq t^{-1} for tritium in all cases, thus the response does not accurately account for tritium movements in UK EPR. The response (Ref. 107) to RO-UKEPR-74.A1 (Ref. 9) also does not provide estimates for tritium movements in the GWPS; however the plant vent will be monitored to control aerial discharges.

949 The LWPS sampling system (TEN) allows samples to be taken from both low and high activity sources using either a sample sink or a glovebox that is filtered (with High Efficiency Particulate Air (HEPA) filter and an iodine trap) then vented (to the GWPS). Sampling lines are stainless steel and flowrates are such that sampling times of only a few minutes are expected, minimising waste generation (although this is recycled back to the LWPS).

950 The UK EPR LWPS uses well proven techniques for chemical treatment of the liquid wastes. I am content with the design described from a Reactor Chemistry perspective.

4.5.1.3 Summary

951 Based upon the evidence presented during GDA, the main conclusion I draw for the assessment of Reactor Chemistry aspects of the radwaste systems in UK EPR is:

- The UK EPR radwaste systems for safely handling gaseous and liquid radioactive wastes are functionally very similar to many operating PWRs. The precise designs for UK EPR, particularly for the GWPS, are somewhat different to other PWRs but the chemical processes and technology are well proven and should provide adequate controls. The impact of theses systems on those they support appears to have been considered thoroughly by EDF and AREVA in the design.

952 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.5.1.4 Assessment Findings

953 Based upon the assessment of radwaste systems in UK EPR described in Section 4.5.1 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-37*** *– The Licensee shall generate a justification for limits and conditions associated with activity in the Gaseous Waste Processing System (GWPS). This should consider all forms of activity and associated maintenance and testing of the GWPS. This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated, however consideration should be given earlier to ensure the design is adequate to support the limits and conditions. Target milestone – Initial Criticality.*
>
> ***AF-UKEPR-RC-38*** *– The Licensee shall generate further details and evidence to support the operation of the Liquid Waste Processing System (LWPS) evaporator, including consideration of chemical effects in operation, such as boron crystallisation, activity accumulation or precipitate generation. This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated, however certain aspects may require earlier consideration, for example, during procurement. Target Milestone – Initial criticality.*

4.5.1.5 GDA Issues

954 Based upon the assessment of radwaste systems in UK EPR described in Section 4.5.1 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.5.2 Assessment – Component Cooling Water System

955 UK EPR, like all PWRs, has a large number of pumps and heat exchangers inside the Nuclear Island which together produce significant quantities of reject heat. In order to assure safe operation and function of these components a heat removal system is required. These functions are provided by the Component Cooling Water System (CCWS). This system is described in the PCSR (Ref. 11, Section 9.2.2) and SDM (Ref. 81). The CCWS cools a number of important components during normal reactor operations and shutdowns. The safety significance of these components varies, for example:

- A1 (F1A in France) – Low Head Safety Injection (LHSI) and Medium Head Safety Injection (MHSI) heat exchangers.
- A2 (F1B in France) – Fuel Pool Cooling System (FPCS) heat exchanger and RCP thermal barrier.
- C3 (F2 in France) – Chemical and Volume Control System (CVCS) non-regenerable heat exchanger.
- Other (non-safety) - The heat exchangers in the Containment Cooling and Ventilation System (CCVS).

956 The UK EPR CCWS consists of four separate and independent trains with each train providing cooling to the heat exchangers of the four SIS / RHRS trains via a closed cooling loop consisting of a pump and a heat exchanger (cooled by the Essential Service Water System (ESWS). The configuration of the system is such that the CCWS loops which cool the SIS / RHRS are independent, and the FPCS connection can be maintained during outages. The CCWS pipework is made from carbon steel, except for the ESWS heat exchanger tubes which are made from titanium. Materials used in the

various heat exchangers depend upon the served system conditions, but include carbon steels, stainless steels and copper alloys.

957 During Step 4 the assessment of the CCWS concentrated on two aspects of the CCWS design, namely:

- Chemistry control and addition provisions (e.g. sampling arrangements).
- CCWS Leaks either into the CCWS, especially from active sources (i.e. controls, mitigation, remedial actions), or leaks from the CCWS, especially to sources where there is a risk of boron dilution or contamination with CCWS conditioning agents.

958 Responses to TQs during Step 3 indicated a phosphate based chemical treatment was anticipated (TQ-EPR-102, Ref. 102). The Step 4 PCSR states that the CCWS cooling fluid is demineralised water which is chemically treated to prevent corrosion of equipment but no further details are presented on the proposed chemistry regime. As this is an important system and chemistry supports it safe operation, I would expect more details to be provided in the safety case either directly or referenced. These should include a specification of the detailed CCWS chemistry with evidence that the chosen regime is adequate. The specification should encompass early leak detection. My review of the consolidated Step 4 PCSR produced in March 2011 (Ref. 105), see Section 3.3, confirmed that such information was not presented in the PCSR. I consider this to be an Assessment Finding (**AF-UKEPR-RC-39**).

959 TQ-EPR-1429 (Ref. 8) queried details of the anticipated chemistry for the UK EPR CCWS and further details of the “anti-carbonation” devices. EDF and AREVA did not respond to this TQ during preparation of this report, thus no details have been provided of the expected UK EPR CCWS chemistry in time for my assessment during GDA. EDF and AREVA did not respond to this TQ until the middle of May 2011. The lack of information presented in this area is a failure to meet my expectations for GDA. However, despite the omission of most of the operating chemistry regime for the UK EPR CCWS, based upon the system similarity to current operating plants and the use of such phosphate based chemistries, I am content that a suitable CCWS chemistry could be defined and operated in UK EPR and the design should not be fundamentally different from other PWR plants in this respect; however this will need to be fully justified and reviewed once full details are available. This is related to Assessment Finding **AF-UKEPR-RC-01**.

960 Similarly, I consider that several of the Reactor Chemistry parameters related to the CCWS operating chemistry should be part of the plant operating Limits and Conditions, due to their importance in controlling corrosion and maintaining the integrity of the system, particularly across pressure boundaries. No details are provided in the consolidated PCSR (Ref. 105) on such aspects, either in the Reactor Chemistry (5.5) or Limits and Conditions (18.2) chapter. This is related to Assessment Findings **AF-UKEPR-RC-02** and **AF-UKEPR-RC-39**.

961 Chemical dosing of the CCWS is performed by the SIR, as described in Section 4.4.2.1.7.

962 TQ-EPR-787 (Ref. 8) requested details of the CCWS interfaces with served systems, including details of the interface (materials, chemistry of the served system). The purpose of this TQ was to understand where the main risks of leakage in the CCWS exist.

- Leakage into the CCWS will introduce active primary coolant into the CCWS fluid. The main risk of leakage into the CCWS is from those sources at highest pressure, which are those associated with the RCP thermal barriers and the CVCS heat exchanger. Detection of such leakage will be possible due to the CCWS level measurements in the expansion tank, via activity monitoring or, in the case of the RCP thermal barrier, by abnormal temperature or pressure readings. Isolation of these sources is initiated automatically, limiting transfer of activity. The expansion tank is sized to accept such leakage for 30 minutes. More minor leaks are more likely to be detected in routine chemistry sampling of the CCWS. Should significant leakage occur, fission gases would be removed from the CCWS expansion tanks by the building ventilation systems.

- Leakage out of the CCWS will be detected by level measurements in the CCWS system or by routine chemical measurements in the served systems.

963 Overall, while EDF and AREVA have not presented a sufficient safety case for the CCWS of UK EPR from a chemistry perspective, based on the evidence I have seen to date and provided the Assessment Findings highlighted above can be satisfactorily resolved, I am content that an adequate case could be made for the UK EPR CCWS for GDA. Further work is required in this area as the design progresses.

4.5.2.1 Summary

964 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of the CCWS in UK EPR are:

- EDF and AREVA have presented very limited and broad details on the expected operating chemistry regime for the CCWS, which is used to limit corrosion related failures on a number of safety-related heat exchangers. Based upon the design as presented, I believe that an adequate case could be made for this system from a chemistry perspective. More details will be needed in the safety case as the design is developed.
- Arguments made regarding leak detection and mitigation appear reasonable and should have minimal safety implications from a Reactor Chemistry perspective.

965 Overall, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.5.2.2 Assessment Findings

966 Based upon the assessment of CCWS chemistry in UK EPR described in Section 4.5.2 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-39*** *– The Licensee shall include the safety aspects of the Component Cooling Water System (CCWS) chemistry in the safety case. This should include specifications for the detailed CCWS chemistry, including evidence that the chosen regime is adequate. This Assessment Finding should be completed before initial plant operations. Target Milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

4.5.2.3 GDA Issues

967 Based upon the assessment of the CCWS in UK EPR described in Section 4.5.2 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.6 Accident Chemistry

968 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 practice, 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.

969 The following sections summarise my assessment of the UK EPR safety case for chemistry during accidents and faults. I sampled a number of faults, both Design Basis Accidents (DBA) and Beyond Design Basis, or Severe Accidents (BDBA or SA), and those systems provided in the design of UK EPR to mitigate chemical hazards that may arise, such as hydrogen or fission product release into the containment. The overall assessment approach was to identify the chemical assumptions made by EDF and AREVA and to form a judgement on their adequacy or otherwise. Most of the assessment of chemistry in faults took place during Step 4, in conjunction with the fault studies and severe accident inspectors, where appropriate.

970 It is important to note that EDF and AREVA claim that severe accidents (i.e. those resulting on core damage) are "*virtually excluded*" by the UK EPR design and the design of UK EPR has been optimised to minimise the risk of accidents. This has been reflected in our assessment of these events, which has been proportionate to the likelihood of such accidents occurring and has concentrated on the fundamental chemistry assumptions which underpin the safety case to check these are appropriate and that there are no "*cliff-edge*" effects.

4.6.1 Overview

971 PWRs have three successive barriers which prevent the release of radioactivity during an accident; the fuel cladding, the primary circuit and the containment. In normal operation, the primary barrier to escape of nuclear material is the cladding of the fuel itself, which retains over 99% of the nuclear material in the reactor. Failure of the fuel cladding releases radioactivity into the primary circuit, where it can be released to the containment if this barrier also fails. There are no universal statements that can be made about the quantity and levels of radioactivity released during an accident as it depends heavily on the precise sequence and conditions. However, most accidents within the design basis of the plant do not result in large amounts of damage to the fuel, but may result in some radioactive release from the plant. In our assessments, ND considers accidents to be 'severe' if significant damage to fuel cladding could occur as a result of the accident.

972 There are two fundamental requirements during an accident in a PWR, control of reactivity and ensuring adequate cooling. UK EPR includes a number of engineered safety systems to provide these functions, including:

- The emergency core cooling system, which combines the functions of safety injection (SIS) and shutdown cooling (RHRS), is organised into four separate and independent trains. Each train is fitted with an accumulator, a low pressure injection pump, a medium pressure injection pump and heat exchanger with water supplied from the In-containment Refuelling Water Storage Tank (IRWST).
- Two independent trains of Extra Boration System (EBS) which provide concentrated boric acid to the RCS. Each train consists of a pump and storage tank, connected to two hot legs.

- The containment building is provided with a metal liner to ensure very low leakage rates. The containment building is double walled to allow collection and filtration of any leakage before release to atmosphere. All penetrations emerge into connected buildings so that leakages may be collected and filtered.
- The Emergency Feed Water System (EFWS) is organised into four separate and independent trains, each with its own water tank and pump, which supply separately one of the four SGs.

973 The safety functions provided by these systems are assessed elsewhere (Ref. 58), and the control of chemistry in these during normal operation was assessed in Section 4.4.2 of this report. This means that many systems that provide normal functions for the reactor can also provide mitigation in an accident, including the SGs, In-Reactor Water Storage Tank (IRWST) and other systems that can provide emergency cooling to the reactor core. For example; some of the core coolant may be vented into the IRWST to reduce reactor pressure and the IRWST water may also be used to inject into the RCS.

974 In accident conditions, the extent of radioactive release is dependent on the amount of water remaining in the Reactor Pressure Vessel (RPV) and whether there is damage to the fuel cladding, control rods or the fuel material itself. The temperature of the fuel and the extent of the zirconium-steam reaction are key parameters determining amounts of steam, hydrogen and radioactive material evolved in the core. Evolved radioactive components not redeposited inside the reactor are expelled to the containment, becoming the ‘source term’. UK EPR is designed to contain and stabilise the molten fuel material inside the containment even if it melts through the RPV. The system that performs this function is known as the Core Melt Stabilisation System (CMSS), or colloquially as the ‘core catcher’. To control releases in such an event, UK EPR is designed to:

- Provide and maintain a containment barrier, in the form of the reactor building with a minimal leak rate and a ventilated annulus.
- Vent the reactor vessel within the containment building, to reduce stored pressure.
- Close the main steam valves to prevent leakage via the turbine building.
- Remove any combustible gases produced - in a controlled manner to avoid explosion.
- Collect fission products in the sumps within the containment, including use of a recirculated water spray within the containment building.
- Provide clean air for the operators in the Main Control Room.

975 My assessment of accident chemistry spanned the full range of accidents that might occur in UK EPR; I sampled one fault within the design basis, the Steam Generator Tube Rupture (SGTR) event, assessed the control of hydrogen and fission products, which could occur in both design basis and beyond design basis events, and finally considered the most severe accident whereby the reactor core melts and is contained within the Core Melt Stabilisation System (CMSS) in UK EPR. An important part of the assessment of all the areas was the source term. Thus, the areas identified for assessment during Step 4 were:

- Steam Generator Tube Ruptures.
- Hydrogen Control.
- Fission Product Control.
- Core Damage including the Core Melt Stabilisation System.

These are described in the following sections.

4.6.2 Assessment – Steam Generator Tube Rupture Events

976 The Steam Generator (SG) heat transfer tubes are effectively a barrier between the active primary circuit and the non-active secondary circuit of a PWR. The function of these tubes is to allow heat transfer from the primary to secondary circuits; hence they account for the majority of the primary circuit surface area (typically > 60%) and are numerous small diameter tubes with relatively thin walls to facilitate easy heat transfer. Faults involving Steam Generator Tube Ruptures (SGTRs) are important within the safety case because this mechanism can potentially result in a route for primary coolant activity to be released to the environment.

977 Assessment of these events began during Step 3, and concentrated on gaining a general understanding of where chemistry was being applied by EDF and AREVA in the analysis. The PCSR (Ref. 11) provides details on the assumptions used to derive the radiological consequences of the SGTR events, many of which are related to the underlying chemistry. The approach adopted for UK EPR was assessed further throughout Step 4, with the overall objective of my assessment being to demonstrate that the treatment of chemistry during SGTR events in UK EPR was consistent and transparent and took adequate account of chemistry as appropriate.

978 A TSC contract (ND1806) was undertaken on SGTR chemistry and produced two review reports in this area; firstly to define ‘relevant good practice’ in iodine chemistry during SGTRs (Ref. 97) and then to review the specific treatment in UK EPR (Ref. 98). The results of these reviews are consistent and integrated with the assessment that follows.

979 The UK EPR PCSR has considered SGTR events as both a PCC-3 event (frequency between $1x10^{-4}$ and $1x10^{-2}$ per year) for a double-ended rupture of a single tube (Ref. 11, Section 14.4.6) and as a PCC-4 event (frequency between $1x10^{-6}$ and $1x10^{-4}$ per year) for a double ended rupture of two tubes in a single SG (Ref. 11, Section 14.5.10). Radiological consequences for each event are also presented (Ref. 11, Section 14.6.7 and 14.6.8). EDF and AREVA include a number of assumptions in the analysis, which are claimed as pessimistic, for example; the tube rupture is located at the bottom of the SG tube bundle, on the cold side, which maximises the SGTR leak flow rate.

980 Activity release caused by an SGTR is dependant upon both the fault sequence and the chemistry during the fault. There are essentially three potential mechanisms by which active species can be released to the environment during an SGTR:

- As volatile gaseous species
- As soluble species entrained in steam droplets
- As liquid releases caused by overfilling of the SG

981 Chemistry is primarily concerned with the first of these as the main chemistry consideration during a SGTR is essentially that of iodine; iodine is of particular significance due to its radiological consequences and potential volatility at low and moderate temperatures typical of those experienced during SGTR events. A number of chemistry factors are important in determining the extent of iodine releases including the prevailing primary and secondary chemistry conditions, temperature, radiation exposure, reaction kinetics and thermodynamics, geometric factors and partitioning coefficients. When all of these factors are considered it is possible to predict the volatility of iodine which will determine the quantity released into the gaseous phase.

982 Numerous TQs were raised on SGTR events during Step 4. In reviewing these responses it is clear that the data presented in the responses to these queries is different from that given in the Step 4 PCSR in a number of ways, which are discussed in more detail below. The PCSR (Ref. 11, Section 14.6) explains these two different methodologies to assess radiological consequences of design basis accidents, based upon the German and French approaches. The German approach was used during the UK EPR design phase, while the French approach was applied during licensing of FA3 in France. The PCSR data represents the German approach, while the TQ responses tend to revolve on the French approach (although not exclusively). This immediately makes it difficult to clearly understand the assumptions in the UK EPR safety case. This needs to be resolved, with the site specific PCSR presenting a clear and consistent safety justification for SGTR events, based upon a single set of assumptions. I consider this to be an Assessment Finding **AF-UKEPR-RC-40**.

4.6.2.1 Source Terms

983 The source term used in the analysis of SGTR events presented in the PCSR is the standard UK EPR source term (Ref. 60), using the "*biological design*" values (DPB). These represent values for fission and corrosion products of at least twice the values in the "*realistic*" spectra, which themselves represent plant measurements from comparable plants (N4). This results in an initial primary coolant activity of 3.3 MBq kg^{-1} Dose Equivalent (DE) ^{131}I.

984 The response to TQ-EPR-748 (Ref. 8), raised to query the source terms used, included an analysis of SGTR events using the 'French' assessment methodology (Ref. 61). This analysis uses different values from these used in the PCSR. In this case the "*tech spec*" (DSE) primary coolant activity was used. This is based upon the operating specifications used at EDF plants, which leads to an initial primary coolant iodine activity of 20 MBq kg^{-1} DE ^{131}I. This is many times higher than that seen in EDF plants on average, and higher than that seen even with significant fuel failures.

985 An important consideration in SGTR events is the 'spiking factor' applied to transient events. Due to the thermal-hydraulic changes a short term increase (or spike) in fission and corrosion product activities is seen in the coolant. This spiking is due to an increase in release rates from the cladding gap of defective or damaged fuel and is therefore important to take into account when estimating source terms. The PCSR analysis uses a spike which results in a maximum spike factor of around 30 in 50 minutes, resulting in a ^{131}I activity of 50 MBq kg^{-1} DE ^{131}I.

986 Similarly the response to TQ-EPR-748 used a different spike model. The maximum value applied in this case was 150 MBq kg^{-1} DE ^{131}I, again based upon French fleet feedback. The timing of the peak value used was 90 minutes. Plant data shows the peak typically occurs between 3 and 6 hours, with only 10% under 3 hours, but 90 minutes was retained to be conservative.

987 There is no general consensus for a spiking factor to be applied during SGTR events, and basing the value on operational experience appears a reasonable approach. This means that, internationally, values range from 25 to 80, and it can be seen that the cases presented for UK EPR bound these values. Earlier spiking should tend to be conservative, with higher volatility at higher temperatures. Irrespective of whether the PCSR values or TQ response values are used, the UK EPR source term appears to be conservative.

4.6.2.2 Chemistry Considerations

988 At a fundamental level the operating chemistry of UK EPR will be very similar to all other operating PWRs and as such no major departures in behaviour during SGTR events would be expected. The main plant specific difference will be related to the chemistry conditions of the coolant during the accident, which control iodine speciation and hence volatility. The primary coolant hydrogen concentration in UK EPR (which is lower than comparable PWRs) and the mass and chemistry of the make-up flows may mean that reducing conditions are removed by addition of sufficient dissolved oxygen.

989 Based on the analysis presented in the PCSR it was not apparent what chemistry effects had been considered. In fact, discussions with EDF and AREVA experts suggested that the calculations in the PCSR were based upon the assumption that all iodine in the primary coolant was in an involatile form and remained so during the transient (i.e. chemistry was not explicitly considered). TQ-EPR-747 (Ref. 8) requested evidence that appropriate chemical conditions were maintained to support this assumption. The response did not satisfactorily address the concern and implied a different argument than that given in the PCSR, namely, releases are bounded by droplet entrainment assumptions.

990 TQ-EPR-165 (Ref. 8) further queried this assumption. In this case the response presented arguments for the iodine behaviour based on equilibrium thermodynamic considerations. Effectively the argument presented was based on defining the dominant iodine species at a given pH and potential, however this neglects the fact that other species may also be present at any given point on the pH/potential diagram. Without knowing the concentration of these species it is not possible to determine if they are significant or not, in terms of consequences and releases. The response also does not consider radiolytically oxidised iodine, which may be significant should the hydrogen excess be lost from the primary coolant due to addition of oxygenated safety water sources.

991 The response attempted to demonstrate that the addition of IRWST and EBS water during the transient does not result in the addition of sufficient dissolved oxygen to remove the RCS hydrogen. This is based upon a total make-up of around $50m^3$ (from the PCSR analysis). Although not stated in the response this would consume the hydrogen of around 25 m^3 of RCS coolant, meaning that hydrogen will still be present in the RCS at the end of the transient. It is noted that this appears to be contradictory to the statement that 200 m^3 of primary coolant is transferred to the SG. It is not clear why this discrepancy exists, or the consequence of this on the results presented, but suggests that the remaining make-up water (probably from the CVCS) has not been considered. This is one of the gaps in the safety argument that the Licensee should address in finding **AF-UKEPR-RC-40**.

992 Conditions in the secondary circuit are also important during the fault. Initially they will be alkaline reducing but will change during the transient as primary coolant and emergency make-up water are introduced and steam is lost. The response to RO-UKEPR-73.A1 (Ref. 176) indicates the “*normal*” primary to secondary leak rate is assumed as 4 kg hr^{-1}, based upon plant OEF. A conservative assumption of all the leakage occurring in a single SG is assumed, with 99.75% retention of volatile species in the SG water (with the remaining 0.25 % leaving entrained in water droplets). This maximises the initial SG secondary side inventory.

993 Arguments are made in the response to TQ-EPR-165 (Ref. 8) that no further oxidation of the iodine that is transferred from the primary circuit occurs. On the basis that oxidising conditions do not result in the primary coolant, and due to the low rates of thermal and

radiolytic oxidation expected in the SG, this is a reasonable argument, but as with the primary circuit rationale the arguments made are not supported by evidence which clearly links them back to the PCSR and transient analysis for UK EPR.

994 A final case presented in the response considers the effects of an oxidising environment in the SG. This is claimed to be penalising, but it does not consider an oxidising environment in the primary circuit. The arguments presented are again based upon simple equilibrium thermodynamics which do not completely preclude the formation of volatile species, as discussed elsewhere in my report. For a case where the secondary circuit only is oxidising the arguments made are reasonable and could be shown to be conservative, especially compared to the assumed steam entrainment. However, should the case include oxidising conditions in the primary coolant, and hence radiolytic oxidation, this could lead to significant volatile iodine in which case the arguments present are not substantiated. This is one of the gaps in the safety argument that the Licensee should address in finding **AF-UKEPR-RC-40**.

995 A further argument made is that even if significant (volatile) I_2 was transferred to the SG it would be expected to hydrolyse to involatile hypoiodous acid (HOI), under the expected chemical conditions. Although technically reasonable, this argument is somewhat weak as it is based upon equilibrium constants which are subject of much uncertainty. Changing the value by a factor of 10, which is within the error bands presented in the EDF and AREVA response, would result in significant volatile iodine release.

996 It is also notable that the effect of other volatile iodine species has not been considered in the response although it is likely that these can be considered negligible, compared to the other assumptions used. Hydrogen iodide (HI), for example, is volatile at higher SG temperatures.

997 As a result of the assumptions made above regarding chemistry, the assumption in both sets of analysis is that iodine is released only as soluble species entrained in the released steam. For the PCSR cases this used a factor of 0.25%. TQ-EPR-746 (Ref. 8) requested clarification of a number of areas related to this assumption. This response confirmed that a carryover fraction of 0.25% is assumed for steam produced from the bulk secondary fluid. A reference is given to support lower values but the possibility that higher values could occur during an SGTR do not seem to have been considered. Contrary to the information given in the PCSR, the 0.25% carryover does not appear to be applied to rupture from an uncovered tube, where an entrainment factor of 1% is used. The analysis provided in response to the TQ-EPR-746 (Ref. 8) appears to consider releases at the entrainment value of 1%. For both cases it is considered that the steam release fraction is likely to be very conservative. Previous UK analysis used values orders of magnitude lower for recirculating conditions.

998 The main influence for chemistry on the break location is whether mixing or flashing of the influent primary coolant occurs. This is accounted for in the use of 0.25% or 1% entrainment for the radioactivity transferred.

999 The response also clarified that, as expected, 100% of noble gases are released during an SGTR.

1000 The conservatisms assumed on the entrainment factors in either SGTR case presented by EDF and AREVA should take account of any potential releases due to the chemistry. Thus, overall, I consider the cases presented are conservative and demonstrate that UK EPR is capable of meeting UK expectations for SGTR events. However, as any chemistry is no longer driving the consequences, the arguments EDF and AREVA provide on the chemistry aspects are oversimplified and are not consistent with our expectations; for example, use of a lower entrainment factor with the chemistry as presented could underestimate the releases. This is part of Assessment Finding **AF-UKEPR-RC-40**.

4.6.2.3 Fault sequences

1001 Assessment of the fault sequences are not within the remit of the Reactor Chemistry assessment, rather with fault studies and this is reported separately (Ref. 58). However the fault sequence could have a direct effect on the chemistry and it was important to establish that the faults considered are actually bounding in terms of the chemistry.

1002 In response to TQ-EPR-574 (Ref. 8), EDF and AREVA argued that the effect of increasing the number of broken tubes is to accelerate termination of the leak, due to a more rapid equalisation of pressure between the primary and secondary sides. While the results are not completely consistent with the cases presented in the PCSR, the results show that the losses from the primary circuit were indeed lower than the single or double tube rupture cases.

1003 TQ-EPR-169 (Ref. 8) queried whether the PCSR faults presented are bounding from the chemistry point of view. The particular concern related to the possibility that other fault variants could introduce higher levels of oxygen into the primary circuit, thus jeopardising the claims made on maintaining reducing conditions in the coolant, or that SG dry-out could occur. The response did not explicitly address this concern, instead referring to the more general discussion provided in the response to TQ-EPR-165 (Ref. 8). There is no discussion of how the case described in the TQ response relates to the sequences in the PCSR, or justification that the amounts of IRWST and EBS injection are the maximum that could be attained. As outlined in the previous section, the argument presented does not consider the radiolytic production of volatile iodine species in the primary coolant if reducing conditions are not maintained.

1004 The adequacy of claims made on preventing SG dry-out is assessed elsewhere (Ref. 58). However, it is notable that even though EDF and AREVA claim this is unlikely, "*no vaporisation of solid deposits would actually occur".* This is contrary to experimental observations and testing of dry-out phenomenon and is unsubstantiated. If dry-out cannot be discounted, the response regarding release is unsatisfactory. This also should be addressed by the Licensee as part of finding **AF-UKEPR-RC-40**.

1005 In December 2010, EDF and AREVA proposed to include a design change (CMF 22, affecting recategorisation of the KRT-RES activity detection system) into the UK EPR design (Ref. 62). This would change the mitigation scheme for 2A SGTR events and may alter the transient analysis. The effects of this change on chemistry are expected to be small, but may need further assessment when complete. I consider this to be an Assessment Finding (**AF-UKEPR-RC-41**) and I support a related Fault Studies Issue in this area, **GI-UKEPR-FS-04**, see Ref. 58.

4.6.2.4 Radiological Consequences

1006 As with the fault sequence, assessment of the radiological consequences of SGTR faults is reported elsewhere (Ref. 58). As can be seen from the preceding sections there are significant differences in the assumptions used in both the PCSR and TQ analysis (or German and French approach), relating to the source term, spike factors and carry over. Overall, the French approach is more conservative and should yield higher releases. A comparison of the calculated releases in both cases confirms this, with the values quoted in the PCSR orders of magnitude lower. However, despite these significant differences the radiological consequences quoted in both cases are identical which cannot be the case without significantly different assumptions in the release modelling. This discrepancy needs to be resolved on a site specific basis. This is related to Assessment Finding **AF-UKEPR-RC-40**.

4.6.2.5 Summary

1007 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of SGTR events in UK EPR are:

- There are no novel chemistry differences in UK EPR compared with other PWRs, so there is no reason to consider different phenomenon. This means that the consequences of a given event would thus be similar to other reactors, as long as the same assumptions can be made about the factors controlling the release.
- There are differences between some of the data and methods given in documents supplied for GDA and in the PCSR, which are discussed above. This needs to be resolved, with the site specific PCSR presenting a clear and consistent safety justification for SGTR events, based upon a single set of assumptions. I have raised an Assessment Finding in this area.
- The source terms are based on plant data from French and German stations, and are conservative with regard to the relevant measurements.
- For wet reducing SGTR faults, the overriding chemistry argument is that formation of volatile iodine will be suppressed by the reducing conditions in the coolant. The arguments made in this regard are reasonable, especially when compared with the assumed droplet carryover.
- For wet oxidising SGTR faults, the chemistry assumptions made are not reasonable. However, these releases are still expected to be negligible when compared to the assumed droplet carryover. Should the droplet carryover be lowered the chemistry assumptions would need to be reviewed. Evidence has been presented which concludes that oxidising conditions are not produced during SGTR faults in UK EPR, although the link between these and the PCSR are uncertain and need to be clarified and do not fully demonstrate the bounding nature of the sequence. However, it has been shown that even if this were not the case, the assumed droplet carryover is so high that the contribution of volatiles would be negligible.
- For dry SGTR faults, the chemistry arguments made are incorrect and would lead to an underestimation of the consequences. EDF and AREVA claim that dry-out cannot generally occur in a design basis sequence since additional failures would be necessary. While not assessed as part of this assessment, if dry-out cannot be discounted, the response regarding release is unsatisfactory as it does not take account of experimental results on iodine release from evaporating films. I have raised Finding **AF-UKEPR-RC-40** covering this.
- The PCSR activity releases are significantly lower than the values quoted in the response to TQs, but the radiological consequences are unchanged. This suggests an inconsistency between the methods and data presented in the PCSR.

1008 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA. The overall safety case for SGTR events is however incomplete and ND has raised a GDA Issue (**GI-UKEPR-FS-04**) with several Actions to obtain the necessary improvements.

4.6.2.6 Assessment Findings

1009 Based upon the assessment of SGTR events in UK EPR described in Section 4.6.2 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-40*** *– The Licensee shall update the safety analysis for Steam Generator Tube Rupture (SGTR) events presented in the safety case to be a clear and consistent safety justification for such events, based upon a single set of underlying assumptions. The chemistry aspects of the safety analysis should be consistent with current experimental data and knowledge on iodine chemistry. The assumptions used should be clearly linked to the supporting transient analysis and the behaviour of the plant systems and where bounding assumptions are used these should be demonstrably so. This Assessment Finding should be completed before first active operation of the plant. Target Milestone – Initial criticality.*
>
> ***AF-UKEPR-RC-41*** *– The Licensee shall consider the impact of the proposed design change (CMF22) on the Steam Generator Tube Rupture (SGTR) chemistry assumptions used in the safety analysis presented in the safety case. This Assessment Finding should be completed before first active operation of the plant. Target Milestone – Initial criticality.*

4.6.2.7 GDA Issues

1010 Based upon the assessment of SGTR events in UK EPR described in Section 4.6.2 above, I have identified no Reactor Chemistry GDA Issues in this area. However, the ND Fault Studies Inspector has identified **GI-UKEPR-FS-04**, which I will support as appropriate.

4.6.3 Assessment – Combustible Gas Control

1011 During a number of design basis and potential severe accident sequences the possibility exists for the generation of hydrogen rich atmospheres within the containment of any Light Water Reactor (LWR). The major concerns regarding hydrogen are that the pressure or temperature loads from combustion may damage containment or that important safety-related equipment may be damaged. In order to assess the possible threats, it is necessary to understand how hydrogen is produced, how it is transported and mixed within containment, and how it combusts.

1012 Assessment in this area began during Step 3, but was very limited in nature, focussing on identifying the arguments and functionality for the UK EPR combustible gas control systems. As with all accident analysis this is a complex area, with the chemistry aspects closely related to the thermal hydraulics, accident progression and system responses. While I have supported the overall Fault Studies assessment in this area, the primary aim of the Reactor Chemistry assessment has been to determine that the rates of hydrogen production and reasonable and justified and that the chemical performance of the mitigation systems would meet the likely demands placed upon them. The consequence of combustion, in terms of its effects on the structure of UK EPR is assessed in Ref. 121.

1013 At the end of Step 3, I raised RO-UKEPR-44.A3 (Ref. 9) requesting EDF and AREVA to provide a roadmap for the chemistry of severe accidents. EDF and AREVA provided a number of specific detailed reports in response, a number of which contain information relevant and integrated into the assessment of combustible gas control that follows (Refs 66, 67, 68, 69 and 70).

1014 My assessment has also been informed by a TSC contract which reviewed both relevant good practice (Ref. 71) and the UK EPR provisions (Ref. 72) for control of combustible gases.

4.6.3.1 Combustible Gas Control Overview

1015 The potential for hydrogen build up in UK EPR under design basis or severe accident conditions come from the possibility for water radiolysis, fuel cladding oxidation or structural corrosion, amongst others, which might produce large quantities of hydrogen. In addition, the UK EPR severe accident mitigation strategy is designed to react core debris with sacrificial concrete as part of the stabilisation process. This would generate further hydrogen plus a significant quantity of carbon monoxide.

1016 The containment arrangement in UK EPR must also be considered for the combustible gas control process. The UK EPR design presented for GDA features a ‘two-room’ containment, as is currently being constructed at Olkiluoto 3 (OL3), where the containment area is divided into ‘accessible’ and ‘inaccessible’ parts for 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. For this system to work, efficient mixing and dilution is required for the smaller inaccessible area volume to mix with the much larger accessible part volume (64,000 m^3). These aspects are assessed elsewhere (Ref. 73).

1017 The UK EPR strategy for containment combustible gas management is described in the PCSR (Ref. 11, Section 6.2.4) and the corresponding SDM (Ref. 63). The system is known as the Combustible Gas Control System (CGCS). Several sub-systems form the CGCS, and have specific functions such as hydrogen removal or mixing. While it is apparent that these functions are all intimately linked, the principal chemistry related system is that which removes the hydrogen, which in UK EPR is based upon the use of Passive Autocatalytic Recombiners (PARs). PARs use catalytic material (Pd or Pt based) to oxidise hydrogen and carbon monoxide and, as the name suggests, are passive in nature requiring no external inputs to function (other than sufficient oxygen in the air). 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.

1018 A typical PAR device is shown below (Ref. 63):

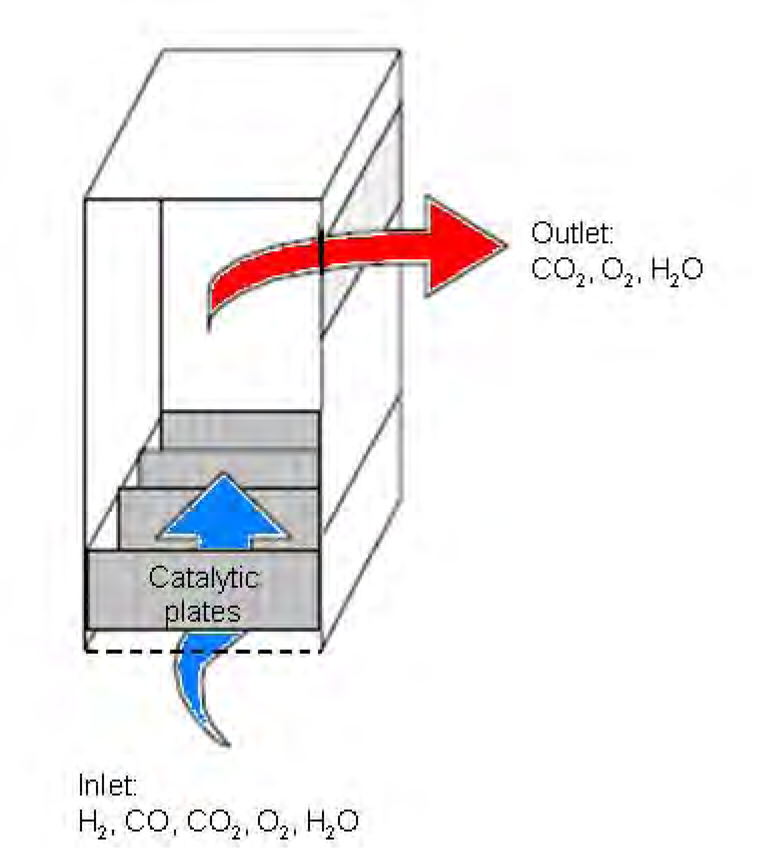


Figure 23: Typical Passive Autocatalytic Recombiner

1019 The UK EPR houses 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 (SG compartments, RCP, RCS, PZR, PRT 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 DBA and severe accident events. Two different size of PARs are used with correspondingly different hydrogen depletion rates; 41 type FR1-1500T (5.4 kg hr^{-1} hydrogen removal), “*large*”, and six type FR1- 380T (1.2 kg hr^{-1}), “*small*”. The combined depletion rate for the entire system at full capacity is claimed as around 220 kg hr^{-1} at 1.5 bar abs and 4 vol % hydrogen.

1020 The CGCS is an important system for the overall accident mitigation strategy for UK EPR due to claims made regarding:

- The practical elimination of highly energetic events including a containment hydrogen management system intended to eliminate the possibility of a hydrogen explosion (i.e. in the short term).
- A system to provide removal of hydrogen from the containment atmosphere in the long term, thus maintaining containment integrity.

4.6.3.2 Source Terms

1021 When considering the generation of combustible gases during an accident scenario there are three principal aspects which relate directly to the design of any mitigation system; the mass and the rate of production and the gas composition, all of which depend on the details of the particular accident scenario. Therefore a single accident cannot be used to represent all particular sequences that could occur, although clearly some are more likely to occur than others or may be more challenging to the design.

1022 For this reason it is common to classify the source term in terms of ‘fast’ or ‘slow’ production mechanisms. Fast production mechanisms for hydrogen include zirconium oxidation, steel oxidation, core-water reactions and Molten Core-Concrete Interactions (MCCI). Examples of slow production mechanisms include radiolysis of water and corrosion of zinc-based paint, galvanized steel or aluminium. Some of these mechanisms occur in-vessel and others ex-vessel. More than one mechanism could contribute to the production of hydrogen at any given time in a particular accident sequence. The UK EPR severe accident mitigation scheme, which includes an ex-vessel phase (See Section 4.6.5), therefore could include all of these potential mechanisms in addition to generation of combustible carbon monoxide. The approach taken by EDF and AREVA for quantifying the source term in UK EPR is described below, in terms of the possible in-vessel and ex-vessel phases, preceded by a discussion of which specific accident scenarios have been used to bound the mitigation system design.

1023 An important distinction that needs to be made here is 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 RO-UKEPR-78.A2 (Ref. 9), for which a response was not received until 8 April 2011 and hence was not assessed. I have raised **GI-UKEPR-RC-01** to cover this.

1024 However, EDF and AREVA did provide detailed information on the intended approach and background for the analysis which will support the design in addition to some modelling results from the design phase of the FA3 EPR which are very similar to UK EPR. This formed the basis of the assessment that follows. Irrespective of the assessment that follows, the final UK EPR analysis needs to be reviewed to ensure consistency with the conclusions of my assessment. I consider this to be an Assessment Finding **AF-UKEPR-RC-42**.

4.6.3.2.1 EDF and AREVA Selection of Accident Scenarios

1025 For UK EPR the demonstration of the effectiveness of the CGCS in UK EPR is based upon an extensive calculation process using numerous computer codes, as described in Ref. 64. These codes build in both complexity and detail throughout the sequence, with a greater number of scenarios examined earlier in the sequence. Selection of sequences is based upon initially examining a large range of scenarios to bound the overall performance of UK EPR, including hydrogen generation, with further refinement of the sequences for the later, more detailed and specific analysis. The main steps, along with the codes used, are:

- Initial screening analysis of a large number of calculations (about 100) of the in-vessel phase with the Modular Accident Analysis Programme (MAAP4) code. This produces the mass and release rate of hydrogen (as well as steam).
- Analysis of the ex-vessel phase of the accident using COSACO. This is the equivalent of the MAAP4 analysis for the ex-vessel phase and produces the mass and release

rates for hydrogen and MCCI gases. As discussed above, only a limited number of cases (about 3) are examined using COSACO.

- Analysis of the containment performance using the Containment Code System (COCOSYS), taking the mass and energy release values derived from MAAP4 and COSACO. This stage provides more detailed information on the hydrogen depletion rate and average gas concentrations in the containment. A reduced scenario set is analysed (about 10), which are considered the more penalising cases.
- Analysis of a further subset of key scenarios (about 5) with the Computational Fluid Dynamics (CFD) code GASFLOW. This provides more detailed analysis of, for example, the containment atmosphere mixing process, PAR performance or thermal loads from combustion and recombination on structures. The same key scenarios are also analysed with the CFD code COM3D, which is used to demonstrate that Deflagration to Detonation Transition (DDT) does not occur and that the combustion pressure loads do not compromise the containment or inner structures important to safety.

1026 The analysis procedure for combustible gas mitigation is demonstrated below (Ref. 64):

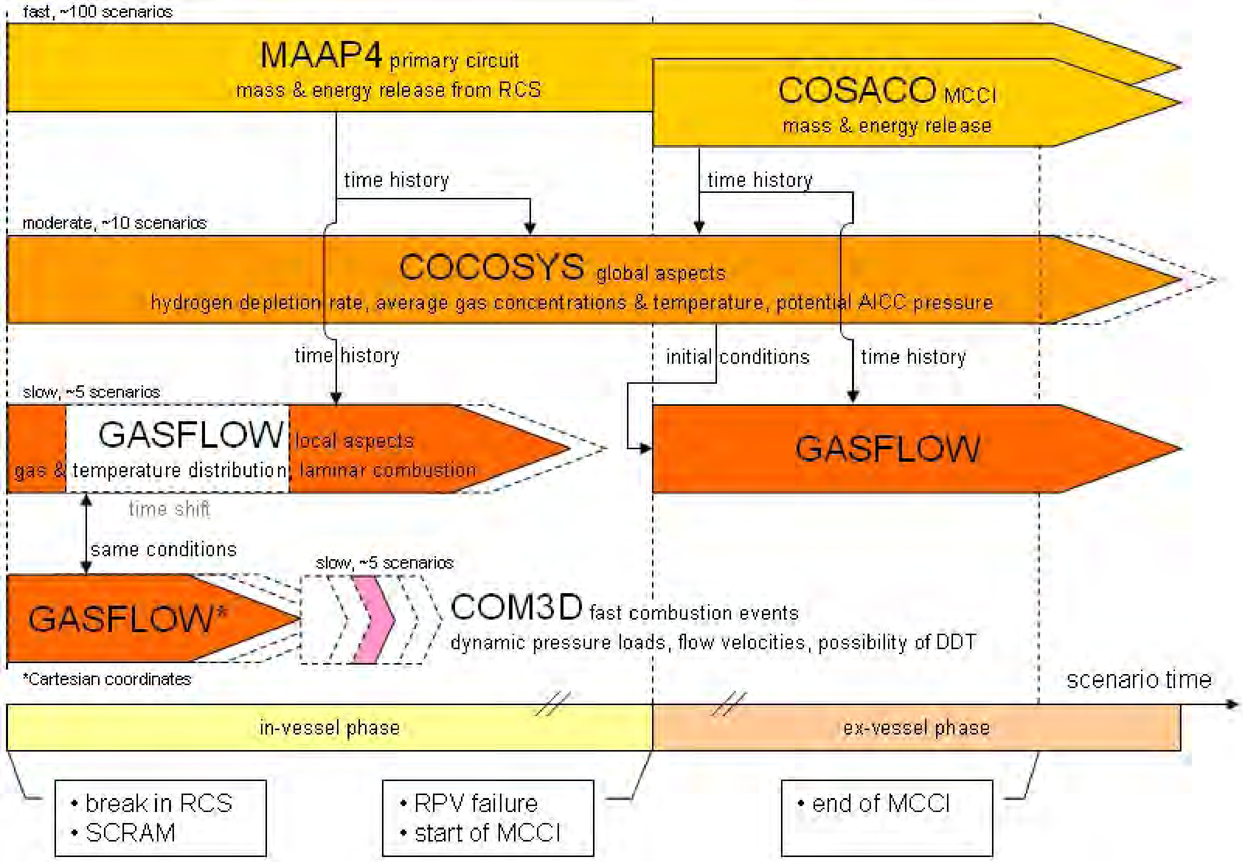


Figure 24: UK EPR Analysis Procedure for Design and Assessment of the Combustible Gas Mitigation System

1027 It is beyond the scope of this assessment to review each of these codes in detail; however a number of the most important chemical aspects of these codes, as relevant to combustible gas control in UK EPR, were assessed as detailed later in this report.

1028 An important point for the UK EPR CGCS design is that the PAR arrangement is optimised for relevant severe accident scenarios, but is also capable of reducing hydrogen concentrations in DBA events. This is due to the distribution of PARs in equipment and operation areas and because of the large decrease in combustible gases generated during DBA events; thus while the assessment that follows is largely based upon severe accident events it is generally applicable to DBA sequences. EDF and AREVA make similar arguments regarding hydrogen generation in shutdown states (where the quantities are comparable but the peak generation rates are lower) and I accept these arguments as reasonable.

1029 In the safety case, EDF and AREVA make a distinction between those accident cases which demonstrate the performance of the CGCS, and are the basis of its design, and those which demonstrate robustness and margins. These are referred to as the “*representative*” and “*bounding*” scenarios respectively. Representative scenarios feature core melt with successful depressurisation of the RCS and can include, for example, Small Break Loss of Coolant Accidents (SBLOCA), Large Break Loss of Coolant Accidents (LBLOCA) and Loss of Off-site Power (LOOP). Bounding scenarios are generally similar but feature further ‘aggravating’ conditions such as delayed depressurisation or late reflooding. Action 2 of GDA Issue **GI-UKEPR-RC-01** requires EDF and AREVA to identify a suitable bounding case for UK EPR. The exact scenarios can be determined during Phase 2 as part of the analysis described above. By way of illustration, representative scenarios yield around 500–800 kg of hydrogen and bounding scenarios yield up to 1000 kg. EDF and AREVA state that the maximum amount that could be generated by all the zirconium in UK EPR is around 1300 kg. I have raised a Finding **AF-UKEPR-RC-42** concerning all the other aspects of performance, not addressed by the bounding case, such as longevity and ex-vessel contributions to combustible gases.

1030 The CGCS is a complex system, demanding analysis by a range of computer codes. I consider the general analysis approach to be a reasonable methodology for demonstrating the suitability of the combustible gas control systems in UK EPR. The stepwise aggravation in accident conditions which is implicit in this approach provides a degree of confidence that the analysis should be conservative. I am content that provided the scenarios selected and the chemical treatments can be considered bounding, a suitable case can be made on this basis, but this needs to be confirmed. This is related to an Assessment Finding **AF-UKEPR-RC-42**.

4.6.3.2.2 In-vessel Sources

1031 If primary coolant is lost during an accident and make-up flow is insufficient the core will uncover causing the fuel rods to heat up. The extent and rate of this is dependant upon the accident sequence. Heat transfer from the fuel rods to the steam is inefficient and the fuel temperature increases, leading to the oxidation of fuel cladding and the generation of hydrogen. This reaction becomes significant above around 1100 °C due to an oxide phase change, with the heat of oxidation causing feedback further accelerating the reaction rate. The process eventually becomes self limiting due to the availability of oxidant (steam). The UK EPR depressurisation system, if successful, will have already depressurised the RCS before this point thus clad ‘ballooning’ may cause local blockages and further reduce the quantity of hydrogen generated. Production of hydrogen from steel out of core surfaces is expected to be negligible in this case, but will still include in-core surfaces.

1032 Should the accident continue, eventually the core components, including the fuel will melt. The composition of the core is such that melting can occur in a variety of ways, some involving complex chemical reactions. Logically, those components with the lowest melting point melt first, potentially interacting chemically with other components, until the final phase of the melting process occurs at around 2500 °C when the remaining ceramic materials begin to melt and relocate to the lower head of the RPV. Further hydrogen can be generated during transfer of molten core material to the lower head as, despite the high temperatures, a pool of coolant may still remain in this area. The predicted amount of hydrogen during these latter phases is subject to much greater uncertainty than with an intact core structure, mainly due to uncertainties in the actual metal surfaces available for reaction. Attempts to recover a partially degraded core by reflooding will most likely result in a significant increase in the hydrogen generation due to an increase in steam availability.

1033 In UK EPR the in-vessel sources of hydrogen are calculated using the Modular Accident Analysis Programme (MAAP4). The use of MAAP is discussed further in Section 4.6.5.1. EDF and AREVA consider three sources of hydrogen during the in-vessel phase; zirconium, steel and boron carbide oxidation. Ref. 65, "*In-vessel analysis, Hydrogen source term*", however indicated that no boron carbide had been considered. This is relevant for UK EPR which uses hybrid control rods which include boron carbide, which can potentially generate more hydrogen per mass of material than zirconium. The response to TQ-EPR-1206 (Ref. 8) clarified this assumption and provided results for cases using both Silver INdium CADmium (SINCAD or AIC) and boron carbide control rods. Unfortunately the version of MAAP4 used only allowed a single control rod material to be used. The analysis used a LOOP scenario and showed only a modest overall increase (approximately 50 kg) in hydrogen with fully boron carbide control rods, coupled with less zirconium oxidation. This is due to a competition between the zirconium and boron carbide for the available steam. This is considered bounding by the uncertainties in the MAAP4 analysis, but the case presented does not include reflooding. Based on the total mass of boron carbide in UK EPR the maximum hydrogen that could be produced is around 80 kg. In addition to hydrogen the boron carbide oxidation may also produce both methane and carbon monoxide. Depending upon the reactions this could be up to 126 kg carbon monoxide or 72 kg methane. The impact of these additional combustible gas releases is not discussed in the response and although these may be considered bounded by the overall design, the UK EPR safety case should consider this source explicitly. This is related to an Assessment Finding **AF-UKEPR-RC-42**.

1034 For hydrogen production, the MAAP4 models have been benchmarked against relevant experimental tests and the predicted hydrogen production should be similar to that obtained with other codes. The kinetic oxidation models in the UK EPR MAAP4 analysis are believed to be the most consistent with knowledge in this area, so can be considered adequate.

1035 The other variable in MAAP4 which could influence the extent and rate of hydrogen generation is the temperature selected to define the collapse of the cladding. EDF and AREVA use a temperature of 2227 °C, which is consistent with current knowledge. Both of these factors would tend to produce conservative estimates for the CGCS design basis.

1036 Much greater uncertainties exist in the later stages of the MAAP4 predictions for UK EPR. During melt relocation to the lower head the amount of hydrogen generated is limited by the surface area of the melt, which itself is subject to uncertainty on the fragmentation that will occur. Comparable, although not identical, experimental testing in this area yielded variable hydrogen generation although the results generated for UK EPR are broadly similar to other codes in this respect. Considering the limited contribution this aspect makes to the overall hydrogen generation in the in-vessel phases these uncertainties appear tolerable, although a more robust case would be beneficial.

1037 During those scenarios which feature late reflooding the UK EPR analysis predicts a modest increase in the hydrogen generation. This is another area of uncertainty, with the mass and rates directly linked to the state of the core at the time of reflooding. By choosing a 'high' clad collapse temperature EDF and AREVA optimise the time with an ordered core structure, thus maximising the hydrogen produced during any reflood. The best comparison for these effects comes from comparison with the Three Mile Island 2 (TMI-2) accident. MAAP predictions of the amount of hydrogen generated are generally understood to be reasonable, but the timings are subject to greater uncertainty. As these scenarios are those in the bounding category, which are used to demonstrate margin in the design rather than the demonstration of the CGCS against the design basis, this uncertainty is acceptable. Generally, this means that the bounding cases are subject to greater uncertainties.

1038 The ND Severe Accident Inspector for UK EPR commissioned a TSC (Sandia) to undertake independent confirmatory analysis using the MELCOR code (Ref. 100). Although only a limited number of accidents were considered during this work, in terms of hydrogen production the analysis was in agreement with the EDF and AREVA information presented in the safety case for in-vessel hydrogen sources, within the bounds of uncertainties, lending confidence to the UK EPR predictions. A fuller description of this analysis is given in Ref. 73.

1039 Overall, the size of the in-vessel hydrogen source term presented for UK EPR can be considered reasonable, aside from the uncertainty over boron carbide. However, I have raised a GDA Issue **GI-UKEPR-RC-01** concerning the rate of this release, see below.

4.6.3.2.3 Ex-vessel Sources

1040 For severe accidents in UK EPR the accumulation of molten core material on the lower head of the RPV is assumed to fail the vessel. The depressurisation system and lack of lower head penetrations in the UK EPR RPV means that the failure mode is most likely to be a local failure near the level of the molten pool in the lower head or a global failure, rather than a localised melt ejection from the bottom of the vessel. In UK EPR, a depressurised reactor vessel should reduce the potential for creep rupture-induced vessel failure, as would the presence of water in the lower head, however vessel failure is still predicted. On vessel failure the molten material is relocated to the reactor pit where it reacts with the sacrificial concrete in this location. Given sufficient concrete ablation, eventually the plug at the base of the transfer pit fails and the corium is relocated to the spreading area, via the transfer tunnel, which is lined with further sacrificial concrete to react with the core debris. The chemistry that occurs through these phases is complex, and a more detailed description is given in Section 4.6.5. Those aspects relevant to the CGCS are discussed further below.

1041 The molten core debris will consist of a mixture of metal and oxide species. It is the metal species that generate further hydrogen, and in the case of MCCI, carbon monoxide as they are oxidised by interaction with the concrete. The core debris composition depends on the accident sequence and the availability of oxidising material during the in-vessel phase, however as the EPR MAAP4 analysis predicts less than 50% zirconium oxidation and the debris will incorporate an additional mass of metal from the core and vessel materials, generation of significant quantities of hydrogen and MCCI gases is predicted in all cases. The oxidising material in the concrete that give rise to hydrogen and carbon monoxide are water and carbon dioxide respectively, while other species such as haematite and silica can oxidise the metal, but without generation of combustible gases.

1042 EDF and AREVA use the COSACO code to model this gas generation (and the associated metal oxidation). COSACO takes inputs from the corresponding MAAP4 analyses for the accident progression and core debris composition. In essence the combustible gas generation rate is proportional to the rate of concrete ablation as it is assumed that most of the water (steam) and carbon dioxide released will contact molten metal material before release. Clearly, if this assumption was found to be incorrect (for example, due to gas by-passing the debris or a more oxidised molten pool) the combustible gas release during this phase would be lower than predicted by COSACO, providing comfort that the predictions can be considered bounding for the source term.

1043 The rate of concrete ablation is a heat transfer problem involving the heat input from the core debris and the decomposition enthalpy of the concrete; however this is not an easy process to model. Since concrete is a multicomponent mixture a single melting point cannot be determined, instead a range of melting / decomposition occurs between the first and last melting component. Similarly, as the thermal conductivity of concrete is low, the surface in contact with the core debris can reach a melting temperature, loose integrity, become buoyant in the denser core debris and detach exposing the underlying concrete. The decomposition process is what drives the ablation. EDF and AREVA assume that this process occurs when the solid fraction in the concrete is equal to 0.5. The concrete ablation rate is discussed further in Section 4.6.5. This is a key driver in determining the rate of combustible gas formation in UK EPR. Due to these uncertainties, COSACO has been validated against a large number of large-scale experiments involving both oxidic and metallic melts, with reasonable agreement (see Ref. 70).

1044 Unlike the in-vessel analysis with MAAP4, the ex-vessel COSACO analysis conducted by EDF and AREVA for UK EPR will consider only a small number of sequences. This is because the main variable which affects the MCCI releases is the time between the start of the accident and the time of contact between the core debris and the concrete; this affects the decay heat power of the core debris. In these different scenarios the integral mass of combustible gases is very similar; however the generation rates vary by factors of up to two. This is not surprising given the fundamental heat transfer nature of the ablation process. For the COSACO analysis it is assumed that complete relocation into the pit from the vessel occurs as a single pour event, as this generates conservative results with respect to hydrogen production rates.

1045 Preliminary results from independent confirmatory analysis described in Section 4.6.3.2.1 (Ref. 100) showed similarly consistent results with the EDF and AREVA information for the ex-vessel phase, including generation of carbon monoxide. I conclude that, provided the rates of ablation are well predicted by COSACO, then the prediction of the rate of generation of combustible gases can be considered to be reasonable for use as the source term.

1046 Long term combustible gas production mechanisms, such as radiolysis, are not presented by EDF and AREVA in the UK EPR safety case. EDF and AREVA argue that it is not necessary to explicitly consider these later phases as the main determining factor in the UK EPR CGCS design is the rate of hydrogen production, which is bounded by the early phases. This assumes long term availability of the PARs in the post severe accident environment. There is a gap in the safety case for the later phases which needs to be supported by specific analysis to support these arguments. For GDA, I am satisfied that the arguments made by EDF and AREVA appear reasonable and this can be undertaken at a later stage of Phase 2. This is related to Assessment Finding **AF-UKEPR-RC-42**.

4.6.3.3 Chemistry in the PARs

1047 EDF and AREVA claim that the UK EPR CGCS, and hence the PARs, are designed to satisfy the following requirements:

- 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% by volume shall be small enough to prevent flame acceleration according to the σ and λ criteria outlined in Section 4.6.3.4 below.
- The maximum amount of hydrogen, resulting from the oxidation of all zirconium in the core, is reduced to a global average below 4% within 12 hours, see Section 16.2.2.2.3 in Ref. 11.
- 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, see Section 16.3.1.3.2 in Ref. 11.

4.6.3.3.1 Oxidation of Hydrogen

1048 The use of catalytic materials to oxidise hydrogen to water is a well proven technology. However, as described in the previous sections, the generation of combustible gases in UK EPR during an accident results from many processes which could produce an aggressive environment inside the containment. Therefore, the ability of the PARs to withstand the various products released during a severe accident including steam, aerosols, fission products and sprays, as well as the containment temperatures and pressures, is a key claim in the UK EPR safety case. In addition the normal environmental conditions in the containment during operation may pose challenges to the PARs should they be required, due to corrosion, accumulation of dust or contamination with materials which inhibit the catalytic plates. The impact of these on the recombination rates of the PARs is an important aspect of the design.

1049 TQ-EPR-649 (Ref. 8) was raised to understand any difference in the UK EPR PARs compared to current or previous generations of recombination units. The response provided confirmed that all EPRs (FA3, OL3, Taishan) will have the same PAR designs, but no details were given on comparison to other LWRs. TQ-EPR-1212 (Ref. 8) further queried this point, however the response indicated that there were no differences whatsoever between the UK EPR PARs and any other LWR with installed PARs. I find this response difficult to believe. I consider it unlikely that all PARs will have the same catalysts material, active surface area, housing design etc. The response to RO-UKEPR-78.A1 (Ref. 101) provided a list of plants which have installed AREVA PARs, which included 74 PWRs (including all the German and French units), suggesting a mature design.

1050 A potential concern with the UK EPR design approach is the adoption of a single design of PAR, which means that Common Cause Failure (CCF) type problems could affect the entire system. In the response to TQ-EPR-651 (Ref. 8) EDF and AREVA claim that this aspect is satisfactorily addressed by the extensive test and experimental programme which supports the PAR qualification. The range of single and multi parameter tests conducted on PARs, including AREVA UK EPR type PARs, indicates that the chance of a particular environment completely stopping the PARs functioning is very unlikely. EDF and AREVA claim that further margin is provided in the CGCS design to allow for underperforming PARs (i.e. the source terms are pessimistic and bounding cases have also been analysed).

1051 The response did indicate that "*only a few observations on delayed start-up of individual plates*" had been observed following several hundred inspections on in-service PAR units. It is argued that the performance of these degraded catalyst plates can be 'regenerated' by a high temperature thermal treatment. TQ-EPR-1202 (Ref. 8) queried the cause of this deterioration. The response suggested that the cause was most likely fumes of contamination generated by maintenance activities close to the PAR. EDF and AREVA recognise the potential for this type of poisoning and propose removal or covering of PARs in such circumstances. EDF and AREVA claim that testing of PARs following an exposure to solvent (paint) and welding fumes showed the functional resistance of the catalyst materials. It is argued that, should such poisoning occur undetected, the PARs will effectively 'self-clean' during operation. The high temperatures generated on functioning plates (within the same unit) will effectively subject contaminated plates to a thermal treatment similar to that proposed to regenerate defective plates. This is reasonable provided that there is adequate 'clean' catalyst in a particular PAR unit to raise the temperature effectively.

1052 TQ-EPR-1202 (Ref. 8) also queried the testing undertaken on 'aged' PARs. These tests were undertaken on catalytic plates removed from a German plant after five years. These plates were found to be contaminated with hydrocarbon residues from an unknown source. Testing found that, although the start-up rates were slower, eventually the plates functioned at the nominal depletion rates expected. TQ-EPR-654 (Ref. 8) asked for details of the maintenance and testing provisions for the PARs. EDF and AREVA propose a periodic test programme in which around 25% of the installed PARs are tested by removing a few catalytic plates for testing at each outage. The removed plates are exposed to hydrogen gas and the depletion rate is measured, with a defined removal rate criterion which instigates regeneration or replacement if not met. This appears a reasonable basis for a PAR maintenance programme, but details on the selection procedure for which PAR will be important. This may be more important for those PARs which are in inaccessible locations, such as on the polar crane. I consider this to be an Assessment Finding **AF-UKEPR-RC-43**.

1053 TQ-EPR-1216 (Ref. 8) queried the removal of PARs during outages. The response indicated that only the PAR on the RPV head or those affected by maintenance need to be removed routinely. For cases where more extensive removals are necessary a specific assessment would be undertaken. This is related to Assessment Finding **AF-UKEPR-RC-43**.

1054 A number of queries on the design basis for the UK EPR CGCS were raised in TQ-EPR-652 (Ref. 8). EDF and AREVA claim that the CGCS is designed on the basis of 100% zirconium oxidation, producing around 1300 kg hydrogen. The reference quoted to support this (Ref. 65) does not actually contain such an analysis, only providing the in-vessel analysis. IAEA Safety Guide No. NS-G-1.10, (Section 6.24, Ref. 24) supports this position, stating; *"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."* EDF and AREVA have interpreted this to mean 100% zirconium oxidation throughout the entire accident sequence. At a high level this is a reasonable argument, but with the mitigation system based upon catalytic processes there is a limit on the rates at which the combustible gases can be removed, hence the important factor for the PARs is the rate of production. PARs are likely to struggle with high production rates and the impact on UK EPR needs to be demonstrated. This is a fundamental aspect of the design that needs to be demonstrated from a chemistry point of view. As such, I consider this to be a GDA Issue, **GI-UKEPR-RC-01.**

1055 The technical basis for using PARs as a means of reducing combustible gases in LWR containments is based mainly on the results of a large range of experimental test programmes. TQ-EPR-653 (Ref. 8) queried which had been used by EDF and AREVA as part of the qualification of the UK EPR PAR designs. The response cited a comprehensive range of tests, from single tests to full severe accident tests involving exposure to degradation products of a degraded core. Further results were provided in response to RO-UKEPR-78.A1 (Ref. 101). EDF and AREVA claim that the qualification of the recombiners addresses, amongst other things:

- thermal ageing
- radiation effects (radiation during normal operating conditions and radiation resulting from a core meltdown accident)
- effects of chemical impurities (catalytic poisons, solvents and weld gases and smoke coming from oil and cable fires)

1056 The main experiment which supports PAR use during severe accident conditions was a part of the PHEBUS programme (FPT3). This test examined the potential poisoning effects of representative containment environment conditions at scaled down hydrogen recombiner samples, exposed to containment environment conditions representative of a realistic severe accident scenario. This confirmed operation of AREVA PARs under representative severe accident conditions, although notably other PARs failed completely or suffered from reduced performance. This lends confidence in the UK EPR PAR design.

1057 While it is clear from the results presented that the UK EPR PARs should retain most of their functionality during postulated severe accident conditions, it also showed some uncertainty regarding reduced performance, including:

- 5% reduction due to containment sprays
- 10% reduction due to cable burning
- "*reduced*" performance in one of six PHEBUS 2 tests, which could not be explained or reproduced
- Failure of two PARs in PHEBUS 3 tests (although not AREVA PARs)

1058 It was also not demonstrated how the results cited in the response to RO-UKEPR-78.A1 (Ref. 101) relate to the model used for the analysis. Ref. 101 appears to provide a lot of performance figures for non-AREVA PARs, but these lack context in many instances making it difficult to gauge their relevance to the CGCS in UK EPR. As a result, it would be difficult to say that the model predicted all of the experimental results. Some results of this type were presented and show good agreement (Ref. 74), but these tests only include hydrogen without poisons. This aspect was discussed above, under TQ-EPR-1202, 1206 and PHEBUS, and in the context of its application within the UK EPR modelling. I believe that this aspect can be addressed with an examination of the experimental evidence as presented and would provide much greater clarity and comfort that the case presented is sound. I consider this to be an Assessment Finding **AF-UKEPR-RC-44**. In addition to these findings, I have raised a GDA Issue (**GI-UKEPR-RC-01**) which requires application of the model to situations where several of the PARs have been poisoned.

1059 Overall, I am satisfied EDF and AREVA have made an adequate case for GDA for the use of PARs for hydrogen control in UK EPR, provided the detailed analysis supports this. This is related to Assessment Finding **AF-UKEPR-RC-42**.

4.6.3.3.2 Oxidation of Carbon Monoxide

1060 As described in Section 4.6.3.2.3, carbon monoxide (CO) is produced during MCCI phases in UK EPR. This is an additional source of oxidisable gas which can react on the PARs. EDF and AREVA have performed experimental testing using carbon monoxide (CO) to determine the effect on the PARs. This showed an increased rate of reaction for mixed carbon monoxide (CO) and hydrogen, thus the use of a model assuming only hydrogen recombination is conservative from the perspective of recombination rates (RO-UKEPR-78.A1, Ref. 9, and Ref. 74). For those cases where long term consideration of the containment behaviour is required, including CO, EDF and AREVA extend the modelling to specifically include a function for the oxidation of CO, which is very similar to the function used for hydrogen. It is noted that this is currently only applied to the ex-vessel phase, thus neglecting any impact of CO produced from boron carbide as described in Section 4.6.3.2.2.

1061 A key assumption in the UK EPR analysis is that combustible gases generated during MCCI are combusted as they are produced. This is because the gases are produced at a temperature much above the auto ignition limit. Analysis using the GASFLOW code shows this always to be the case. In order to account for this process when analysing for thermal loads the analysis converts the CO into an equivalent mass of hydrogen on an energy basis (i.e. 1 g of CO is equal to 0.083g of hydrogen in energy terms), although as discussed in Section 4.6.3.3.4, this significantly underestimates the potential flow through the PARs.

1062 As the oxidation of CO involves the same fundamental processes as for hydrogen, the same comments as in Section 4.6.3.3.1 apply.

4.6.3.3.3 Impact of PARs on other Chemical Processes

1063 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 a high temperatures. During a severe accident iodine is the main concern and much effort is put into its management, including containment sprays and buffered sumps. A large portion of fission products released from fuel during an accident are in the form of metal iodides, which are relatively involatile and are efficiently captured. These aspects are discussed further in Section 4.6.4.

1064 The RECI analytical experiments have shown that metal iodides (importantly CsI) are not stable and yield gaseous iodine when heated, in a humid atmosphere, at temperatures representative of recombiner operation (Ref. 75). As compared with thermodynamic equilibrium calculations, experimental results from PHEBUS-FP yielded a somewhat higher gaseous/total iodine ratio in the gas and aerosol mixture entering the containment, which has been potentially attributed to such an effect (Ref. 76). TQ-EPR-1428 queried the potential for the PARs in UK EPR to affect fission product distribution in containment in a similar manner. The response states that, in summary, this potential effect is not included in the current UK EPR analysis, but can be considered “*negligible*” due to the bounding source term used for UK EPR. EDF and AREVA indicate that a study of this effect is scheduled for 2011, but provide no further details. Limited information on this topic was also provided in the response to RO-UKEPR-78.A1 (Ref. 101) which states that; "*The aerosol tests Aer-2 and Aer-5 have shown – for the investigated parameter range – that the hot catalyst surfaces are not able to produce gaseous iodine from CsI in a mentionable quantity. Contrary, tests HR31.2 and HR31.3 show that conversion of CsI aerosol to gaseous iodine was found with conversion rates that bring the gaseous iodine formation into a source-term relevant range* [3%]. *The PARs showed same behaviour as in the Aer-test series. Therefore, the investigation of production of gaseous iodine from CsI was not conclusive in the presented tests and the topic remains open to future investigations.*"

1065 This is potentially an important characteristic of the UK EPR severe accident scenarios and the safety case should reflect this. In order to provide further reassurance that this is not a significant concern, and is indeed "*negligible*" and bounded, analysis to demonstrate the potential impact of operation of the UK EPR CGCS on iodine volatility in containment is needed. I consider this to be part of GDA Issue **GI-UKEPR-RC-01**.

4.6.3.3.4 Modelling of PARs

1066 The main code used for the determination of the recombination performance of the UK EPR CGCS is COCOSYS (Containment Code SYStem). COCOSYS is used to model the overall containment performance but in the context of combustible gas control it is used to determine overall recombiner efficiency, average hydrogen and steam concentration, average gas temperature and containment pressure. These results are also used to select relevant scenarios for detailed analysis of local aspects with the GASFLOW and COM3D codes.

1067 As part of the response to RO-UKEPR-44.A3 (Ref. 66), EDF and AREVA outlined the basis of the modelling undertaken to demonstrate the satisfactory performance of the combustible gas mitigation system for UK EPR during severe accident scenarios. Further details were also provided in the responses to TQ-EPR-649 to 655, 783 and 789 (Ref. 8), including the report detailing the validation methodology for the combustible gas control system in EPR (Ref. 64).

1068 Following a technical meeting with EDF and AREVA in March 2010, when the CGCS modelling was discussed, TQ-EPR-1206 (Ref. 8) was raised to understand the model used to represent the PARs. Despite the increase in model complexity at the later stage of UK EPR calculations, it became apparent that the same governing equations were used to describe the recombination process for the PARs. The suitability and sufficiency of these equations to adequately represent the chemical and physical phenomena that occur during and as a result of recombination is clearly an important element of the overall modelling approach both in terms of the effects on PAR operation and the effects of PAR function on containment performance. This is implicit in the SAPs (Ref. 4), FA.18 "*Fault Analysis: Assurance and Validity of Data and Models*" and associated paragraphs (552 to 556). The response to this TQ described the method used to determine the depletion rate of the UK EPR PARs and the "*empirical model*" used in the UK EPR modelling. Testing was undertaken at different hydrogen concentrations and the depletion determined, along with other parameters such as pressure and temperature. Based on these results it was found that the depletion rate was dependant on the pressure and hydrogen concentration (i.e. it is determined by those parameter which affect mass transfer to the catalytic surfaces). This type of test is useful in determining the 'baseline' capacity of the PARs, but does not take account of any impact of environment or degradation. RO-UKEPR-78.A1 (Ref. 9) was raised to further understand the PAR model and the potential effects this has on the modelling results.

1069 The PAR model operates between 0.5 and 8% hydrogen. Below this level the PAR is assumed not to function and above this level the recombination rate is assumed to plateau. The recombination does not start until hydrogen is at 2%. Increasing pressure results in a recombination rate increase. Oxygen concentration affects the PAR operation, with an oxygen starved gas resulting in a reduction in the PAR performance by 40% compared to identical conditions but with oxygen excess. These overall governing parameters appear reasonable.

1070 A number of other potential effects are discussed in the response. EDF and AREVA claim that the experimental test programme does not support modification to these parameters to account for potential effects of poisons or contamination and that the effect of steam is only seen during start-up of the PARs, and is accounted for in the model by the hysteresis in the start of recombination to 2%. This has been tested in experimental programmes and the assumption is considered bounding, with earlier start-up possible.

1071 As a result this means that the UK EPR PARs are assumed to work at 100% ‘efficiency’ throughout a severe accident (i.e. 100% of the inlet hydrogen is removed). EDF and AREVA claim that this is bounded by the current analysis using representative and bounding scenarios and an analysis using COCOSYS with 15% PAR removal (selective removal of 6 equipment room PARs and 1 dome recombiner) during a SBLOCA which showed the system design was met with a reduced overall PAR capacity of 83%. This analysis showed total hydrogen increase in containment of around 50 kg at the time of RPV failure and local hydrogen increases of less than 1%. This analysis was an early analysis of a recombiner arrangement different to UK EPR so is not directly applicable. It is also not clear how the system would behave given an overall efficiency reduction in all recombiners, as opposed to selective removal of some entire units, given that this cannot be completely ruled out. As described above, such effects have been observed experimentally. Overall, I believe that some sensitivity analysis on this basis needs to be performed for UK EPR showing the effect of a global reduced recombiner performance on UK EPR. I consider this to be a GDA Issue, **GI-UKEPR-RC-01**.

1072 A further consequence of the empirical model used to describe the PARs is that the equation acts to alter the mass flow through the unit to maintain the calculated depletion rate (i.e. operation of a PAR at 50% efficiency will result in a doubling of the flow rate). This constraint has a number of implications on the results for a given set of conditions, namely, assuming the PAR does not actually operate at 100% efficiency results in:

- Underestimation of the flow through a given PAR
- Overestimation of the exhaust gas temperature

1073 This should result in a conservative estimate of the CGCS behaviour. However, no consideration is given to local flows in the model (i.e. convective flows in containment acting in the opposite direction to the PAR flow or inside the PAR unit). EDF and AREVA acknowledge that no experiments consider this aspect, which may be significant in UK EPR where the dominant mixing flow in the containment is natural convection. It is considered likely that this could be suitably addressed via a similar sensitivity study to the efficiency assumptions described above. This is part of GDA Issue **GI-UKEPR-RC-01**.

1074 The model for combustible gas reduction, as described, appears to be a reasonable compromise between complexity and adequacy, when balanced against the overall hydrogen risks in UK EPR. It is notable that a similar model is used in other accident codes, such as MELCOR. I consider that an adequate case has been made for the use of this model for GDA, although I note concerns related to the efficiency and flow assumptions that the model introduces but believe these can be resolved by provision of the sensitivity analyses as part of GDA Issue **GI-UKEPR-RC-01**.

4.6.3.4 Combustion

1075 Even with the CGCS in UK EPR it is likely that some combustion may occur. This in itself is not a problem provided the pressure and temperature loads this generates are within the capabilities of the design. The extent and type of combustion is strongly linked to the accident sequence. While the depressurisation system for severe accidents in UK EPR is primarily present to avoid high pressure phenomena (for example; Direct Containment Heating (DCH) by steam) a secondary effect is the release of large quantities of steam into the containment as the primary coolant flashes. Although this poses hazards for containment pressurisation, in terms of combustion hazards this is potentially beneficial due to steam inerting of the atmosphere. Furthermore, core debris quenching by cooling water can inert the mixture by production of extra steam releases. Subsequent operation of the containment spray system may reduce the steam content making mixtures potentially combustible again. The impacts of combustion processes on the containment are assessed elsewhere (Refs 73, 121 and 184), while the chemical aspects are discussed below.

1076 The overall approach used by EDF and AREVA is based on "*an assessment of the hydrogen combustion risk by application of experimental criteria for the non-occurrence of flame acceleration and transition to detonation and by calculating the adiabatic isochoric complete combustion (AICC) pressure, and exemplary calculations of flame behaviour and pressure loads from combustion at critical conditions and locations where, according to the above mentioned criteria flame acceleration with the potential to DDT cannot be excluded, using a CFD code specialized for such simulations*." (Ref. 64). This approach appears consistent with the other modern approaches to combustion analysis in LWRs, such as the Nuclear Energy Agency (NEA in the Organisation for Economic Cooperation and Development (NEA) report on this topic (Ref. 77).

1077 Hydrogen-air-steam mixtures can burn in several ways dependant upon the conditions; namely as diffusion flames, slow deflagrations, accelerated flames and detonations. EDF and AREVA consider each of these combustion modes for UK EPR. This is improved over historical considerations where only global combustions were considered and reflects modern practice for LWRs:

- Diffusion flames (or stationary flames) result when combustible gases are released into an environment, creating a flammable plume. In UK EPR these are predicted to occur during the MCCI phase when released gases are above the auto-ignition temperature in the reactor pit and spreading area. This is the least damaging combustion, provided the thermal loads do not result in harm to surrounding equipment.
- Deflagrations and detonations are rapid burning of often pre-mixed gases. The speed of the combustion is important in determining the consequences, with detonations the quickest and potentially the most damaging and unpredictable. Thus, it is important that the transition from deflagration to detonation (DDT) is avoided, as is claimed for UK EPR. Accelerated (or fast deflagration) flames can be considered between the two and can in themselves provide relatively high loads due to feedback as they burn.

1078 For slow deflagrations MAAP, COCOSYS and GASFLOW can calculate the pressure in the containment due to Adiabatic Isochoric Complete Combustion (AICC), which is penalising from a temporal-thermal perspective as this assumes complete combustion with no heat losses to structures. This most likely is bounding for slow events and involves only mass balances in its treatment of the burn chemistry. EDF and AREVA claim that the AICC pressure will remain below the containment design pressure for "*representative*" scenarios, but not for all "*bounding*" scenarios, although it is below the test pressure.

1079 Flame acceleration and transition to detonation are complex phenomena. In order to overcome these difficulties much effort, internationally, has been put into identifying criteria under which flame acceleration and DDT can be expected. In order to assess if these processes are likely to occur in UK EPR, EDF and AREVA make use of the σ and λ criteria which define boundary conditions where flame acceleration and DDT have a potential to occur; in both cases value of >1 indicate that such conditions cannot be excluded, compared to values many times higher when such conditions would be expected. The advantage of this approach is that it limits the time spent calculating detailed and complex combustion modes. Used appropriately they can provide a conservative analysis of combustion risks. Such criteria are described both by EDF and AREVA (Ref. 64) and by the OECD NEA (Ref. 77).

1080 As described in Section 4.6.3.2.1, EDF and AREVA use a number of codes to model hydrogen behaviour in the containment, including its combustion. GASFLOW is a CFD (computational fluids dynamics) code that is used to model the gas and temperature distribution in the containment. GASFLOW is the code that uses the above criterion to determine the combustion modes. The detailed analysis of the combustion process is performed by COM3D, which models fast turbulent combustion events in great detail over a few seconds, in particular DDT.

1081 Most of the experimental validation of combustion phenomena has concentrated on H_2-air-steam mixtures. However, for UK EPR, significant amounts of CO and CO_2 will also be generated in the containment and there is little information available on flame acceleration and DDT in H_2-air-steam-CO-CO_2 mixtures. The conservative approach adopted by EDF and AREVA should mean that any effects of this are restricted, but this should be reviewed as further experimental data becomes available. I consider this to be an Assessment Finding **AF-UKEPR-RC-45**.

1082 It is possible that the PARs themselves may act as ignition sources for combustion if the rate of removal cannot match the rate of generation. EDF and AREVA recognise this point in the response to RO-UKEPR-78.A1 (Ref. 101). Tests in the H2-KALI, H2-PAR and ThAI test facilities investigated the ignition of hydrogen-rich mixtures by PARs, and the influence of steam on ignition potential. This showed that ignition is possible when the catalyst plate reaches approximately 900°C and occurs where the hot, hydrogen-lean mixture from the PAR exhaust meets the cooler, hydrogen-rich mixture in the containment. Ignitions were observed at around 10 volume % hydrogen as a result of PAR operation. EDF and AREVA state that further investigations on this phenomenon are planned for the near future, although no details are given. The impact of these phenomena on the UK EPR combustion analysis is unclear and will only be resolved by provision of the specific UK EPR analysis. This is related to Assessment Finding **AF-UKEPR-RC-42**.

1083 Overall, EDF and AREVA have deployed an extensive array of the most modern analysis techniques and understanding of these phenomena in LWRs. The approach lends confidence that UK EPR has been analysed to high standards and, subject to satisfactory conclusion of GDA Issue **GI-UKEPR-RC-01** and the findings described in Section 4.6.3.6, the CGCS should offer adequate protection from these hazards.

4.6.3.5 Summary

1084 There is a range of accident scenarios producing varying amounts of hydrogen at different rates, all with discrete probabilities. For this reason, my assessment has been careful to ensure that bounding scenarios have been identified appropriately and adequately analysed. Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of the combustible gas mitigation system in UK EPR are:

- EDF and AREVA have provided a justification for the design of the UK EPR CGCS, which takes account of the appropriate factors, including; the source term, the provision of protection systems for design basis and severe accidents, consideration of a range of accident scenarios and resulting hydrogen levels, validation data used to support the capability of the PARs, PAR location in relation to hydrogen releases and containment mixing behaviour and analysis of combustion hazards.
- The intended modelling approach to demonstrate the CGCS in UK EPR has been described in detail, including the chemical models. The approach adopted is sophisticated and comprehensive and could be considered to be at the leading edge of such nuclear safety analysis. I am satisfied with the suggested approach and content that this is a reasonable basis on which a case can be presented for UK EPR. A response to my initial concern regarding the modelling of the chemical depletion of hydrogen has been presented by EDF and AREVA.
- PAR devices manufactured by AREVA have been specified to provide the hydrogen removal capacity in the UK-EPR CGCS. The operation of these devices is supported by an extensive qualification programme and the operational experience of ~2500 devices already installed, with up to 15 years in service. The supporting experimental test programme is broad and comprehensive, ranging from small scale individual tests to large scale complex geometry tests under representative severe accident conditions. I am content that an adequate case has been made for the use of PARs for combustible gas control in UK EPR, however, it must be noted that successful operation of the PARs depends to a significant extent on effective operation of the CONVECT system of rupture panels and mixing dampers, and the ability of the system to homogenise the hydrogen concentration quickly and effectively. Research presented by EDF and AREVA has shown that PAR catalyst plates mainly non-consumable, capable of operating in steam-inerted environments, resistant to water ingress and long-term degradation, and are not subject to significant performance degradation by poisons.
- The case presented for the UK-EPR CGCS indicates that the appropriate criteria have been used in the design, justification and modelling of the system; however, the capabilities of the system and the margins available have not been demonstrated entirely adequately. EDF and AREVA did not provide specific analysis for UK EPR in time for assessment during GDA. Therefore, whilst the basis of the design has been outlined satisfactorily, several areas need further work and these are the subject of a GDA issue and several Assessment Findings.

1085 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA, provided the GDA Issues are adequately addressed.

4.6.3.6 Assessment Findings

1086 Based upon the assessment of combustible gas mitigation in UK EPR described in Section 4.6.3 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-42*** *– The Licensee shall undertake UK EPR specific analysis to support the Combustible Gas Control System design for UK EPR. This analysis should adequately cover all phenomena that may occur during such accident sequences. This analysis should cover the effects of* B_4C *control rods in the UK EPR design and include demonstration of the long-term plant behaviour post accident. This Assessment Finding should be completed before fuel is first loaded into the reactor. Target Milestone – Fuel Load.*
>
> ***AF-UKEPR-RC-43*** *– The Licensee shall review and document the examination, maintenance, inspection and testing arrangements for the Passive Autocatalytic Recombiners (PARs). This should include consideration of Operational Experience Feedback and the protection requirements during non-power operations. This Assessment Finding should be completed before fuel is first loaded into the reactor. Target Milestone – Fuel Load.*
>
> ***AF-UKEPR-RC-44*** *– The Licensee shall demonstrate that the experimental testing of the PARs matches the boundary conditions used in the safety analysis, including under representative severe accident conditions. This Assessment Finding should be completed before fuel is first loaded into the reactor. Target Milestone – Fuel Load.*
>
> ***AF-UKEPR-RC-45*** *– The Licensee shall review the influence of CO and* CO_2 *on fast deflagration and DDT (Deflagration to Detonation Transition) combustion analysis in terms of the most recent experimental work and incorporate this into the plant analysis as appropriate. This Assessment Finding should be completed prior to first fuel load. Target Milestone – Fuel Load.*

4.6.3.7 GDA Issues

1087 Based upon the assessment of combustible gas mitigation in UK EPR described in Section 4.6.3 above, I have identified the following GDA Issue which requires resolution:

> ***GI-UKEPR-RC-01*** *– Combustible Gas Control Systems – Impact of Passive Autocatalytic Recombiners during accidents.*

1088 The complete GDA Issue and associated action(s) are formally defined in Annex 2.

4.6.4 Assessment – Fission Product Control

4.6.4.1 Assessment – Source Terms

1089 The UK EPR containment building structure is described in the PCSR (Ref. 11, Section 6.2). It comprises two concentric shells separated by a ventilated annular space, the inner shell is steel-lined. The inner containment building holds the reactor and a number of cooling systems for normal and emergency use. In the GDA design, the inner containment is held at reduced pressure and has no vent. Like FA3 the inner containment would be sealed in an accident so that EDF and AREVA can make the claim that it retains virtually all radioactive materials released in accidents. This claim is significant because EDF and AREVA expect that the reactor vessel would fail in the very unlikely event that an accident resulted in severe core damage. If this occurred, it must be assumed that the inner containment would become the primary barrier to all of the radioactive material that was airborne following such an event.

1090 In many accidents postulated for UK EPR, the pressure and temperature in containment would also rise as steam would be released from the hot reactor core. To stop steam challenging the structure and to prevent expulsion of radioactive material under pressure, a Containment Heat Removal System is provided, see figure below from Ref. 160.

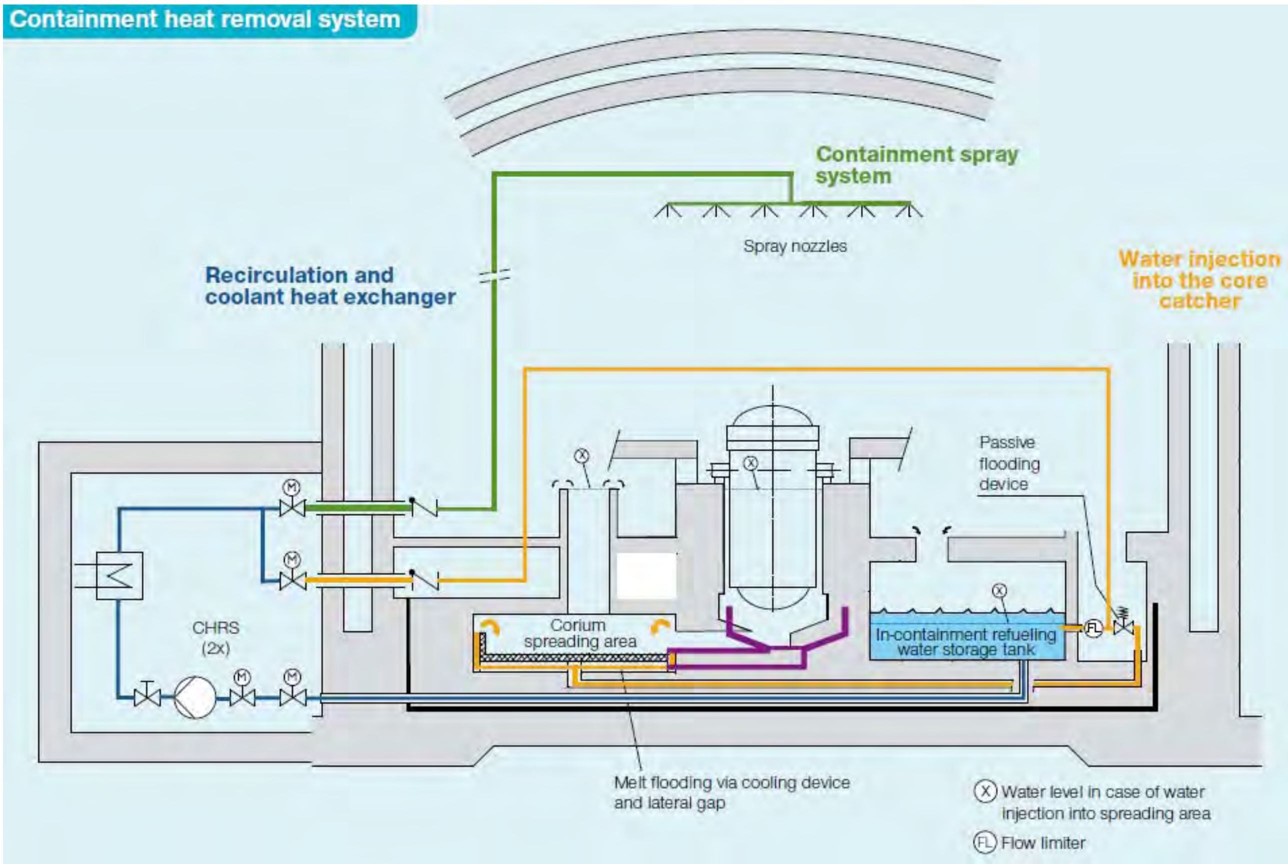


Figure 25: UK EPR Containment Heat Removal System

1091 Other features to note in the figure above include the corium spreading area and the CHRS plant room, which is outside the double-walled containment (on the left of the figure). There are three small ⊗ symbols on the diagram; the lowest shows the levels of water in the IRWST and spreading compartment after flooding by the IRWST. The highest two ⊗ symbols show the level reached once the CHRS has flooded and finally cooled the reactor and molten core.

1092 Claims for the integrity of the containment were assessed elsewhere in ONR, and my assessment concentrated on the amount of radioactivity available for release from UK EPR and its form, because doses to humans would be directly proportional to the source term. The fission products produce heat, so that water in the spreading compartment and IRWST may boil. The spray system is intended to suppress aerosols and most of the iodine, but does not suppress the iodine that is in organic form. Operation of the spray may also make any hydrogen – air mixture more flammable. Note that the spray system is not claimed for the control of fission-products and this introduces a degree of pessimism into the assessment made by EDF and AREVA. Because the sprays are not claimed, my assessment concentrates on the adequacy of the system without sprays and potential negative affects from using the CHRS.

1093 The following SAPs were relevant to this part of my assessment; EKP.2, ECV.3, FA.17, 19 and 22 (Ref. 4), which was supported by experts at my TSCs, who reported in Ref. 135. My assessment is principally based on the responses made by EDF and AREVA to Regulatory Observation RO-UKEPR-44.A3 in Refs 69 and 70, plus their responses to a number of TQs.

1094 In normal operation, the containment in UK EPR would be split into two zones separated by a system of relief and vent panels. In a severe accident these would be opened and the containment would act as a single large volume. In the following paragraphs, I use the word containment to refer to the single large volume within the inner containment shell.

1095 For UK EPR, EDF conducted the analysis of potential radioactive release to the public. For their calculations, EDF took pessimistic assumptions and relied on a simplified method developed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France.

1096 The prediction of steam pressures, sizing of heat exchangers, and other effects of heat and radiation was undertaken by AREVA, these were “best estimate” assessments of the chemistry of accidents and used sophisticated simulation codes, including MAAP (Ref. 163), COCOSYS and their own code; COSACO.

1097 Both EDF and AREVA generally ignored use of the CHRS spray. This was claimed to lead to greater pessimism in their respective analyses.

1098 My assessment covered the prediction of source terms, the operation of the CHRS and the redistribution of heat. It also included the validation and verification of chemistry aspects of some of the methods used by EDF and AREVA and generally my conclusions refer to both sets of analyses.

4.6.4.2 Source Terms

1099 In an accident, a small fraction of the radioactive material in the containment atmosphere will escape due to a low rate of containment leakage, which will be 0.3% by volume per day, according to Section 16.2 of the PCSR (Ref. 11). Therefore the size of the source term within containment must be estimated in order to predict the consequent doses to the public.

1100 The main chemical factors affecting the source-term are:

- The temperature reached in the accident affects the rates of release from damaged fuel. The release of gases such as krypton is quick and the release of materials like uranium is slow.
- Whilst nuclear fuel at the start of an accident will be mostly in the form of uranium dioxide, as an accident progresses, it is known the cladding zirconium would react with steam and the fuel to produce uranium and other metals. If this happens, the chemistry of other nuclear material present will also change. This is also called the oxidation state or index of the corium.
- The most important nuclides, in terms of doses from any reactor accident, are radioiodines. The chemistry of iodine is complex and highly dependent on the alkalinity of the water in the coolant, sprays and sumps.

1101 The state of oxidation and the temperature have a significant effect on several radioactive materials like caesium, molybdenum, tellurium and silver, which can take volatile forms under some conditions.

1102 The release fractions from the molten EPR core are shown in the table below and compared with the release fractions recommended to the US Nuclear Regulatory Commission (NRC) in Ref. 125;

Group / Nuclide		**UK EPR Value (**Ref. 11)	**NUREG-1465 Value** (Ref. 125)
Noble gases	Xe, Kr	1	1
Halogens	I	1	0.75
Alkali metals	Cs, Rb	1	0.75
Tellurium	Te	0.91	0.305
Antimony	Sb	1	0.305
Barium group	Ba, Ce, Np, Tc, Ru, Rh,	0.325	0.12
Strontium	Sr	0.065	0.12
“Noble” metals	Ru, Rh, Pd, Mo, Tc, Np	0.0325	0.005
Cerium group	Ce, Np	0.0325	0.0055
Zirconium	Zr	0.03	0.0052
Lanthanides	La, Nd, Nb, Pr, Y	0.02	0.0052
Plutonium	Pu	0.00325	0.0055
Not specified	Pm, Am, Br, Se, Co	-	0.05 ~ 0.3

Table 15: UK EPR and NUREG-1465 Recommended Release Fractions

1103 Both columns in the table include in-vessel and ex-vessel contributions to the source term. The fractions recommended by the NUREG guide Ref. 125 are generally lower because it assumes a significant proportion of the fission-products (FPs) are retained within the reactor vessel and pipework even if some escapes. No credit can be given for retention within the cooling circuit of UK EPR, since EDF and AREVA assume the reactor vessel must fail beyond a certain temperature in the accident. These FP release fractions used for UK EPR are also mostly higher than currently used for the rest of the French fleet.

1104 I obtained a copy of an assessment made by EDF of their own source-term methodology Ref. 127 through TQ-EPR-1084. This contains recommendations for source terms for future use by EDF. The release fractions for molybdenum (Mo) and barium (Ba) used for UK EPR are smaller than those recommended for EDF use in Table 10 of Ref. 127, but these are minor elements in terms of the overall release. The difference may arise from assumptions made for releases due to melt-concrete interactions. These can double the ex-vessel releases for less volatile nuclides but the corium-concrete interaction in UK EPR is arrested by the spreader.

1105 The two exceptions of note are the release fractions for strontium (Sr) and plutonium (Pu). The release fractions quoted in the PCSR for these nuclides are lower than recommended in Refs 125 and 127. Being a small fraction of the total release, neither would affect the radiation exposure from an accident in the short term. I find that the Licensee should ensure that evidence is generated for the release fractions for plutonium and strontium and their longer-term consequences in a UK context, and this is part of Assessment Finding **AF-UKEPR-RC-46**.

1106 The radioactivity in the nuclear fuel is multiplied by these fractions to predict the amount of radioactivity in the containment atmosphere which is intended to be pessimistic. In TQ-EPR-190, I asked EDF and AREVA to confirm the reference fuel type was bounding for the release calculation. They confirmed that it corresponded to the most energetic fuel type and age, since they used 18 month MOx fuel as a reference. MOx fuel is used in France but is outside the scope of GDA, it is nevertheless suitably pessimistic for calculations of this type.

1107 Assuming a release of 100% of the iodine and caesium is notable. Overall, I consider these fractions are consistent with good practice (Refs 125 and 126) for an acute release. Once released into the containment air, EDF and AREVA calculate the sedimentation of the aerosol under gravity, which quickly reduces the airborne radioactivity within the containment before it could leak. Since the CHRS sprays are not claimed for control of radioactivity in UK EPR, I assess aerosol sedimentation next before considering the chemistry of iodine.

1108 Once airborne in the containment, the evolution of the source-term was calculated using a method recommended by IRSN. It was predicted that 1,000kg of aerosol were produced in one hour, into a single volume of 50,000m^3. The IRSN method calculates the fraction of nuclear material remaining airborne in the containment by a summation of exponential decay terms. This models 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. Because the IRSN method would predict airborne concentrations decreasing to infinitesimal levels at long times, a cut-off is applied, around the airborne concentration of fresh air.

1109 The IRSN method was developed from the results of international experimental programmes such as VERCORS (Ref. 165) and PHEBUS (Ref. 166). In these experiments, samples of irradiated nuclear fuel were heated, sometimes to melting, in order to measure the immediate fission product release and other phenomena. These are amongst the most modern and relevant test data available, although some of the findings from PHEBUS have still to be adequately explained.

1110 In TQ-EPR-1188, I requested a comparison of the airborne aerosol calculated by the IRSN method with the MAAP computer code, both with and without sprays. The MAAP code attempts to predict the temperatures and timings of a release, calculating release rates from the melt and subsequent sedimentation rates inside containment. The methods it uses are older than those used by IRSN. For instance it models the kinetics of fission-product release using a method based on experiments and a method developed at Oak Ridge in the 1980’s, known as CORSOR. The treatment is simple; a species is assumed to be completely evaporated at temperatures above its melting point. MAAP has a module which claims to model more detailed iodine chemistry, but this was switched off in calculations for UK EPR.

1111 In providing verification of the airborne radioactivity calculated by MAAP, Areva provided references to a number of comparisons with other codes in Ref. 163. Overall I concluded that MAAP4 will provide reasonable approximations to the oxidation, temperature and liquid fractions for the fuel at a given composition and heat. These are used to provide estimates of hydrogen / steam (Section 4.6.3.2.2), check the source term and provide inputs to other computer codes. I consider it provides a reliable comparison for the IRSN method. Other codes could equally have been used for this purpose.

1112 Without sprays, MAAP predicted airborne radioactivity which was a factor of ten lower than the IRSN method. From this, I conclude that the IRSN method is pessimistic in terms of aerosol levels in the main containment. With sprays, the aerosol radioactivity was a factor 1000 lower than calculated by the IRSN method, but the CHRS in UK EPR would not be activated until a few hours into an accident.

1113 Apart from the aerosol source term, it is also necessary to consider the fraction of the iodine that is in gaseous form. Elemental iodine is gaseous, but readily trapped by alkaline water or special filters designed for the purpose. Organic iodine is not so easily prevented from escaping, because it is relatively chemically inert. Recognising that organic iodine can be produced, Ref. 125 states that “*A rational model for organic iodine would consider both its formation and production in a time-dependent fashion….”*

1114 EDF and AREVA assume that 100% of the iodine and caesium are released from the core “*within the first few hours*”. The fraction of iodine released in elemental form from the core is assumed to be 2.5% (Ref. 11). The fraction released in gaseous organic form is quoted as either 0.15% or 0.2% (depending on the document) and the rest is aerosol, Refs 127, 129 and 130).

1115 A European-wide review of DBA analysis for Large-Break LOCAs (Ref. 126) identifies an organic fraction of 0.2% for the iodine releases occurring during the “dry” phase (roughly 10% of the elemental iodine). In this scenario, a high proportion of the iodine released (60%) is produced in elemental form later in the accident, during the “wet” phase due to the quality of the reflood water and not as a result of core melting. However Ref. 126 does not recognise any organic products during the ”wet” phase. Thus, only 0.037% of the total elemental iodine is assumed to convert to the organic form following the European approach. This percentage appears unrealistically small, however calculating the organic fraction by multiplying the elemental release by 10% would increase the iodine release by two orders of magnitude, which would be unrealistically high. I find there is still much uncertainty in this figure, even if the true proportion is small, and this is part of Assessment Findings **AF-UKEPR-RC-47** and **AF-UKEPR-RC-49** which require a more realistic treatment of iodine release phenomena.

1116 Refs 125 and 126 respectively provide the US and European guidance. Ref. 127 updates and interprets them for EDF 900 and 1300 MW reactors, and notes that 30% of the airborne iodine can be organic in the longer term. The recommendations of Ref. 127 seem only to have been considered to apply to the early dry phase of the release from the core, TQ-EPR-1084.

1117 My assessment of the release turns to the retention of the iodine by the CHRS and IRWST and the re-release of iodine. The response to TQ-EPR-1188 claimed it was pessimistic to ignore the combination of iodine with silver in the sump and the radiolytic reactions that produce iodine oxides. I consider these are not pessimistic assumptions for the rate of removal of iodine, because silver would only stabilise iodide in the sump and the oxides of iodine are volatile. However, these effects should not have a great impact on early-phase releases calculated by the pessimistic method used for UK EPR.

1118 In addition to iodine and aerosols, the release to the environment also comprises the gaseous radionuclides. The release of ^{133}Xe would be 10,000 times greater than ^{131}I in units of Becquerel, although the PCSR did not distinguish these in terms of the public dose, in units of mSv. I find that the Licensee should quantify the proportions of gaseous elements contributing to the public consequences, so the significance of organic iodine and xenon can be compared. This is part of **AF-UKEPR-RC-47**, to ensure that analyses of xenon and iodine are proportionate.

1119 All these methods are focussed on the early phases of an accident and its mitigation within the first 1 - 2 days. These methods may not applicable to events late in the timing of an accident, for two reasons:

- In responding to TQ-EPR-834, EDF and AREVA said the detailed chemistry of iodine (in whatever form) was unimportant because the bulk of the activity was retained by the IRWST. As the water used to cool the spreading compartment could contain appreciable quantities of iodine from the first phase of the accident, boiling in the spreading area could create a significant second release, even if there was less iodine available. Boiling of IRWST water in the spreading area makes the biggest contribution to containment pressure but boiling of the IRWST water in the spreading area was not included in the source term for the public consequence.
- Once most of the radioactivity has been swept into the sumps and IRWST by the sprays, the effect of recirculating the sprays would be to re-suspend the activity by spraying it into the containment. The spray water is made alkaline to control any iodine re-release caused this way. The eventual proportions of radioactivity in the IRWST, containment air and other locations will be determined by a balance of the spray re-suspension rate and the true deposition rate. This will be higher than the ultimate airborne activity calculated either by the IRSN method or the cut-off assumption used by EDF and AREVA. Responding to TQ-EPR-1188, EDF and AREVA said they intend to improve upon these estimates in the next phase of the project.

1120 Neither effect may be large when compared to the pessimistic calculations used in the PCSR, but they determine the size of releases later on in an accident and outside the main containment. Consequently, this may influence the quality of engineering demanded of ancillary systems, such as the CHRS plant room discussed below. Both these effects were modelled using COCOSYS and I expect continued refinement of these calculations during Phase 2, **AF-UKEPR-RC-48.** In TQ-EPR-1188, EDF and AREVA stated that natural deposition will apply to releases from the spreading area as it would to releases from the core, effectively limiting any airborne radioiodine to levels lower than from the dry phase release. This assumption should be justified.

1121 The nature of the phenomena occurring in the later stages of an accident may be speculative and not amenable to large-scale testing and validation. EDF and AREVA sometimes used COCOSYS and MAAP to model equivalent aspects of the same phenomena, yet comparisons between these two codes were never reported to ND. By running these codes to compare outputs from the later stages of a potential accident, valuable insights should be gained. Therefore, I find that the Licensee should ensure that the comparisons between COCOSYS and MAAP undertaken by EDF and AREVA are reported. Ref. 128 only compares the output of MAAP to the input of COCOSYS. This is also part of finding **AF-UKEPR-RC-55.**

1122 A related GDA Issue on hydrogen control (**GI-UKEPR-RC-01**) contains an action relating to iodine chemistry in Passive Autocatalytic Recombiners, which also relates to TQ-EPR-1428.

1123 I conclude that the assumption of full fuel melting and gas release and the use of the IRSN method, are both highly pessimistic assumptions for early-phase releases. The provision of a buffered water spray system, as is provided in many other existing LWRs, provides additional benefit over and above the figures claimed for UK EPR.

4.6.4.3 In-Containment Systems

1124 The Containment Heat Removal System (CHRS) is described in the PCSR (Ref. 11, Section 6.2.7). The CHRS is used to control the containment pressure and achieve long-term cooling of the IRWST and the molten corium in the spreading compartment. The CHRS also provides a function to scrub fission products from the containment atmosphere. It is not claimed for the severe accident and not used for most design-basis events, although it is always available. Two trains of CHRS are included in the UK EPR design, both taking supply from the IRWST. Each train consists of a pump and heat exchanger (cooled by a dedicated cooling system) which supply the dome spraying system (when operated to remove FPs – two other outlets can be used depending on the accident conditions). The sprays consist of a ring equipped with spray nozzles located in the dome of the containment. The condensate, which is generated by the sprayed coolant from the steam within the containment atmosphere, flows back to the IRWST and is then recirculated.

1125 EDF and AREVA have considered controls on the use of (especially fibrous) insulation materials in the plant in Ref. 193. This states that preference would be given to the encapsulation of insulation materials by metal cladding, but the PCSR did not indicate which materials had been chosen. Should fibrous material reach the IRWST (due to the failure of cladding for instance), silicates or zeolite-forming solutes may be carried into the core and impair heat transfer during an accident. Also, other materials may be introduced into the containment building during a shutdown, and these may place an additional burden on the sump filtration system. These aspects are included in Assessment Finding **AF-UKEPR-RC-50**.

1126 In postulated accidents, the alkalinity of the containment spray in recirculation mode directly affects the retention of inorganic and elemental forms of iodine. The UK EPR CHRS includes a sodium hydroxide injection circuit for this purpose. This consists of atmospheric pressure sodium hydroxide tanks, a venting line, a sodium hydroxide mixing device and three injection lines; two directed towards the Safety Injection System (SIS) and one towards the CHRS downstream of the main pump. Other chemicals such as solid tri-sodium phosphate have been used rather than aqueous sodium hydroxide, but I consider both are suitable.

1127 The quantity of alkali should be sufficient to counteract all the boric acid within containment. However other acidic gases can be produced through pyrolysis and radiolysis in some circumstances. I requested quantification of this effect in TQ-EPR-1193, and EDF and AREVA said their calculations also didn’t include alkaline compounds of lithium and caesium hydroxides, which should cancel out any acidic products. EDF and AREVA did not provide adequate assurance of the thermodynamic data and production rate of acids and fumes in the containment by pyrolysis or radiolysis. Responding to TQ-EPR-1193, EDF and AREVA said that ignoring these effects tended to cancel the un-quantified effects of alkaline fission products on iodine chemistry of the In-Reactor Water Storage Tank. Both effects should be quantified. I consider this to be an Assessment Finding, **AF-UKEPR-RC-50**.

1128 EDF and AREVA provided their analysis of fission-product behaviour (Ref. 128) used for the equipment survivability assessment. TQ-EPR-1401 asked EDF and AREVA if the COCOSYS model included the sprays. Apparently COCOSYS is capable of modelling sprays but this option was not used for UK EPR, in order to maximise pessimisms in the calculation, because sprays can be expected to help wash fission products into the IRWST in the early stages of an accident.

1129 Once most of the fission-product aerosols have settled and drained into the IRWST, the effect of the recirculating spray in the later stages of an accident would be to put them back into the containment atmosphere. Therefore, it would be useful to see calculations by COCOSYS, MAAP or both, of the amounts of radioactive material airborne with and without sprays at various times. This is finding **AF-UKEPR-RC-49** and a part of **AF-UKEPR-RC-46**. EDF and AREVA recognise that sprays have the potential to redisperse material in Ref. 185 and are considering specifications in the OSSA (Operating Strategies for Severe Accidents) to switch off the sprays and initiate "Active Mode" sump cooling after a certain time.

1130 The CHRS is outside containment and potentially provides an escape route for radioactivity. I asked EDF and AREVA about losses from CHRS lines in TQ-EPR-1400. They replied that the CHRS equipment will be qualified to severe-accident conditions. It is in a closed building with air filters and a sump with leak-detection. Dedicated valves have been incorporated into the CHRS lines, to isolate the containment should a leak be detected outside containment. EDF and AREVA described other features of the CHRS equipment, such as double-bellows on the valves, which make it leak-tight.

1131 The water flowrate through the sprays of UK EPR is lower than in some current LWR designs. The water flowrate was reduced deliberately by AREVA to slow the rate at which steam condenses. This is claimed to bring two benefits for the containment shell:

- it prevents rapid depressurisation; and
- variations in hydrogen concentration are homogenised without increasing the explosion risk, Ref. 184.

1132 The second effect is relevant because the PARs take time to remove hydrogen and explosion is much less likely if the atmosphere is heavy with steam.

1133 I am content that the basic design concept for the in-containment system is sound. I have looked at the implementation and consider these aspects have been thoroughly considered by EDF and AREVA for UK EPR.

4.6.4.4 Ex-Containment Systems and Vents

1134 Provision of a filtered vent for the main containment was requested by The Radiation and Nuclear Safety Authority, Finland [STUK] but was considered disproportionate by the Nuclear Safety Authority, France (ASN) and Nuclear Regulatory Commission (US NRC). Other parts of UK EPR do have vents, including the CHRS plant room and the Annulus Ventilation System (AVS), discussed below.

1135 For most accidents within the design-basis, UK EPR is designed to retain the potential release within the double-walled containment building. In a severe accident, I notice that the CHRS system would pump most of the mobile activity out of the containment and through the CHRS plant room, see the figure at the beginning of Section 4.6.4.1. TQ-EPR-1400 questioned the potential leak path via the CHRS. EDF and AREVA state that the CHRS is designed for severe-accident conditions, can handle water at 100°C and has sumps which can detect leakage. However this room was not included in assessments by EDF and AREVA for the severe accident and the IRWST water can reach 160°C. My TSC estimates that at a leak rate of 44 cm^3 per minute the CHRS plant room could match the leak rate from the main building. This leakage rate may be challenging for sump detection and the leakage rate that matches the main containment leak rate decreases with time.

1136 I find that the Licensee should ensure that evidence exists for the prevention of release of biologically significant nuclides (like caesium) as well as iodine from the CHRS. This should address topics such as the sensitivity of the sensors in the CHRS room sump and the impact of CHRS line isolation, **AF-UKEPR-RC-48.**

1137 The Annulus Ventilation System (AVS) is described in the PCSR (Ref. 11, Chapter 6.2.2). This system maintains the annulus at sub-atmospheric pressure during normal operations, transients and accidents. During normal operations a single High Efficiency Particulate Air (HEPA) filter train is used. In a severe accident the extracted air would be filtered via (one of two separate trains of) HEPA and iodine filters before release via the plant stack.

1138 The AVS and CHRS plant room have a vent and filters. In TQ-EPR-1188.5, I asked EDF and AREVA what account had been taken of the form of iodine in the specification of filters for UK EPR. In reply, they confirmed that the filters had not yet been chosen, but a standard of 99.9% retention for particulates and 99% for organic iodide will be specified. EDF and AREVA point out that their basic calculated releases from UK EPR assume an aerosol efficiency of 99%, i.e. filtration which is ten times less effective than will actually be specified.

4.6.4.5 Summary

1139 Based upon the evidence presented during GDA, the main conclusions I draw from my assessment of accident source terms and fission product control within the containment of UK EPR are as follows:

- EDF and AREVA have provided estimates of the source term within containment which are highly pessimistic for short-term releases. Specifically, no credit has been taken for the sprays, which introduces as much as a factor of ten pessimism into predicted accidental releases to the environment.
- The basic principle of a recirculating alkali spray in UK EPR is used in many PWRs. The UK EPR is slightly different to some, in using sodium hydroxide to buffer the solution and using a relatively low water flowrate. These aspects are acceptable.
- Estimates of the source terms from containment at longer timescales, and sources outside the main containment (“containment bypass”) are probably too low. Specifically, the replies to TQ-EPR-1193 and 1400 were inadequate. I have raised an Assessment Finding for the Licensee to provide more realistic estimates of radioactive release from sources outside the core, including the quenching phase and CHRS.
- Some approximations used by EDF and AREVA could lead to underestimates of releases from the main containment. These include release fractions for certain longer-lived nuclides and the treatment of organic iodine. As the UK EPR achieves regulatory targets by some margin, I consider such discrepancies as minor.
- The ND Inspector for Radiological Protection has concluded Assessment Findings covering doses to persons on the site, requiring a site-specific analysis to UK standards and I support this conclusion.
- The Licensee will specify filters to achieve an overall dose reduction that is effective as part of their normal business. These will be tested during cold operations, when the vents and filters are commissioned, since the types of filter can affect the pressures.

1140 When taken as a collective answer, the TQ responses under this area add significantly to the UK EPR safety case for fission product control. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.6.4.6 Assessment Findings

1141 Based upon the assessment of accident source terms in UK EPR described in Section 4.6.4 above, I have identified the following Assessment Findings which need to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as appropriate, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-UKEPR-RC-46*** *- The Licensee shall demonstrate that the release fractions for plutonium and strontium in a severe accident, and their longer-term consequences are appropriate for the UK EPR. This Assessment Finding should be completed before the Pre-Operational Safety Report (POSR) is effective. Target Milestone – Fuel load.*
>
> ***AF-UKEPR-RC-47*** *- The Licensee shall quantify the proportions of gaseous elements contributing to the public consequences in the acute and longer timescales of an accident, so that evidence for the proportion of organic iodine can be generated if significant. An alternative analysis may be agreed with the regulator. This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.*
>
> ***AF-UKEPR-RC-48*** *- The Licensee shall demonstrate that the source term takes account of other sources, such as plant rooms, painted surfaces and the spreading compartment, at different times and examine the sensitivity of their existing analyses to re-release of captured iodine. This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.*
>
> ***AF-UKEPR-RC-49*** *- The Licensee shall ensure that equilibrium levels of airborne fission-products within the containment are calculated and verified both for prolonged transients and events over longer timescales. This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.*
>
> ***AF-UKEPR-RC-50*** *- The Licensee shall estimate the quantities of all possible chemical species that could degrade the performance of the IRWST and analyse their downstream effects on cooling and radioactive release. Possible sources from different events include; acidic fumes from radiolysis or pyrolysis, working materials introduced during shutdowns and leaching from solid materials trapped in the strainers. Each of these could reduce the quality of the water in the IRWST and impair heat transfer or iodine retention. This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.*

4.6.4.7 GDA Issues

1142 Based upon the assessment of accident source terms in UK EPR described in Section 4.6.4 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.6.5 Assessment – Core Damage Including the Core Melt Stabilisation System

1143 In the UK EPR design, EDF and AREVA claim that a core melt is “virtually precluded”. If there was severe core damage and a core melt occurred, the overall design intent of UK

EPR is to retain the molten radioactive material within the containment shell. To achieve this, UK EPR has been designed with a Core Melt Stabilisation System (CMSS), colloquially known as the ‘core-catcher’, to spread, cool and retain molten core material (also known as corium). To allow the catcher to fulfil its function the intention is to keep the reactor pit dry.

1144 The Core Melt Stabilisation System (CMSS) collects a molten core in the pit below the reactor pressure vessel for several minutes. When a fusible plug fails, the CMSS purposefully directs the liquid corium towards a spreading area, where it can be cooled and solidified by water from the IRWST.

1145 This is a fairly novel feature for a PWR, and has received extensive analyses, much funded by the European Union (EU). Many of these have addressed questions of making a CMSS work. My assessment has focussed on the potential for core melting to make an accident worse, i.e. to identify any potential “cliff edge” effects, in terms of re-criticality, radioactive release, explosion or chemical attack on the structure.

1146 UK EPR has numerous systems to provide emergency cooling and prevent core damage occurring, and these have been assessed by my colleagues in ND. There are special instruments in the reactor to detect when core damage is about to start. If this were detected, cooling would be deliberately stopped and the CMSS would come into action. This part of my assessment starts at the point where this has already occurred. The methods and approximations used to predict physical properties of the melt were also reviewed for me by my TSCs, Refs 135 and 136.

1147 At the start of GDA, EDF and AREVA outlined their claims for the CMSS and provided research papers that showed how such a system might work, but no analyses specific to UK EPR. In 2009, I raised Regulatory Observation Action RO-EPR-44.A3, asking EDF and AREVA to provide an ‘auditable trail’ which would allow assessment of severe accident chemistry to follow the ‘claims-arguments-evidence’ path for UK EPR. Over the following months, EDF and AREVA provided Refs 66, 68 and 70 providing substantive documentation for the CMSS with summaries of the analyses they performed when designing EPR.

1148 First, it is necessary to describe the steps by which EDF and AREVA claim that a molten core would be stabilised by the CMSS, Ref. 68 and the following figure shows the principal components of the Core Melt Stabilisation System, taken from Ref. 11, Section 16.2.2.4.

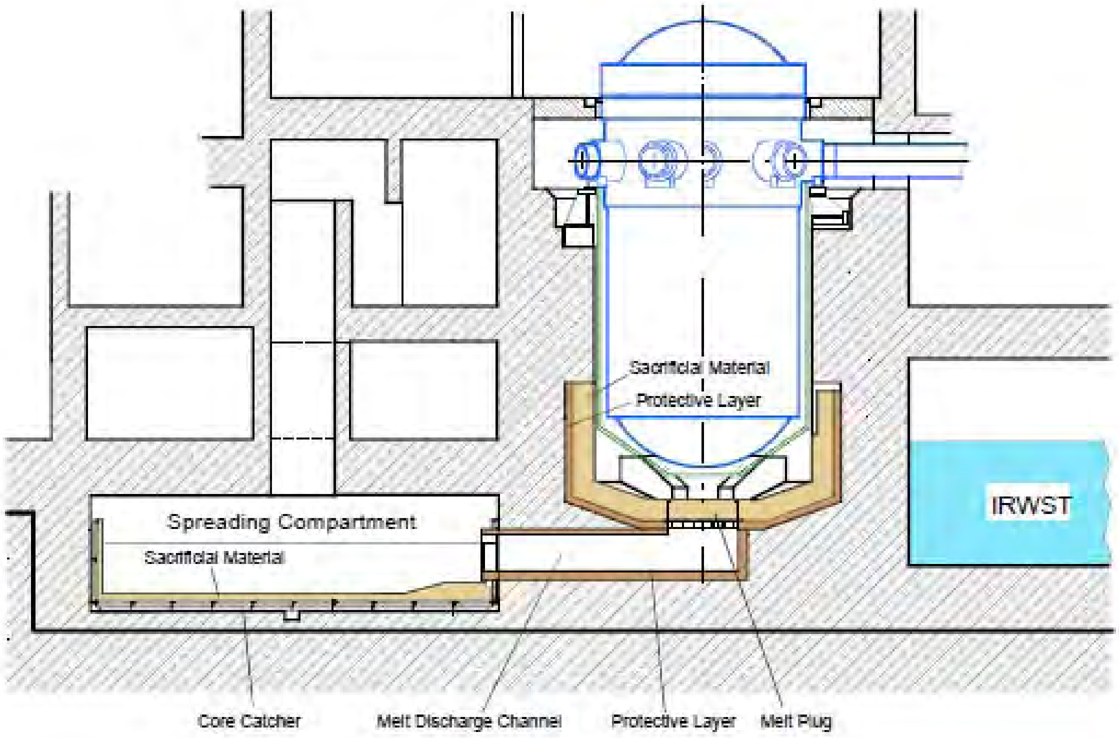


Figure 26: UK EPR Core Melt Stabilisation System

1149 Once the core, comprising reactor fuel, control rods and various structural elements began to melt it would drain and collect in the lower head of the reactor vessel (within the lower curved blue line in the diagram). If the temperature of the corium reached around 2,500 °C, the lower head would fail and release the molten corium into the reactor pit, the region of the diagram outside the blue line and inside the light-brown lining of sacrificial concrete. Underneath most of the sacrificial concrete, there is a thinner lining made of zirconia protecting the underlying structure, shown in dark brown. Whilst cooling in the pit, the corium would react and mix with the sacrificial lining and gradually melt through a plug in the bottom. UK EPR is designed so that failure of the plug results in the corium pouring through the melt discharge channel and into the spreading compartment. When doing this, it can have a temperature greater than 2,000°C.

1150 The floor of the spreading compartment contains a network of water cooling channels, consisting of iron blocks covered by several cm of silicaceous concrete. After arriving in the catcher, there is a feature designed to release water from the IRWST to cool the floor of the catcher and then flow onto the top of the spread corium.

1151 In TQ-EPR-1222, I asked EDF and AREVA what consideration had been given to premature failure of the reactor vessel, caused by the focussing effect described by Seiler in Ref. 177. They replied that MAAP always predicted creep rupture as the first failure mode in a dry reactor pit. This always occurred earlier than the time taken for a focussing effect to develop. Focussing was more likely as a failure mode if the pit was full of water.

1152 The pit in which the UK EPR reactor sits has a melt plug at the bottom. It's purpose is to remain solid long enough for all of the corium to drain from the reactor vessel and be conditioned by the sacrificial concrete lining. After that time, the plug is supposed to melt and release the corium through the transfer channel into the spreading area. The plug is 50 cm thick because the COSACO simulations predict the core would most likely have emptied by the time that half the plug had ablated (melted or decomposed). This leaves a further 25 cm to ablate before the transfer takes place, which is enough time to condition the melt, TQ-EPR-1348.

1153 The fundamental aim of the CMSS design is to spread the corium out so that it cools and solidifies as quickly as possible, without attacking the structural concrete of the building or falling into water. The silica in the floor of the spreading compartment would help to solidify the corium. A melt that was too cool to proceed through all these stages should be an early success for the CMSS, since the goal is to cool and solidify the melt before it does any more harm.

1154 If the corium reaches the catcher, it is spread over a wide, flat area where it fuses metal rods which open valves that supply water from the IRWST. The water flows through channels under the spreading area and then onto the top of the corium. As the corium is very hot, this produces a lot of steam. In TQ-EPR-1187, I asked EDF and AREVA to consider various faults in which the water either arrived too early or water-hammer disrupted its delivery. In trials commissioned by STUK for instance, severe water-hammer in a mock-up of the catcher destroyed viewing windows. In their reply, EDF and AREVA provided sufficient evidence that the design of the actual CMSS was sufficiently robust to withstand these effects.

1155 SAPs FA19 and FA20 (Ref. 4) state that the user of computer codes is responsible for checking their accuracy and verifying that software produces consistent results wherever necessary. In the following subsection, I assess the application of chemical modelling in the main computer codes used to model the performance of the CMSS in the event of a severe accident.

4.6.5.1 MAAP and COSACO Computer Codes

1156 Whilst there have been many small-scale experiments demonstrating features of the CMSS, predicting the behaviour of the whole system requires computer modelling. I raised TQ-EPR-768 and EDF and AREVA provided Ref. 131 to outline how these codes were related. The following figure summarises the relationship between codes used for design and assessment of the Core Melt Stabilisation System by EDF and AREVA, Ref. 131.

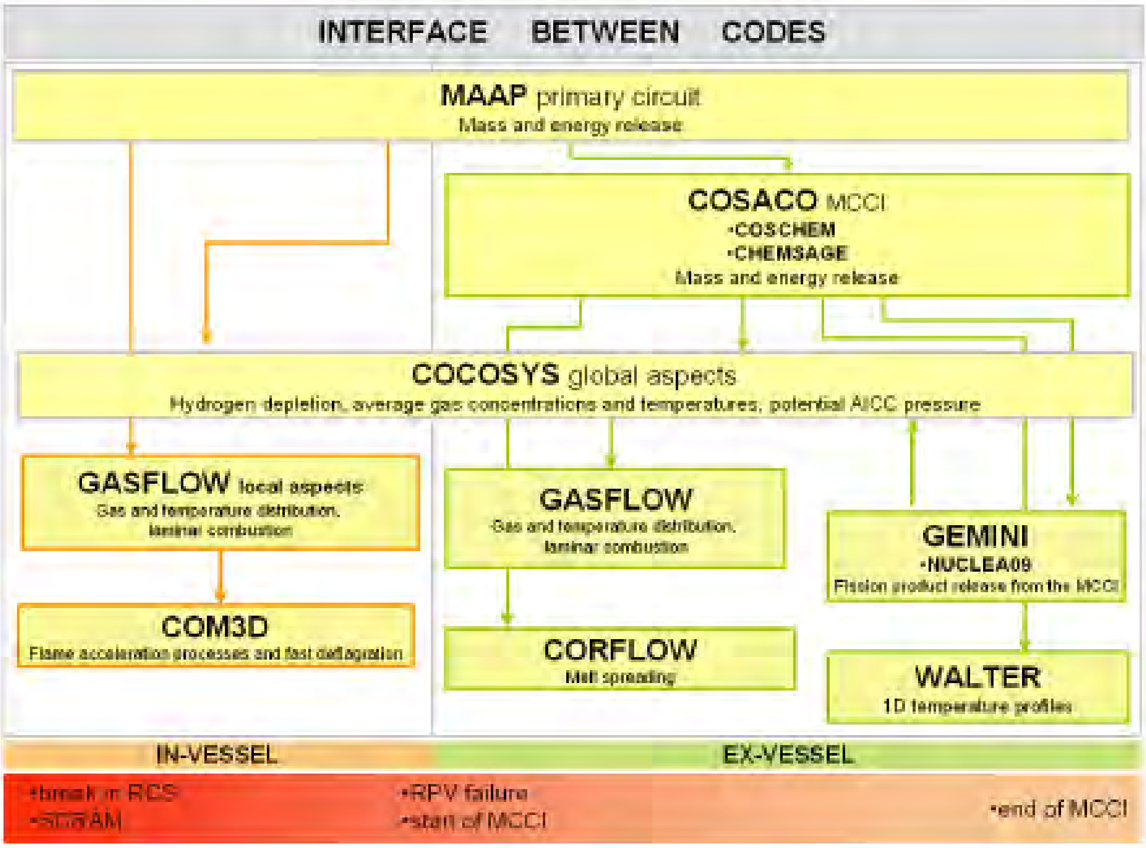


Figure 27: UK EPR Analysis Procedure for Design and Assessment of the Core Melt Stabilisation System

1157 The analysis of the design begins with a number of simulations of events in the core using MAAP, a commercial code produced by Fauske and Associates in the USA. These simulations are used to calculate the timing and inventory of the release to the pit. The inventory consists of all the molten material, plus some core material that may not have melted and minus some of the fission products that have turned to vapour and were lost from the core.

1158 The primary code used for simulation of the Molten Corium-Concrete Interaction (MCCI) that would take place in the reactor pit and spreading compartment is COSACO, an in-house code developed by AREVA at Erlangen. MAAP cannot be used to simulate the spreading compartment as it is designed to simulate the core and cooling circuits of a reactor.

1159 TQ-EPR-1189 was raised to clarify the outputs from the MAAP simulations. Specifically, if the vessel fails at the side and the corium is layered, the composition of corium may change during delivery to the pit. EDF and AREVA confirmed that the final form of the corium in the pit does not depend on the failure mode of the reactor vessel. EDF and AREVA believe that the corium is fully mixed once it has left the vessel. For the pouring phase, EDF and AREVA use both the COSACO code and MAAP. They use the corium composition calculated by MAAP as the starting condition for COSACO at the start of the pour but continue to use MAAP for the radioactive release predictions. COSACO is only used to predict the conditions that equipment must survive and not releases to the environment. I find that a comparison of both codes should be reported to demonstrate the boundary conditions are reasonable and to verify their input to source-terms, see finding **AF-UKEPR-RC-53**.

1160 During the pit retention phases, the COSACO code predicts significant production of hydrogen and steam, but releases of volatile fission-products that are small and cease once hydrogen production stops.

1161 MAAP and COSACO use various databases for the prediction of chemical and physical properties used for severe-accident modelling and my assessment of these follows.

4.6.5.1.1 MAAP and MATPRO

1162 MAAP makes use of the MATPRO collection of physical properties, the MATerial PROperties system developed by the Idaho National Engineering and Environmental Laboratory for the RELAP5 and SCDAP severe-accident codes, Ref. 146. When MATPRO was developed, there were data for (U, Zr, O) mixtures and melts up to 2,273K, as could be used in detailed models for fuel, but no data for mixtures of these three elements with iron.

1163 Because there are many different substances in the reactor, melting may pass through phases of softening, mixtures of liquids plus solids then separation into one or more liquid layers. The approach taken in MAAP is to use interpolation to derive properties for four-component (U, Zr, Fe, O) and higher-order mixtures. No attempt at detailed chemical modelling is made because a) the validation data did not exist when it was written and b) computing restrictions on complex properties modelling. This leads to inconsistencies in parameters such as component thermal capacities and simplifications such as solid and liquid mixtures having the same compositions. Nevertheless, the MATPRO models do reflect the key features of the U-Zr-O system including the eutectic and extended mutual solubilities at higher temperature. The MAAP code does not predict whether corium will form different layers but the user can specify whether the corium will be layered or mixed.

1164 On melting, thermal conductivity decreases and convection takes over as viscosity decreases. The thermal conductivity of uranium dioxide was incorrect in MATPRO and any deficiencies in MATPRO data have not been corrected by the authors. However, the thermal conductivity of the melt has only a small effect on the timings of events and the dominating factor appears to be the total heat. Unlike MATPRO, MAAP does include the heats of melting, as mass and energy are conserved in this code, Ref. 135. This gives better agreement with experiments than achieved by MATPRO itself.

1165 In RELAP5 and SCDAP, MATPRO is a software library but EDF and AREVA use MATPRO as a reference data compilation, TQ-EPR-1195. As a result, MAAP is not tied to using all of the MATPRO data.

1166 There are better ways of modelling the properties of a corium, my TSC for instance used the SGTE database to check some of the MAAP results. Overall I conclude that MAAP will provide reasonable approximations to the oxidation state, temperature and liquid fractions for the fuel at a given composition and heat. These are used (Ref. 135) to provide estimates of hydrogen / steam before the vessel fails (Section 4.6.3.2.2) and to check the source term (Section 4.6.4.2).

1167 The reaction between zirconium and steam is a most significant source of hydrogen gas. For a while, this reaction also generates a lot of heat. MAAP models this reaction and the reaction of steam with steel which produces less hydrogen and heat. Hydrogen is produced rapidly while the fuel is melting, but the production rate slows down as the melt collects and the metallic surface area decreases. A later phase of hydrogen production is modelled by COSACO.

1168 Whilst this is happening, nuclear material with a low melting point is vaporised. This results in the source term assessed in Section 4.6 of this report.

4.6.5.1.2 COSACO and GEMINI

1169 I raised TQ-EPR-1191 to question the description of COSACO given in Ref. 70. In reply, EDF and AREVA outlined the basis of some of the chemical and physical properties used by COSACO which are calculated differently from MAAP.

1170 The COSACO and the Gibbs Energy Minimiser (GEMINI) codes are used by AREVA to assess the conditions within containment that equipment in UK EPR must withstand. COSACO models processes taking place in the reactor pit and subsequent transfer of the melt to the spreading area. GEMINI was used by AREVA to predict fission-product volatilities. Responding to RO44.A3, EDF and AREVA provided Ref. 186 describing the methods used by COSACO and outlining some of the benchmarks and comparisons undertaken to validate the code. It is clear that COSACO made much more sophisticated use of chemical modelling through use of a package called CHEMAPP (which is a Chemistry Application programmatic interface to CHEMSAGE) and I raised TQ-EPR-1347 in order to understand the origin and consistency of the chemical databases underpinning the calculations by CHEMAPP and GEMINI.

1171 Both CHEMAPP and GEMINI are chemistry modelling programs which, when coupled to a thermochemical dataset, can predict the chemical composition of specific chemical mixtures. They both use the Thermodynamic Database for Corium (TDBCR) and NUCLEA datasets but these must be reformatted for use in CHEMAPP, whereas GEMINI can use TDBCR and NUCLEA directly. TDBCR is used for fission-products and structural materials whereas the more recent NUCLEA includes uranium chemistry. I consider the TDBCR and NUCLEA datasets to be the best thermodynamic data currently available for modelling these mixtures, even though some simplifications have to be made.

1172 Responding to TQ-EPR-1347, EDF and AREVA said that a full check of the consistency of the results from using TDBCR / NUCLEA with GEMINI or with CHEMSAGE (Ref. 14) is practically not feasible. Instead they rely on suppliers to validate the algorithms in GEMINI and CHEMAPP. The whole code system of COSACO - CHEMAPP - TDBCR was validated against various experiments using prototypic core melts, including the Advanced Containment Experiments (ACE) and the Melt Attack and Coolability Experiments (MACE), at Argonne. In the case of NUCLEA, a recent preliminary test calculation of one arbitrarily selected input system indicates equilibrium amounts deviating by “less than a few percent”. A simple verification for consistency of the whole modelling process from chemical properties to overall phenomena would be to conduct a comparison of MAAP and COCOSYS over the period where their scope overlaps. EDF and AREVA undertake these calculations anyway, but the comparisons are not reported. I find that this would not only check their consistency but also ensure the most bounding results have been used, **AF-UKEPR-RC-55**.

4.6.5.1.3 Computer Codes Summary

1173 Despite the great uncertainties involved in making predictions under these conditions, it would not be productive to try and improve the chemistry in the current generation of accident modelling codes, such as MAAP or COSACO, since their accuracy is derived from the overall energy balance and timing of known phenomena. The methods and approximations used to predict physical properties of the melt were also reviewed for me by my TSC, (Refs 135 and 136) who also agree with this conclusion. EDF and AREVA have conducted parallel simulations with COSACO and MAAP for the period when corium exits the RPV, and I find that a comparison of their outputs should verify that chemistry has been modelled consistently by these two codes, **AF-UKEPR-RC-53**.

4.6.5.2 Choice of Concrete Linings

1174 Temporary melt retention is achieved by a layer of sacrificial concrete through which the melt must erode before it contacts and destroys the melt gate and spreads into the core catcher. Behind this layer in EPR, there is a thinner layer of a refractory brick protecting the structure.

1175 EDF and AREVA presented Ref. 178 in order to justify their choice of the sacrificial concrete (FESI-PZ15-8) for the reactor pit lining. They claim that use of this concrete yields melt properties which are favourable for melt spreading. As the amount of sacrificial concrete is predictable and limited, it is claimed to adjust and restrict the spectrum of melt compositions at the time of spreading.

1176 The sacrificial concrete does not contain limestone because corium and limestone would produce carbon dioxide that would increase pressure in the containment building. Silicaceous concrete produces less gas, which EDF and AREVA believe will improve sideways attack making concrete consumption more even.

1177 The protective bricks underneath the sacrificial layer will be made from a proprietary form of zirconia, called ZETTRAL^{TM} 95GR. The other refractory liners considered were oxides of uranium, thorium or magnesium. The first two would become heavily radioactive near a reactor core. Pure magnesium oxide has a higher melting point than pure zirconia but melts in mixtures with corium at a lower temperature and also reacts with steam. Magnesium oxide is however a component of ZETTRAL^{TM} as a stabiliser, as I would expect. The refractory liner has been qualified up to 15 minutes with simulated corium. To maximise the life of the liner, AREVA has developed the composition of the sacrificial concrete layer to reduce the temperature of the corium and its aggressive chemical nature.

1178 If metallic elements in the corium reached the zirconia lining at high temperature, the zirconia lining would be damaged. Theoretically there is enough oxygen in silicaceous concrete to oxidise the entire mass of remaining zirconium to zirconium dioxide before it reaches the zirconia liner but the temperature would be very high. Concrete loaded with haematite (ferric oxide) has been specified for UK EPR because it decomposes at a lower temperature than silicaceous concrete and helps to cool the corium. Because zirconia reacts with ferrous oxide, AREVA has undertaken studies to demonstrate that the reaction of zirconium with haematite produces iron and not ferrous oxide. Undertaken with the GEMINI code, these calculations showed that there should not be much ferrous oxide in the melt once all the zirconium had been oxidised, Ref. 181.

1179 Some silica is retained in the sacrificial concrete for strength and because it may help to trap some of the fission products. According to tests sponsored by AREVA, concrete type [redacted] has overall very similar strength as ordinary concrete. The heats of reaction and densities of silica and haematite do differ, but in a way that tends to cancel, Ref. 178.

1180 EDF and AREVA believe the haematite reduces the effective melting temperature of the corium by decreasing its viscosity, allowing it to flow through the transfer channel as it cools. According to Ref. 178 the viscosity of the melt settles to a level compatible with heat transfer from the bulk to the sides of the pit, regardless of the type of concrete used. However, the concrete composition dictates the temperature for which this viscosity is reached.

1181 The designers of the concrete subjected it to a range of physical and chemical tests for strength in normal use and at high temperatures with molten uranium dioxide and zirconium.

1182 The sacrificial concrete is loaded with haematite which serves to keep the cooling corium liquid enough to run through the melt discharge channel. I raised TQ-EPR-1192 questioning some of the claims made for this material in UK EPR:

- EDF and AREVA do not claim that haematite reduces fission product releases compared with a ‘pure’ siliceous concrete. They claim there is only 5% of the volatile fission-product left to be released by this stage in an accident and that silica helps to stabilise the remaining fission products.
- In the ACE experiments, interactions between zirconium and other metallic components of corium with siliceous concrete produced silicon monoxide vapour that blocked pipes. COSACO does not model silicon monoxide but EDF and AREVA argued that any silicon monoxide would have to pass through the corium and therefore be scrubbed by it.
- The largest scale of test that EDF and AREVA quoted for the sacrificial concrete involved 54kg of simulated corium in the VULCANO facility, details of which were provided with TQ-EPR-1286. The tests were undertaken to qualify the concrete for OL3 and the results showed that sacrificial concrete was like ordinary concrete. More tests have been conducted (e.g. CORESA) using larger quantities of ordinary concrete.
- EDF and AREVA believe that corium attack of the pit wall stops when all the sacrificial concrete has been consumed and it reaches the zirconia liner. The corium may overtop the sacrificial concrete for a few minutes at the end of the in-pit phase if gas production is high.
- COSACO predicts there is enough time for water from the IRWST to cool and solidify the corium before it dissolves through the floor and blocks the water delivery channels.
- There is enough sacrificial concrete to convert any metallic zirconium to zirconium dioxide in all scenarios.
- EDF and AREVA have included failure to open the water valves from the IRWST in their Probabilistic Safety Assessment Analysis (PSA) analysis for UK EPR.

1183 I discussed the relative rates of vertical and sideways attack on concrete in the reactor pit. Very rapid vertical attack would cause the pit plug (or “gate”) to open prematurely. This might result in corium solidifying in the exit channel and blocking discharge to the spreading area. Rates of vertical attack tend to be high with metallic melts where there is a lot of gas produced by the concrete, as witnessed in the COMET tests, Ref. 179. If an energetic corium attacked the concrete much faster in some directions than others, it may not reach the spreader but come to rest in some other part of the containment. This would delay final stabilisation of the event. I therefore find that the Licensee should provide confirmation of the effect of ablation in different directions, **AF-UKEPR-RC-51**. The ND Fault Studies Inspector has raised a finding covering the implications of different rates of ablation in different directions, which I support.

1184 Ferric iron can increase the viscosity of some melts, depending on their composition. In their response to TQ-EPR-1192, EDF and AREVA did not provide experimental evidence that the iron in the concrete effectively reduces the viscosity of the corium. However, the design of UK EPR seems to be very tolerant to inaccuracies of this nature.

1185 The provision of these features are an advance on previous generations of PWR and I consider the sacrificial concrete [redacted] and zirconia ZETTRAL^{TM} 95GR to be well-characterised and suitable materials for their function. This should not preclude the development and specification of other materials to an equivalent standard for UK EPR, if the need arose. I note that EDF and AREVA have not specified the trace element content of the sacrificial concrete [redacted], many tonnes of which are just beyond the RPV. I find that the licensee should assess the content of elements in the sacrificial concrete that would be activated and specify low restrictive compositions if appropriate in order to minimise the level of activation to as low as reasonably practicable. I consider this to be an Assessment Finding **AF-UKEPR-RC-52.**

4.6.5.3 Steam Explosion

1186 When high-temperature melts are dropped into water, a steam explosion can sometimes ensue. Some melts (like tin or alumina) almost always explode whereas others (like uranium dioxide) do not. Various attempts have been made to predict whether one mixture might be more dangerous than another, however, a full explanation of the causes of steam explosions does not exist (see Ref. 10) and regulators must instead rely on expert judgement, such as the NRC Steam Explosion Review Group (SERG, Ref. 94).

1187 Scenarios in which molten material is dropped into water are generally considered the most hazardous in terms of the risk of steam explosion. Even though the core intentionally melts, the reactor cavity (pit) and the spreader are kept dry in UK EPR. Therefore corium cannot fall into water and the possibility of a hazardous configuration is greatly reduced. EDF and AREVA describe these phenomena in Section 1.3 of the PCSR (Ref. 11), which relies heavily on the conclusions of the steam-explosion review coordinated by US-NRC some years ago. I did not assess the possibility of steam explosion in the reactor vessel or cavity and this was assessed by ND in the context of fault-studies and PSA.

1188 The corium spreading area is initially dry but is later flooded with water from the IRWST in order to quench and finally stabilise the melt. At this stage, there would be water on top of a melt. This raises a possibility of a small steam explosion. Areva staff had indicated that steam explosion was impossible in such a stratified system. I reviewed this claim and compared the arrangement of water over melt in UK EPR with that at Appleby-Frodingham, since in this case a violent steam explosion was caused in a moving truck with water lying on top of a melt in a steelworks, Ref. 182. The conclusions of this review are presented in Ref. 135. Since the corium would be in a thin viscous layer when quenched, and the water would be added gradually, there would only be a possibility of local interaction. In my opinion and that of my TSC, any damage would be localised and small compared to the rest of the reactor under severe accident conditions.

1189 Understanding of steam explosions, including the effects of melt chemistry is gradually developing, e.g. through the Tests for Real cOrium Interaction with water in (TROI) in Korea and the OECD SERENA activity. Since the original SERG reviews for NRC it has become possible to model the effect of chemical reactions between the corium and the water and I find that the Licensee should repeat calculations for small steam explosions and water hammer where there might be reactive elements present, **AF-UKEPR-RC-53.**

4.6.5.4 Corium Re-Criticality

1190 In RO44.A3, I asked EDF and AREVA to provide their analysis of re-criticality in the CMSS. Their response to RO44.A3 includes an assessment of corium re-criticality, outside the RPV, Ref. 66. Ex-vessel re-criticality analysis was performed using a one dimensional model of the melt configuration in the reactor pit and in the spreading compartment. Areva determined $k_{infinity}$ for different water depth and porosities using input from thermo-chemistry analysis for MCCI and melt stabilization in the core catcher and taking account of the composition of corium, densities of the corium phases, level of core melt and temperature of the corium.

1191 The calculation of $k_{infinity}$ was done using the standard AREVA methods (e.g. CASMO) and the scattering cross-sections were taken from standard databases.

1192 The response to TQ-EPR-189 seems to take credit for boron in the corium, AREVA has agreed these calculations should be repeated in more detail, **AF-UKEPR-RC-54** in order to confirm that the margins to re-criticality are very large and would permit some loss of boron, which is volatile. There is a related finding in the report on Severe Accidents and Containment.

1193 The chemistry taking place in the CMSS did not give me cause for concern for criticality but ND expects the licensee to provide a more detailed analysis of this hazard in the PCSR.

4.6.5.5 Operating Strategies for Severe Accidents

1194 The actions that an operations team would need to undertake in order to manage an event involving core damage would be defined in a series of Operating Strategies for Severe Accidents (OSSAs). These were not prepared in time for GDA, but the OSSAs themselves may have a bearing on the outcomes of some of the phenomena outlined above, Ref. 132.

1195 Important activities which have yet to be defined in the OSSA include instructions relating to the supply of water to the reactor pressure vessel and the timing for CMSS activation, Ref. 11, Section 6.2.6. The form of the OSSA may also have an influence on the amount of boron available in the corium to control criticality. The OSSA for UK EPR was not available for GDA and will be assessed during Licensing.

4.6.5.6 Summary

1196 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of core melt events in UK EPR are:

- EDF and AREVA have undertaken comprehensive analyses of the design of EPR and comparisons with test data that demonstrate that the CMSS is capable of performing its design intent. The phenomena occurring in the CMSS are characterized by the radioactive decay energy available and the timings of events. Extremely high temperatures may be reached at times and EDF and AREVA have taken an innovative approach to materials to control any melting and guide it towards a spreading compartment where it could be cooled and solidified effectively.
- The various stages in this process have been validated by numerous experiments and the overall design function verified by the use of sophisticated computer modelling, employing the MAAP and COSACO codes specifically. Subject to some findings

outlined below, I am satisfied with the approach taken by EDF and AREVA in this area.

- The potential for a damaging steam explosion has been largely eliminated by keeping water away from the core if it begins to melt. A simple calculation by AREVA indicates that the potential for recriticality also may be negligible. I have raised two findings on the Licensee to confirm these results with more detailed calculations.
- The use of a depressurisation system and the ex-vessel concept place greater demands on the outer containment system. This is assessed in Section 4.6.4 of my report and in Ref. 73.
- In scenarios where there was insufficient decay energy in the fuel to exercise the CMSS fully, the CMSS would not be needed.

1197 When taken as a collective answer, the TQ and RO responses under this area add significantly to the UK EPR safety case for core melt chemistry. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that EDF and AREVA have made an adequate case to support GDA.

4.6.5.7 Assessment Findings

1198 Based upon the assessment of core melt chemistry in UK EPR described in Section 4.6.5 above, I have identified the following Assessment Findings which need to be addressed, as normal regulatory business, either by the designer or by a future Licensee, as appropriate, during the design, procurement, construction or commissioning phase of the new build project:

AF-UKEPR-RC-51 *- The Licensee shall generate evidence for the relative timings of the melt ejection and concrete ablation/plug failure (i.e. the factors affecting the retention time in the pit) and taking account of the following:*

- *i) The rate of ablation of the haematite-based sacrificial concrete in the axial and radial directions relative to the timescales for the complete ejection of melt from the RPV.*
- *ii) The differences in the rates of ablation between the mixed and the layered condition.*
- *iii) The ablation rate for the condition with a metal layer in contact with the concrete.*
- *iv) Experimental data for the improvement in flow characteristics for FeO1-x containing melts.*
- *v) Thermal stability of the Al-Mg gate (loss of mechanical strength with temperature).*

This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.

AF-UKEPR-RC-52 *- The Licensee shall review and justify the activatable content of the sacrificial concrete used in the reactor pit and specify low trace element content where appropriate. This Assessment Finding should be completed before pouring nuclear safety-related concrete. Target Milestone – Nuclear island safety related concrete.*

> ***AF-UKEPR-RC-53*** *- The Licensee shall analyse the effect of additional heat input from the exothermic chemical reaction between the corium and water on the energy released when they interact. Documentation for this effect should include the justification for any assumptions made. This Assessment Finding should be completed before first nuclear operations with the reactor. Target milestone – Initial criticality.*
>
> ***AF-UKEPR-RC-54*** *- The Licensee shall repeat the analysis of re-criticality in the corium, in more detail to include effects such as boron mixing and volatility. This Assessment Finding should be completed before first active operation of the plant. Target Milestone – Initial criticality.*
>
> ***AF-UKEPR-RC-55*** *- The Licensee shall compare the results from equivalent analyses generated by the MAAP and COSACO computer codes to confirm the bounding results have been used to examine the consequences of severe accident, over the period where their scope overlaps. This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel Load.*

4.6.5.8 GDA Issues

1199 Based upon the assessment of core melt chemistry in UK EPR described in Section 4.6.5 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.7 Overseas Regulatory Interface

1200 In accordance with its strategy, HSE collaborates with overseas regulators, both bilaterally and multinationally. HSE’s Nuclear Directorate (ND) has formal information exchange arrangements to facilitate greater international co-operation with the nuclear safety regulators in a number of key countries with civil nuclear power programmes, including:

- the US Nuclear Regulatory Commission (NRC)
- the French L’Autorité de sûreté nucléaire (ASN)
- the Finnish Säteilyturvakeskus (Radiation and Nuclear Safety Authority, Finland) STUK

1201 US NRC, ASN and STUK are undertaking assessments of the EPR design and I have had some discussions with both US NRC and STUK as part of my GDA assessment process. This exercise has provided a useful exchange of information and has helped to guide my assessment in certain areas, the outcome of which is reported in the text of this document.

4.8 Interface with Other Regulators

1202 I have worked with the Environment Agency as an integral part of the GDA assessment process; although for the EDF and AREVA UK EPR design I have not identified any specific areas of Reactor Chemistry interest where detailed liaison has been considered necessary. I have liaised where the two assessments have overlapped, primarily in areas related to source terms, waste generation and discharge treatment systems.

4.9 Other Health and Safety Legislation

1203 I have considered conventional safety legislation in a general sense as part of my GDA assessment, primarily to ensure that the UK EPR design is capable of being operated and maintained in line with applicable regulations of the Health and Safety at Work etc Act, 1974. I have not identified any concerns during my assessment which would threaten GDA for UK EPR.

1204 More specifically, whilst mindful of conventional chemistry safety regulations, such as the Control of Substances Hazardous to Health (CoSHH) and the Dangerous Substances and Explosive Atmosphere Regulations (DSEAR), these are outside the scope of GDA and I have not assessed against them. However, I have not noted any concerns in these areas during my assessment which would threaten GDA for UK EPR.

5 CONCLUSIONS

5.1 Conclusions from the Assessment

1205 This report presents the findings of the Step 4 Reactor Chemistry assessment of the EDF and AREVA UK EPR reactor. I have assessed:

- The EDF and AREVA safety case for the justification, implications and control of primary coolant chemistry during all modes of operation. This included consideration of nuclear reactivity control using boron, the effects of coolant chemistry on the integrity of pressure boundaries, protection of fuel and core components and production, transport and deposition of radioactivity, including its influence on radiological doses to workers and ultimately to wastes.
- Those features of the design, material choices or chemistry controls which reduce radioactivity so far as is reasonably practicable.
- The main secondary circuit systems which control or are influenced by chemistry. This includes consideration of the implications of system design on chemistry choices and the interaction of chemistry with materials and corrosion susceptibility.
- Those engineered systems which allow the operator to control, monitor or change the plant chemistry.
- The storage of nuclear fuel within ponds, including the effects of pool chemistry.
- Those systems which mitigate the release of radioactivity to the environment in either the liquid or gaseous form.
- Design basis and beyond design basis accidents, including the production, release and control of hydrogen and fission product nuclides.
- The arrangements for moving the safety case to an operating regime, including the derivation of suitable limits and conditions and the arrangements for specifying plant chemistry.

1206 The conclusions from my assessment, for each of these areas are presented below.

5.1.1 Chemistry Standards, Limits and Conditions

1207 The safety case presented by EDF and AREVA includes the expected operating chemistries for many, but not all, of the systems in UK EPR. The omissions will need to be resolved going forward. EDF and AREVA have not yet fully defined the controls which will be placed on these regimes either by limits and conditions or operating procedures. On the basis of the evidence presented I am content that these matters can be adequately progressed by the Licensee and a sufficient case has been made to support GDA.

5.1.2 Primary Circuit

1208 Primary circuit chemistry is a balance between the requirements of minimising radioactivity, protecting the fuel and ensuring the integrity of the structural materials while maintaining sufficient dissolved boron to control nuclear reactivity throughout the cycle. EDF and AREVA have designed UK EPR to use Enriched Boric Acid (EBA). Use of EBA has a number of advantages for chemical safety including a lower volume, higher freezing point and less acidity than natural boron. I assessed systems for managing boron, which include a multiplicity of monitoring devices. ND has requested continued work after Step 4 on the diversity of the boron monitoring system (**GI-UKEPR-FS-01**), which I will support. I have asked EDF and AREVA to quantify the production and loss of impurities in the coolant as part of GDA Issue **GI-UKEPR-RC-02**. With these exceptions, I am content with the proposed design for boron control in UK EPR.

1209 EDF and AREVA have described the expected primary circuit operating chemistry for UK EPR. This has been shown to demonstrate an appropriate balance between the many competing factors and should allow UK EPR to operate safely. While the precise values for limits and conditions necessary in the interest of safety have yet to be finalised and presented to ND, EDF and AREVA have demonstrated a sound understanding of the requirements and our expectations in this area and I am content that the Licensee could adequately define these.

1210 It is normal practice to add some hydrogen to the primary coolant when a PWR is at temperature. EDF and AREVA propose to add a smaller quantity of hydrogen than is currently recommended by many operators. It is clear the design of the reactor is nevertheless capable of supporting a higher level of controlled hydrogen addition.

1211 One technique being applied is the addition of zinc to primary coolant. Traces of zinc are known to control radiation fields within reactors. Thus it appears that zinc addition will be beneficial. So far, EDF and AREVA do not propose to add zinc during commissioning and this needs further assessment. Given developments with robotic methods of inspection and in use of zinc, EDF and AREVA see no need to electropolish the steam-generator internals.

1212 I have assessed the major chemistry systems which allow the licensee to control, monitor and change the primary chemistry, including those that are used during accidents. The UK EPR has a number of sophisticated systems for these aspects which are derived from, and often improve on, successful systems which are in operation in PWRs today.

1213 As well as the operating chemistry an important design choice is the materials in contact with the coolant in any reactor. Many PWRs, from earlier generations of designs, have had problems with corrosion which led to wide variations in radioactivity levels and some cracking of alloys. Whilst cracking should not be a problem in a new reactor like UK EPR there is still variability in the corrosion that leads to cobalt build-up. There have been differences of view between designers on the contribution made by high-cobalt alloys to radiation in a reactor. These alloys are typically hard-wearing for use in parts of reactors subject to repeated movement. Their use has declined over the years but they can only be eliminated if the alternative is suitable. I asked EDF and AREVA to assure me that the cobalt content of alloys in UK EPR has been reduced significantly, which they have done.

1214 During Step 3 I noted that the safety case for UK EPR was almost entirely based on experience with previous reactor designs, none of which were directly comparable to UK EPR. My expectation is that a nuclear safety case should be based upon a balance of experience and supporting calculations. Bounding estimates of the radioactive materials such as cobalt that would be produced by UK EPR, have been provided by EDF and AREVA based on experience and comparisons with other reactors, primarily in France. These estimates took little account of the size and power of UK EPR which are greater than existing French (and UK) PWRs. I commissioned independent calculations which showed that UK EPR will, not surprisingly, produce more of the cobalt isotopes that current French (and UK) PWRs, although this should be proportional to the increased power generation of UK EPR. I have only limited data at this stage, but the calculations are showing the parts of UK EPR that would need attention to assure radioactivity was controlled. In response to my questions on radiation, EDF and AREVA are starting to predict levels of tritium and other quantities, which reveal some improvements to their coolant management strategy may be needed. These figures arrived late in Step 4 and not all of the data have been assessed. These are important additions to the safety case and this process will need to continue as the UK EPR safety case develops during subsequent approval, construction and commissioning stages. This forms the basis of a GDA Issue that I have raised, **GI-UKEPR-RC-02**.

5.1.3 Spent Fuel Pool

1215 The UK EPR spent fuel pool systems are functionally very similar to current PWRs and the design and material choices are consistent. EDF and AREVA have described the spent fuel pool operational chemistry, mostly in responses and documents outside of the Step 4 PCSR. The chemical requirements for such systems are well known and UK EPR has systems for monitoring, controlling and purifying the pool water which can be considered adequate.

1216 The control of radioactivity within the large volume spent fuel pool is important from an ORE, waste and discharge perspective. UK EPR should be at least as capable as current PWRs in controlling the activity in the pool, and may be better due to larger, more efficient treatment systems, but this needs to be tempered against the use of boron recycling. The implications for control of ex-core radioactivity are part of GDA Issue **GI-UKEPR-RC-02**.

5.1.4 Secondary Circuit

1217 Despite some aspects of the secondary circuit being outside of the scope of the GDA assessment, I have assessed a number of aspects of the design including principal material choices, corrosion threats, chemistry control and tolerance of abnormal chemistry. In general, reasonable arguments have been made by EDF and AREVA in these areas although I have identified a number of Assessment Findings where further work will be required going forward.

1218 The principal deficiency is that a holistic analysis for the secondary circuit, considering chemistry and material choices, is not yet available, although I was content with the presentation made in GDA. Moving forward, there will be a need for the Licensee to generate an assessment for the whole of the secondary circuit which addresses the key points identified by my assessment as a minimum.

5.1.5 Ancillary Systems

1219 UK EPR incorporates dedicated systems for the storage, processing and treatment of radioactive gaseous and liquid effluents. These include carbon delay beds for the gaseous wastes,and evaporation and ion-exchange systems for the liquid wastes. These are based on mature and proven technology.

1220 It was less clear what the effect of zinc on wastes would be and I asked EDF and AREVA for extensive evidence for this. This has now been provided and, apart from a question related to the distribution of ^{14}C, which I am content is not a safety concern, I conclude that waste generation should not be significantly worse with zinc addition so that overall, zinc addition will be beneficial. I have assessed the chemistry related to these systems as part of my assessment and am satisfied with these aspects of the design. I have raised findings for the Licensee to define limits and controls for these systems in operation.

1221 The design of the ancillary component heat removal system, the CCWS, incorporates many features of existing power plants. While EDF and AREVA have not yet adequately defined the operating chemistry for this system I can see no reason why one cannot be specified by the Licensee. This will need to be undertaken by the Licensee going forward.

5.1.6 Accident Chemistry

1222 The UK EPR has been designed to prevent accidents and make unplanned releases smaller and less likely. I assessed the chemistry occurring during Steam Generator Tube Rupture (SGTR) events, during accidents which involve generation and release of combustible gases and in the unlikely event of an accident severe enough to melt fuel. These have all been areas of challenge to past reactor designs.

1223 EDF and AREVA presented the chemistry assumptions used in their analysis of SGTR events in UK EPR. Much of the fundamental chemistry is commensurate with what I would expect to see, although a number of the assumptions used may not meet our expectations. The analysis shows that the consequences of the event are not dictated by chemistry factors and are conservatively bounded.

1224 UK EPR features a dedicated safety system which is used to control and remove combustible gases released into the containment during an accident. This system is based on the use of Passive Autocatalytic Recombiners (PARs) which convert hydrogen to water. These devices are new to the UK for this application although are used extensively in Europe and elsewhere and, being reliant on a chemical process, are potentially susceptible to chemical interference. EDF and AREVA provided much information on this system during GDA, including details of the modelling and assessment undertaken, which is sophisticated and comprehensive, and this allayed most of my concerns in this area. However, I am not content that an adequate case has yet been made regarding the effects of degraded PAR performance on the plant, performance under bounding accident conditions or when consideration is given to their potential interaction with volatile iodine. I am content that these can be resolved, but expect this to be done before the start of nuclear related construction and I have raised a GDA issue on this aspect, **GI-UKEPR-RC-01**.

1225 For the extremely unlikely event that the large core becomes hot enough to melt fuel, UK EPR provides a core melt stabilisation system. This comprises a melting pit, a fusible plug, a transfer tunnel and a water-cooled spreader. I assessed the chemical performance of individual steps in this system. I assessed the extensive testing and calculation by AREVA, by European research institutions and elsewhere. I concluded that whilst individual steps in this system have been validated, the composite sequence of steps was not demonstrated. However, such a demonstration is not needed if the core melt is arrested earlier than intended by the design of UK EPR. I am satisfied that its outcome, in terms of the overall containment goal for avoiding a large early release, is assured.

1226 The containment of UK EPR has been designed to retain radioactive material in an accident which simplifies the management of radioiodine. However, EDF and AREVA did not present evidence for the control of late-phase releases and I did not assess iodine release from a LOCA. These omissions should be corrected but are not expected to be significant to the overall safety case.

5.1.7 Overall Reactor Chemistry Safety Case for UK EPR

1227 As a result of the GDA assessments, the PCSR for UK EPR has been updated and now includes a sub-chapter dedicated to Reactor Chemistry. This is a valuable addition to the safety case and will provide a basis for further developments of the plant chemistry. EDF and AREVA have demonstrated that the development of limits, conditions or specifications related to chemistry parameters should be possible for UK EPR. I anticipate that a ‘chemistry manual’ or similar documentation will be required and produced by the Licensee.

1228 It is a fundamental requirement of any quality system that staff responsible for implementation should understand thoroughly the requirements of the specifying organisation. This is particularly important for nuclear purity specifications which are not obvious and apply throughout construction and commissioning and extend even to goods such as seals, tape, towns-water etc. There should be an effective programme to supply the information and documentation needed by the Licensee, during the construction phases as well as operations.

1229 To conclude, I am broadly satisfied with the claims, arguments and evidence laid down within the PCSR and supporting documentation for the UK EPR (Ref. 175). I consider that from a Reactor Chemistry view point, the EDF and AREVA UK EPR design is suitable for construction in the UK. However, this conclusion is subject to satisfactory progression and resolution of GDA Issues to be addressed during the forward programme for this reactor and assessment of additional information that becomes available as the GDA Design Reference is supplemented with additional details on a site-by-site basis.

5.2 Key Findings from the Step 4 Assessment

1230 As a consequence of my assessment of the UK EPR reactor design for GDA, I have identified 55 Assessment Findings and 2 specific Reactor Chemistry GDA Issues that need to be resolved, as appropriate.

5.2.1 Assessment Findings

1231 I conclude that the following Assessment Findings listed in Annex 1 should be programmed during the forward programme of this reactor as normal regulatory business.

5.2.2 GDA Issues

1232 I conclude that the GDA Issues identified in this report must be satisfactorily addressed before consent can be granted for the commencement of nuclear island safety-related construction. The complete GDA Issues and associated action(s) are formally defined in Annex 2.

6 REFERENCES

1 *GDA Step 4 Reactor Chemistry Assessment Plan for the EDF and AREVA UK EPR*. HSE-ND Assessment Plan AR 09/065, November 2009, TRIM Ref. 2009/474637.

2 *ND BMS. Assessment Process.* AST/001 Issue 4 HSE. April 2010. www.hse.gov.uk/foi/internalops/nsd/assessment/ast001.htm.

3 *ND BMS. Technical Reports.* AST/003 Issue 3. HSE. November 2009. www.hse.gov.uk/foi/internalops/nsd/assessment/ast003.htm.

4 *Safety Assessment Principles for Nuclear Facilities.* 2006 Edition Revision 1. HSE. January 2008. www.hse.gov.uk/nuclear/saps/saps2006.pdf.

5 *Nuclear power station generic design assessment – guidance to requesting parties.* Version 3. HSE. August 2008. www.hse.gov.uk/newreactors/guidance.htm.

6 *WENRA Reactor Safety Reference Levels.* WENRA. January 2007. www.wenra.org.

7 *Step 3 Reactor Chemistry Assessment of the EDF and AREVA UK EPR*. HSE-ND Assessment Report AR 09/036, December 2009, TRIM Ref. 2009/389683.

8 *EDF and AREVA UK EPR - Schedule of Technical Queries Raised during Step 4*. HSE-ND, TRIM Ref. 2010/600726.

9 *EDF and AREVA UK EPR - Schedule of Regulatory Observations Raised during Step 4*. HSE-ND, TRIM Ref. 2010/600727.

10 *Berthoud G, Vapor Explosions* in Annual Reviews of Fluid Mechanics pp 573-611 (2000).

11 *UK EPR Pre-construction Safety Report – November 2009 Submission*. Submitted under cover of letter UN REG EPR00226N, 30 November 2009. TRIM Ref. 2009/481363 and as detailed in UK EPR Master Submission List, November 2009 (Ref. 12).

12 *UK EPR Master Submission List*. November 2009. TRIM Ref. 2011/46364.

13 *Reduction in Primary Circuit Radioactivity SFAIRP Based upon the Primary Circuit Materials,* NEEM-F DC 140, Rev A, AREVA, April 2010. TRIM Ref. 2011/92485.

14 *CHEMSAGE – A Computer Program for the Calculation of Complex Chemical Equilibria*; G. Eriksson et al. Metall Trans B v21B, pp1013-1023 (1990).

15 *Generic Design Assessment: Review of Secondary Circuit Chemistry, Materials and Corrosion for the UK EPR*, SPR03860/06/10/25, Issue 1, National Nuclear Laboratory, April 2011. TRIM Ref. 2011/223939.

16 *PWR Secondary Circuit Chemistry, Materials and Corrosion: A Review of International Experience for the HSE PWR Generic Design Assessment*, SPR03860/06/10/10, Issue 1, National Nuclear Laboratory, October 2010. TRIM Ref. 2011/89732.

17 *Radiation Field Comparisons between New Build Designs and Sizewell B*. Issue 05. Hyder Consulting (UK) Ltd. TRIM Ref. 2011/132907.

18 *System Design Manual - Emergency Steam Generator Feedwater System (EFWS) P2 – System operation,* SFL–EFMF 2006.829, Revision E1, Sofinel, September 2008. SFL–EFMF 2006.829, Revision E1 is the English translation of SFL–EFMF 2006.829, Revision E. TRIM Ref. 2011/155551

19 *Step 4 Fuel and Core Design Assessment of the EDF and AREVA UK EPR™ Reactor.* ONR Assessment Report ONR-GDA-AR-11-021, Revision 0. TRIM Ref. 2010/581511.

20 *Classification of Structures Systems and Components,* NEPS-F DC 557, Rev C, AREVA, Jan 2011 sent under cover of letter EPR000738N. TRIM Ref. 2011/85983.

21 *Chemistry Programme for Water Cooled Nuclear Power Plants.* Draft Safety Guide DS388. IAEA. August 2008.

22 *Chemistry Programme for Water Cooled Nuclear Power Plants*. Specific Safety Guide. IAEA Safety Standards Series No. SSG-13. IAEA. 2011. ISBN 978–92 –0–107610–6. ISSN 1020–525X.

23 *Design of Fuel Handling and Storage Systems for Nuclear Power Plants.* IAEA Safety Guide No. NS-G-1.4. IAEA. August 2003. www-pub.iaea.org/MTCD/publications/PDF/Pub1156_web.pdf.

24 *Design of Reactor Containment Systems for Nuclear Power Plants.* IAEA Safety Guide No. NS-G-1.10. IAEA. September 2004. www-pub.iaea.org/MTCD/publications/PDF/Pub1189_web.pdf.

25 *Operating Limits and Conditions and Operating Procedures for Nuclear Power Plants.* IAEA Safety Guide No. NS-G-2.2. IAEA. November 2000. www-pub.iaea.org/MTCD/publications/PDF/Pub1100_scr.pdf.

26 *IAEA Generic Review for UK HSE of New Reactor Designs against IAEA Safety Standards.* HSE. March 2008. www.hse.gov.uk/newreactors/reports/eprriaea.pdf.

27 Pressurized *Water Reactor Primary Water Chemistry Guidelines: Volumes 1 and 2*, Revision 6, Report 1014986, EPRI, December 2007. < EPRI Proprietary Information – viewable at EDF offices only >

28 *Pressurized Water Reactor Secondary Water Chemistry Guidelines* Revision 6. Report 1008224. EPRI. December 2004. http://my.epri.com/portal/server.pt

29 *VGB Guideline for the Water in Nuclear Power Stations with Light Water Reactors (PWR).* VGB-R 401 J 2nd Edition. VGB PowerTech Service GmbH Company, Essen. 1988.

30 *Gordon BM, The Effect of Chloride and Oxygen on the Stress Corrosion Cracking of Stainless Steel: Review of Literature*, Materials Performance, vol 19 (4), 29-38 (1980).

31 *Davis-Besse Reactor Pressure Vessel Head Degradation Overview, Lessons Learned, and NRC Actions Based on Lessons Learned,* NUREG/BR-0353, Rev. 1, US NRC, August 2008. pbadupws.nrc.gov/docs/ML0824/ML082490129.pdf

32 *Review of Chemistry Guidelines and Regulatory Processes in Nuclear Power Plant Chemistry*, NE03118-WX-R-04, Issue 05, Hyder Consulting (UK) Limited, August 2010. TRIM Ref 2011/82713.

33 *Approach for Setting Chemistry Standards in the UK*, 5040-NE03118-WX-R-06, Issue 06, Hyder Consulting (UK) Limited, June 2011. TRIM Ref. 2011/333640.

34 *Assistance and Recommendations for Tritium Management in NPP systems*, EDEAPC080379, Revision A1, EDF, August 2008. TRIM Ref. 2011/85923

35 *Generic Design Assessment: Shutdown and Start-up Chemistry – Review of International Relevant Good Practice*, NNL/SPR03860/06/10/14, AMEC-15913-TR-0001, Issue 1, National Nuclear Laboratory and AMEC Nuclear Limited, March 2011, TRIM Ref. 2011/216977

36 *Generic Design Assessment: UK EPR Shutdown and Start-up Chemistry*, SPR03860/06/10/45, Issue 1, National Nuclear Laboratory, April 2011, TRIM Ref. 2011/216970.

37 *GDA Reactor Chemistry Support – EPR Sampling Review*, SERCO/TCS/ND1908/R003, Issue 1.0, SERCO, November 2010. TRIM Ref. 2011/89753

38 *LCC4 Annual Report.* Advanced Nuclear Technology International. Sweden. October 2008. TRIM Ref. 2010/103651.

39 *System Design Manual – Nuclear Sampling System - Primary Side* (REN [NSS]), Part 2 – System Operation (Stage 2), SFL-EZS-030035, Revision E, Sofinel, December 2008. TRIM Ref. 2011/128129

40 *System Design Manual – Nuclear Sampling System* (Inside RB) (REN [NSS]), Part 2 – System Operation (Stage 2), NESS-F DC625 Revision A, AREVA, November 2009. NESS-F DC625 Revision A is the English translation of NESS-F DC45, Revision D.

41 *Sampling Considerations for Monitoring Corrosion Products in the Reactor Coolant System in Pressurized Water Reactors*, Report 1013668, EPRI, June 2006. my.epri.com/portal/server.pt

42 *Start-up and Shutdown Practices in BWRs as well as in Primary and Secondary Circuits of PWRs, VVERs and CANDUs*, Advanced Nuclear Technology International. Sweden. October 2009. TRIM Ref. 2010/103700.

43 *System Design Manual - Reactor Coolant System (RCS) - Part 2: System Operation*, NESS-F DC 538, Revision A, AREVA, May 2009. NESS-F DC 538 Revision A is the English translation of NFPMS DC 1132, Revision F. TRIM Ref. 2011/86246

44 *System Design Manual – Steam Generator Blowdown System (APG [SGBS]) P2 – System Operation*, SFL-EZS-030046, Revision G, Sofinel, December 2008. TRIM Ref. 2011/155531.

45 *System Design Manual - Main Feedwater System - Part 2: System Operation*, NESS-F DC 576, Revision A, AREVA, September 2009. NESS -F DC 576 Revision A is the English translation of NESS-F DC 70, Revision C TRIM Ref. 2011/86758

46 *Preliminary description of the ATD, CEX, CVI, SIT and SRI systems*, E.T.DOPN/100090, Revision A, EDF, June 2010. TRIM Ref. 2011/155999

47 *System Design Manual - Main Steam Supply System (VVP [MSSS]) - Part 2: System Operation*, NESS-F DC 578, Revision A, AREVA, November 2009. NESS-F DC 578, Revision A is the English translation of NESS-F DC 42, Revision E. TRIM Ref. 2011/92209.

48 *System Design Manual - Chemical Treatment, Injection of Reagents System (SIR6), Part 2, System Operation*, EZS 2008/en/0044, Revision A, Sofinel, November 2008. TRIM Ref. 2011/92204.

49 *SIR System Manual (Stage 1) – Flamanville 3*, 23952 SIR 00010 DSE, Revision D1, EDF, October 2008. TRIM Ref. 2011/155432.

50 *Letter EPR00807N*, 25th February 2011. TRIM Refs 2011/124981 and 2011/128575.

51 *Secondary Coolant Chemistry – Topical Report*, PEEM-F DC 5, Revision A, AREVA, June 2010. TRIM Ref. 2011/92858

52 *FAC in Power Plants, Report 106611*, Revision 1, EPRI, August 1998. < EPRI Proprietary Information – viewable at EDF offices only >

53 *EPRI Utility Requirements Document for Next Generation Nuclear Plants*. EPRI. urd.epri.com/.

54 *System Design Manual – Nuclear Sampling System - Secondary Side* (RES [NSS]), Part 2 – System Operation (Stage 2), SFL-EZS-030030, Revision C, EDF, April 2007. TRIM Ref. 2011/155528.

55 *Design, Construction and Control of EPR pool liners*, ECEIG060543, Revision C1, EDF, June 2008. TRIM Ref. 2011/54558.

56 *System Design Manual - PTR Fuel Pool Cooling System - Part 2 System Operation*, SFL–EF-MF 2006-712, Revision G1, Sofinel, August 2009. SFL–EF-MF 2006-712, Revision G1 is the English translation of SFL–EF-MF 2006-712, Revision G. TRIM Ref. 2011/155550.

57 *Criticality Control in the Spent Fuel Pool for the EDF and AREVA UK EPR*; ND AR11025 App A. TRIM Ref. 2011/36614.

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

59 *EPR FA3 – Specific Activity Concentrations in the Reactor Building*, NEEM-F DC 30, Revision F, December 2007. TRIM Ref. 2011/92987.

60 *Primary Source Term of the EPR Reactor*, ENTERP090062, Revision A, EDF, March 2009. TRIM Ref. 2011/93996.

61 *UK EPR – Radiological consequences for SGTR* (PCC3 and PCC4), ENTEAG080029, Revision A, EDF, June 2008. TRIM Ref. 2011/92457.

62 *UK EPR GDA Project, Design Change Management Form - Functional classification F1B of KRT-RES activity detection channels*, UKEPR-CMF-022, Stage 1, Jan 2011. TRIM Ref. 2011/94445.

63 *System Design Manual - Combustible Gas Control System (ETY), Part 2, System Operation*, EZS/2008/en/0080, Revision A PREL., Sofinel, October 2008. TRIM Ref. 2011/134269.

64 *Computational Validation Method for the Combustible Gas Control System of the EPR™ Containment*, PEPA-G/2010/en/1015, Revision A, AREVA, July 2010. TRIM Ref. 2011/93024

65 *EPR - RF002 – Severe Accident - 5.5.2 In-vessel Analysis Hydrogen Source Term*, NFEPD DC 59, Revision B, Framatome ANP, January 2004. TRIM Ref. 2011/134257

66 *Chemical Aspects of the Models used for the EPR Severe Accidents Analysis*, NEPA-G/2010/en/1021, Revision A, AREVA, April 2010. TRIM Ref. 2011/92488.

67 *UK EPR – Severe Accident Description of the In-vessel Physical and Chemical Models of the MAAP4 Code and its Validation*, NEPD-F DC 197, Revision A, AREVA, May 2010. TRIM Ref. 2011/92490

68 *Functional Principle of the Core Melt stabilization System of the EPR, including a Description of the Relevant Phenomena, the Related Experimental Background, and the Impact of Remaining Uncertainties*, NEPA-G/2010/en/1022, Revision C, AREVA, June 2010. TRIM Ref. 2011/92792.

69 *UK EPR – Severe Accident Description of Corium Behaviour in RPV Bottom Head and Corium Discharge to the Reactor Pit*, NEPD-F DC 202, Revision A, AREVA, August 2010. TRIM Ref. 2011/92993.

70 *Physical and Chemical Models used to Analyse the Interaction of Molten Core Material with Concrete and to Determine the Release of Burnable Gas and Fission Products*, NEPA-G/2010/en/1023, Revision A, AREVA, July 2010. TRIM Ref. 2011/92989.

71 *GDA Reactor Chemistry Support – Hydrogen Control Good Practice Review*, SERCO/TCS/ND1760/R001, Issue 1, SERCO, September 2010. TRIM Ref. 2011/89720.

72 *GDA Reactor Chemistry Support – UK EPR Combustible Gas Control Review*, SERCO/TCS/ND1760/R003, Issue 1.0, SERCO, April 2011. TRIM Ref. 2011/273208.

73 *Step 4 Fault Studies - Containment and Severe Accident Assessment of the EDF and AREVA UK EPR™ Reactor.* ONR Assessment Report ONR-GDA-AR-11-020b, Revision 0. TRIM Ref. 2010/581403.

74 *Work Report, Passive Autocatalytic Recombiner (PAR) Empirical Equation for H_2 and CO depletion Rate Calculation*, NGPS/2003/en/0040, Revision A, AREVA, March 2003. TRIM Ref. 2011/85997.

75 *J.C. Sabroux, M.C. Kissane et al, Investigation of thermo-catalytic decomposition of metal-iodide aerosols due to passage through hydrogen recombiners*, Nucl Eng & Design vol 239 pp3003-3013 (2009).

76 *Clément, B., Hanniet-Girault, N., Repetto, G., Jacquemain, D., Jones, A.V., Kissane, M.P. and von der Hardt, LWR severe accident simulation: synthesis of the results and interpretation of the first Phebus FP experiment FPT0*, P. Nucl. Eng. Design, 226: 5-82 (2003)

77 *Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety*, NEA/CSNI/R(2000)7, OECD Nuclear Energy Agency, August 2000. www.oecd-nea.org/nsd/docs/2000/csni-r2000-7.pdf

78 *System Design Manual - Gaseous Waste Processing System (TEG[GWPS]), P2 – System operation*, SFLEZS030051, Revision E, Sofinel, September 2008. TRIM Ref. 2011/466443.

79 *EPR Activity Concentrations in the TEP, REA, TEG, RPE, TEU and TES Auxiliary Systems*, ENTERP070291, Revision A, November 2007. TRIM Ref. 2011/92969.

80 *System Design Manual – Liquid Waste Processing System (TEU [LWPS]) Part 2: Operation of the TEU [LWPS] EPR FA3 system*, ECEF070502, Revision A1, EDF, January 2010. ECEF070502, Revision A1 is the English translation of ECEF070502, Revision A. TRIM Ref. 2011/155730.

81 *System Design Manual – Component Cooling Water System (RRI [CCWS]), P2 – System Operation (Stage 1)*, SFL-EF MF 2006.446, Revision F1, Sofinel, August 2009. SFL-EF MF 2006.446, Revision F1 is the English translation of SFL-EF MF 2006.446, Revision F. TRIM Ref. 2011/155544.

82 *ND BMS. Guidance on the purpose, scope and content of nuclear safety cases.* T/AST/051 Issue 1. HSE. May 2002. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast051.pdf

83 *ND BMS. Severe accident analysis.* T/AST/007 Issue 1. HSE. June 1999. http://intranet/operational/nsd_bms/tech_asst_guides/tast007.htm.

84 *ND BMS. Heat transport systems.* T/AST/037 Issue 1. HSE. May 1999. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast037.pdf.

85 *ND BMS. ND guidance on the demonstration of ALARP (as low as reasonably practicable).* T/AST/005 Issue 4. HSE. January 2009. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast005.htm.

86 *ND BMS. Internal hazards.* T/AST/014 Issue 1. HSE. August 2008. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast014.htm.

87 *ND BMS. Control of processes involving nuclear matter.* T/AST/023 Issue 1. HSE. August 2008. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast023.htm.

88 *ND BMS. Integrity of metal components and structures.* T/AST/016 Issue 2. HSE. August 2008. www.hse.gov.uk/foi/internalops/nsd/tech_asst_guides/tast016.htm.

89 *ND BMS. Containment: chemical plants.* T/AST/021 Issue 1. HSE. February 2000. http://www.hse.gov.uk/nuclear/operational/tech_asst_guides/tast021.pdf.

90 *ND BMS. Ventilation.* T/AST/022 Issue 1. HSE. June 2000. http://www.hse.gov.uk/nuclear/operational/tech_asst_guides/tast022.pdf.

91 *EPR GDA Design Basis Limits and Development of Plant Operating Limits and Maintenance Schedules*, ECEF102536, Rev A, EDF, Dec 2010. TRIM Ref. 2011/85912.

92 *Response to RO-UKEPR-44.A5 - Item (b)*, Note EDECME100870 sent under letter EPR00693R, Dec 2010. TRIM Ref. 2011/85925.

93 *UK EPR GDA Project, Design Change Management Form - Monophasic start Up mode*, UK EPR-CMF-028, Stage 1, March 2011. TRIM Ref. 2011/140571.

94 *A Reassessment of the Potential for an Alpha-Mode Containment Failure and a Review of the Current Understanding of Broader Fuel-Coolant Interaction Issues,* NUREG-1524, US NRC, 1996. www.osti.gov/bridge/servlets/purl/319665-XmBGWU/webviewable/319665.pdf

95 *CMF 17 – Introduction of 20MND5 material*. In Letter EPR00264N. January 2010. TRIM Ref. 2010/49835.

96 *Design and Construction Rules for Mechanical Components of PWR Nuclear Islands*. RCC-M. ©AFCEN. 2007. www.afcen.com/V22/index.php?menu=rcc_m_en

97 *Generic Design Assessment: Steam Generator Tube Rupture Events, Part 1: Review*. NNL/SPR03860/06/10/04 and AMEC-16056-TR-0001 Issue 2. National Nuclear Laboratory and AMEC Nuclear Limited. April 2010. TRIM Ref. 2011/132693.

98 *Generic Design Assessment: Steam Generator Tube Rupture Events Part 2: UK EPR.* NNL/SPR03860/06/10/22, Issue 1, National Nuclear Laboratory, Feb 2011. TRIM Ref. 2011/91185.

99 *Dutton L M C, Smedley C, Handy B J, Herndlhofer S R. Realistic methods for calculating the release of radioactivity following steam generator tube rupture faults.* EUR 15615 EN. European Commission. 1994**.** ISBN 9789282686676.

100 *Sandia Letter Report, MELCOR Analysis of Station Blackout Accidents in the UK-EPR*, Sandia National Laboratories, DRAFT, July 2011

101 *PAR Qualification Report*, PESB-G/2011/en/1001, Revision A, AREVA, January 2011. TRIM Ref. 2011/86032.

102 *Flamanville 3 EPR - Summary report: specific design provisions related to EPR chemistry*, ECEF072084, Rev A1, EDF, January 2008. TRIM Ref. 2011/85549.

103 *PCSR sub-chapter 5.5 – Reactor Chemistry*, UKEPW-0002-055, DRAFT Issue 00, received in letter EPR00767R, EDF and AREVA, February 2011. TRIM Ref. 2011/134595.

104 *Response to Regulatory Observation Action RO-UKEPR-44.A4 Item (a)*, in Letter EPR00695R, EDF and AREVA, December 2010. TRIM Refs 2011/134571 and 2011/134572.

105 *Consolidated PCSR – Sub-chapter 5.5 – Reactor Chemistry,* UKEPR-0002-055, Issue 00, EDF and AREVA, March 2011. TRIM Ref. 2011/204368.

106 *Tritium Management – Provisions and Limits – UK EPR*, ECEF110161, Revision A, EDF, February 2011. TRIM 2011/128850, 2011/128852 and 2011/128857.

107 *Tritium Evaluation for UK EPR*, PEEM-F DC 62, Revision A, AREVA, March 2011. TRIM Ref. 2011/140075.

108 *Guidance for Care and Management of ILW Packages: Approved Code of Practice*, ET/ACOP/001, Issue 2, October 2004 cited in Atmospheric Stress Corrosion Cracking of Stainless Steels, Nexia Solutions, (05) 6616, 2005.

109 *Generic Design Assessment: UK EPR Shutdown and Start-up Chemistry*. NNL/SPR03860/06/10/45, Issue 1, National Nuclear Laboratory, April 2011. TRIM Ref. 2011/216970.

110 *Generic Design Assessment: Shutdown and Start-up Chemistry – Review of International Relevant Good Practice*. NNL/SPR03860/06/10/14 and AMEC-15913-TR-0001 Issue 1. National Nuclear Laboratory and AMEC Nuclear Limited, April 2011. TRIM Ref. 2011/216977.

111 *Activity Management Methodology Applied to UK EPR*, ECEF102664, Revision A, EDF, December 2010. TRIM Ref. 2011/85913.

112 *Crud evaluation for UK EPR*, ECEF102665, Revision A, EDF, December 2010. TRIM Ref. 2011/85914.

113 *System Design Manual – Coolant Purification, Degasification, Storage and Treatment System (TEP [CSTS]), P2 –System Operation*, SFL-EZS-030008, Revision G. Sofinel. October 2008. TRIM Ref. 2011/86306.

114 *System Design Manual – Reactor Boron and Water Make-Up System (REA [RBWMS]), P2 – System Operation*. SFL-EF MF 2006.401 Revision E1. Sofinel. September 2008 (E) SFL-EF MF 2006.401 Revision E1 is the English translation of SFL-EF MF 2006.401 Revision E. TRIM Ref. 2011/155543.

115 *Step 4 Mechanical Engineering Assessment of the EDF and AREVA UK EPR™ Reactor*, ONR Assessment Report ONR-GDA-AR-11-026, Revision 0. TRIM Ref. 2010/581505.

116 *Step 4 Structural Integrity Assessment of the EDF and AREVA UK EPR™ Reactor.* ONR Assessment Report ONR-GDA-AR-11-027, Revision 0. TRIM Ref. 2010/581504.

117 *GDA Reactor Chemistry Support – UK EPR Materials Pre-Conditioning Review,* SERCO/TCS/ND2350/R003, Issue 01, SERCO, March 2011. TRIM Ref. 2011/135442.

118 *Steam Generator Integrity Assessment Guidelines.* 1012987. EPRI. 2006. my.epri.com/portal/server.pt

119 *EPR UK: SG Tubes – Precautions and Control During Procurement and SG Tubes Manufacturing to Ensure Low Radioactivity*, EFFHQ11.18043, Revision A, AREVA, Feb 2011. TRIM Ref. 2011/128965.

120 *M. Berger, A. Albanese, C. Brun, M-H. Clinard, The Flamanville EPR: The Role of Chemistry in the Design and Development of a Third Generation PWR.* International Conference on Water Chemistry of Nuclear Reactors Systems NPC'08, Berlin 14 – 19 September 2008.

121 *Step 4 Civil Engineering and External Hazards Assessment of the EDF and AREVA UK EPR™ Reactor.* ONR Assessment Report ONR-GDA-AR-11-018, Revision 0. TRIM Ref. 2010/581513.

122 *Boric Acid Corrosion Guidebook*, Revision 1, Report 1000975, EPRI, November 2001. my.epri.com/portal/server.pt

123 *RO-UKEPR-78 - Regulatory Observation Actions on Severe Accidents - Combustible gases in Containment – Full Response*, Letter EPR00848N, April 2011, TRIM Ref. 2011/212902.

124 *Reactor Chemistry PCSR Sub-chapter 5.5 Reference Submittals*; Letter EPR00841N, March 2011. TRIM Ref. 2011/195371.

125 *NUREG 1465 Accident Source Terms for Light-Water Nuclear Power Plants*. USNRC. 1995. www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1465/

126 *Determination of the in-containment source term for Large-Break Loss of Cooling Accident.* Report prepared for the European Commission by AVN, CSN, GRS, IPSN and NNC. EUR 19841 en 2001. ec.europa.eu/energy/nuclear/studies/doc/other/eur19841.pdf

127 *Physical Assumptions for Calculating the Source Term under Severe Accident Conditions,* ENT TH/00.00277 B1, EDF, Dec 2010. TRIM Ref. 2011/85941.

128 *Fission Product Deposition in the Containment on Vertical Walls, Ceilings and Floors in Severe Accidents,* NGPS4/2006/en/1012, rev C, AREVA, April 2006. TRIM Ref. 2011/85859.

129 *Sensitivity analysis for calculation of radiological consequences accidents in the EPR PSAR,* ENTEAG090113, rev A, EDF, April 2009. TRIM Ref. 2011/92467.

130 *UK EPR Severe Accident Source Term Analysis,* NEPS-F DC 462, AREVA, Aug 2009. TRIM Ref. 2011/86233.

131 *Chemical aspects of the models used for the EPR severe accident analysis,* NEPA-G/2010/en/1021, rev A, AREVA, April 2010. TRIM Ref. 2011/92488.

132 *EPR Severe Accident Guidelines - OSSA Overview Report*, NEPS-F DC 302, AREVA, 2008. TRIM Ref. 2011/85869.

133 *Modelling Material and Activity Transport in the UK EPR Primary Circuit*. NNL/SPR03860/06/10/44, Issue 1, National Nuclear Laboratory, Feb 2011. TRIM Ref. 2011/158563.

134 *GDA Reactor Chemistry Support – Materials Conditioning Review*, SERCO/TCS/ND2350/R001, Issue 1.0, SERCO, Feb 2011. TRIM Ref. 2011/131560.

135 *Generic Design Assessment: Severe Accident Chemistry Part 2: UK EPR*. NNL/SPR03860/06/10/41, Issue 1, National Nuclear Laboratory, February 2011. TRIM Ref. 2011/146373.

136 *Generic Design Assessment: Severe Accident Chemistry Part 1:* UK EPR. NNL/SPR03860/06/10/39. Issue 2, National Nuclear Laboratory, Dec 2010. TRIM Ref. 2011/30439.

137 *Generic Design Assessment: Hydrogen addition, Part 1: Review.* NNL/SPR03860/06/10/07, Issue 1, National Nuclear Laboratory, Feb 2010. TRIM Ref. 2010/114013.

138 *Generic Design Assessment: Hydrogen addition, Part 2: H2 addition to UK EPR*. NNL/SPR03860/06/10/38, Issue 1, National Nuclear Laboratory, February 2011. TRIM Ref. 2011/82688.

139 *Magnusson A, Lundgren K, Characterisation of Carbon-14 in Swedish Light Water Reactors*. Radiation Safety Journal v95(Supp2) ppS110-S121. 2008.

140 *Kunz C, Carbon-14 Discharge at Three Light-Water Reactors*. Health Physics v49(1) pp25-35.1985.

141 *Hayakawa H, Yamada K, Umehara R, Shimizu Y, Nishimura T & Ojima Z. Zinc Injection during Hot Functional Test (HFT) in Tomari Unit 3. Symposium on Water Chemistry and Corrosion in Nuclear Power Plants*. Atomic Energy Society of Japan, Nagoya 28-30 October 2009.

142 *Grove C A, Petzold L D. Mechanisms of Stress-Corrosion Cracking of Alloy X-750 in High Purity Water*. J Mater for Energy Systems v2(2), pp147-162. 2008.

143 *Guinard L, Coulet F. Influence of the Initial surface Condition on the Release of Nickel Alloys in the Primary Circuit of PWRs*. BNES Water Chem Conference number 7. 1996.

144 *Review of PWR Steam Generator Tubing Materials Selection, Performance and Manufacturing Routes,* Peter Scott Corrosion Consultant Report Number PMSCC.09.041 (September 2009), TRIM Ref. 2009/376337.

145 GDA *Reactor Chemistry Support – Primary Water Stress Corrosion Cracking Review*. SERCO/TCS/ND2031/R001, Issue 1, SERCO, September 2010. TRIM Ref. 2010/390839

146 SCDAP/RELAP5/MOD *3.3 Code Manual: MATPRO - Library of Materials Properties*. NUREG/CR-6150 v4r2 USNRC. 2001.

147 *Dickinson S, Jones A V. Validation of severe accident codes against Phebus FP for plant applications: status of the PHEBEN2 project*. Nucl Eng & Des v221(1-3) pp225-240. 2003

148 *GDA Lot 9: Primary Circuit Chemistry Review*, NNL/SPR03860/06/10/12, Issue 1, National Nuclear Laboratory, September 2010. TRIM Ref. 2011/131621.

149 *Primary Chemistry Review for the UK EPR Reactor*, NNL/SPR03860/06/10/26, Issue 2, National Nuclear Laboratory, Mar 2011. TRIM Ref. 2011/0135594

150 *Generic Design Assessment: UK EPR Chemical and Volume Control System,* NNL/SPR03860/06/10/23, Issue 1, National Nuclear Laboratory, Feb 2011. TRIM Ref. 2011/76844

151 *Effects of Crud Build-up and Boron Deposition on Power Distribution and Shutdown Margin*. USNRC Information Notice IN 97-85. (1997). www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1997/in97085.html

152 *GDA Reactor Chemistry Support – EPR Primary Water Stress Corrosion Cracking Review*. SERCO/TCS/ND2031/R003, Issue 1.0, SERCO, Jan 2011. TRIM Ref. 2011/60120.

153 *Zinc Injection Benefits and its Implementation Feasibility for the UK-EPR*, EDECME100223, Rev A, EDF, 2010. TRIM Ref. 2011/155881

154 *Reactor Chemistry – Zinc Assessment for EPR UK*, PEEM-F DC 19, Issue 1, AREVA, Sep 2010. TRIM Ref. 2011/93013.

155 *An engineering assessment of zinc addition to PWR primary coolant*. SG-94-02-006. Westinghouse Owners Group. (February 1994). TRIM Ref. 2011/94590.

156 Garbett K. *Development of Corrosion Product Behaviour and Radiation Fields at the Sizewell B PWR from 1995 to 2008*. VGB Journal of Power Technology. December 2008.

157 Garbett K. *Overview of the Impact of Removing Stellite from Konvoi reactors*. BNES 2. Bournemouth pp31-38. (1992)

158 *EPR Flamanville 3 – Report on identifying the chemical and radiochemical parameters for Operating Technical specifications (Level 1 Specifications),* ECEF091642, Rev B1, EDF, Oct 2010. TRIM Ref. 2011/85906.

159 *Identification of the "level 2" chemical and radiochemical parameters, as part of the RGE rules of the Flamanville 3 EPR*, EDECME100781, Rev A, AREVA, Nov 2011. TRIM Ref. 2011/155883.

160 *The Path of Greatest Certainty*; AREVA, Dec 2009. www.areva.com/mediatheque/liblocal/docs/pdf/activites/reacteurs-services/reacteurs/pdf-Plaquette%20EPR-dec09-verte-va.pdf

161 *Reduction In Primary Circuit Radioactivity SFAIRP Based Upon The Primary Circuit Chemistry,* NEEM-F DC 143, AREVA. TRIM Ref. 2011/140420.

162 *Dickinson S, Bachet M, Hussey D*, *High Temperature Speciation of the Nickel/Iron System for Use with the MULTEQ model*; International Conference on Water Chemistry of Nuclear Reactors Systems NPC'10, Quebec, October 2010.

163 *UKEPR – Severe Accident Description of the In-Vessel Physical and Chemical Models of the MAAP4 Code and its Validation*. NEPD-F DC 197, AREVA, May 2010. TRIM Ref. 2011/92490.

164 *Evaluation of Constant Elevated pH Demonstration at Comanche Peak Steam Electric Station*; EPRI, Report 1003408, 2005. my.epri.com/portal/server.pt

165 *Ducros G, Durin M, Fission Product Release under Severe Accidental Conditions: General Presentation of the Program and Synthesis of VERCORS 1-6 Results*, Nucl Eng & Des v208 pp191-203 (2001)

166 *Dickinson S, Jones AV, Validation of severe accident codes against Phebus FP for plant applications: status of the PHEBEN2 project,* Nucl Eng & Des v221(1-3) pp225-240 (2003)

167 *System File Specification, Chemical and Volume Control System (RCV) Part 2: Operation of the system,* NGPS6/2006/en/1008, Rev G, AREVA, Dec 2008. TRIM Ref. 2011/155392.

168 *Equipment Datasheet Coolant Filter RCV2130FI - RCV2150FI,* NEER-G/2007/en/1136 Rev B, AREVA, 2007. TRIM Ref. 2011/155337.

169 *System File Specification, Chemical and Volume Control System (RCV) Part 3 – System Sizing*, NGPS6/2006/en/1018, Revision G. AREVA. Dec 2008. TRIM Ref. 2011/155396.

170 *Lessons Learnt from the Resin Release into the Primary Circuit of the Fessenheim NPP Unit 1 in January 2004 – Impact on the Nuclear Safety*, M Georgescu, EUROSAFE 2004.

www.eurosafe-forum.org/files/pe_83_24_1_1_09_resin_release_fessenheim_nppgeorgescu_031104.pdf

171 *FA3 EPR™ Preliminary Primary Coolant Chemistry Specification*, PEEM-F DC 7, Rev A, AREVA, May 2010. TRIM Ref. 2011/94290.

172 *Reactor Chemistry – Topical Report*, PEEM-F DC 4, Rev A, AREVA, May 2010. TRIM Ref. 2011/92857.

173 *Hansard HL Deb* 23 February 1999 vol 597 cc948-9 hansard.millbanksystems.com/lords/1999/feb/23/drigg-processing-of-nuclear-waste

174 *Overview of the UK EPR™ GDA Submission*, UKEPR-0013-001, Issue 00, AREVA. epr-reactor.co.uk/ssmod/liblocal/docs/overview/2011-overview%20of%20the%20UK%20EPR.pdf

175 *UK EPR GDA Submission Master List*. UKEPR-0018-001 Issue 01. November 2011. TRIM Ref. 2011/552512.

176 *Use of the Source Term in the Different GDA Areas (Response to RO73.A1)*, ECEIG101686, Rev B, EDF, Nov 2010. TRIM Ref. 2011/85917.

177 *Seiler J P. Theoretical Analysis for a Corium Pool with a Miscibility Gap*. Nuclear Technology, v41, pp 233 – 243. 2003.

178 *System CMSS: Justification of the type of sacrificial concrete used in the reactor pit*, NEPS-G/2008/en/1156, Rev A, AREVA, Nov 2010. TRIM Ref. 2011/85984.

179 *Spindler B, Spengler C, Garcia M et al, Simulation of Molten Corium Concrete Interaction in a Stratified Configuration: the COMET-L2-L3 Benchmark,* The 2nd European Review Meeting on Severe Accident Research (ERMSAR-2007) Forschungszentrum Karlsruhe GmbH (FZK), Germany, 12-14 June 2007

180 *System CMSS: Justification of the type of protective layer used in the reactor pit and melt discharge channel*. NEPS-G/2008/en/1157, Rev B, AREVA, Nov 2010. TRIM Ref. 2011/85985

181 *S. Hellmann, F. Funke, V. Lansmann and B. Friedrich, Physico-Chemical and Material Aspects of the Core Melt Retention Concept of the EPR*, OECD Workshop on Ex-Vessel Debris Coolability Karlsruhe, Germany, 15-18 November 1999

182 *The explosion at the Appleby - Frodingham steelworks Scunthorpe*, *4 November 1975 a report*. HSE Publications, ISBN 0 11 88 0 331 X

183 *UK EPR Pre-Construction Environmental Report*; UKEPR-0003-011, Iss 3, EDF and AREVA, Mar 2010. TRIM Ref. 2011/35431.

184 *Effect of Spray Activation on the Reactivity of the Hydrogen Air Steam Mixture,* NGES/2002/en/0018, Rev B, AREVA, 2002. TRIM Ref. 2011/85844.

185 *Containment Heat Removal System,* EPR Technical Report TR 94/13, Framatome, NM/S.93.2661, 1994. TRIM Ref. 2011/94388.

186 *COSACO, An Engineering model for the Simulation of Corium Sacrificial Concrete Interactions, Part B: Validation with the aid of one-dimensional experiements,* Siemens, KWU NA-T/1998/E090a, September 1998. TRIM Ref. 2011/529860.

187 *Pressurized Water Reactor Primary Water Zinc Application Guidelines.* 1013420. EPRI. December 2006. my.epri.com/portal/server.pt

188 *Enclosure of GDA Submission #21: Consolidated Step 4 SSER*, Letter EPR00844N (31 Mar 2011). TRIM Ref. 2011/200260.

189 *P. Jolivet, A. Tamba, F. Chahma, Material Selection According to ALARA during Design Stages of EPR,* Information System on Ocupational Exposure Conference "ISOE" Fort Lauderdale, 2010.

190 *E Baumann & IR Terry, The EPR: A clear step forward in dose reduction and radiation protection*, Nucl Eng & Des v236 pp1720-1727 (2006).

191 *F. Carrette, L Guinard et al, Impact of the Surface State of Steam Generator Tubes on the Release of Corrosion Products in Pressurized Water Reactors.* International Conference on Water Chemistry of Nuclear Reactor Systems in Jeju, Korea, 2006.

192 *Pitting Corrosion of Metals, a Review of the Critical Factors,* Journal of the Electrochemical Society v145 pp2186-2198 (1998)

193 *Study of the Different Thermal Insulation Materials for Reducing the Source Term vis-à-vis Sump Filter Blockage,* ECEMA06010159A. TR 06/260. TRIM Ref. 2011/85856.

194 *Step 4 Probabilistic Safety Analysis Assessment of the EDF and AREVA UK EPR™ Reactor*. ONR Assessment Report ONR-GDA-AR-11-019, Revision 0. TRIM Ref. 2010/581512

195 L*. Guinard, F. Cattant, S. Taunier, J.L. Bretelle, A. Rocher and B. Jeannin*. *General overview of the evolution of international collective radiation exposure and associated good practices*. NPC2008. International Conference on Water Chemistry of Nuclear Reactor Systems. Berlin, Germany. 15-18 September 2008.

196 *Homyk WA, Peters J, Quan B and Nayak U,* Antimony/Beryllium *Secondary Neutron Source Leak at Indian Point 2.* Radiation Protection Management Vol 9 pp65-80 (1992).

197 *Step 4 Cross-cutting Topics Assessment of the EDF and AREVA UK EPR™ Reactor.* ONR Assessment Report ONR-GDA-AR-11-032 Revision 0. TRIM Ref. 2010/581499.

198 *GDA Issue GI-UKEPR-RC-01 Revision 1. Background and explanatory information.* TRIM Ref. 2011/81175.

199 *GDA Issue GI-UKEPR-RC-02 Revision 0. Background and explanatory information.* TRIM Ref. 2011/81178.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
Engineering principles: Key principles		
EKP.2	Fault tolerance	The underpinning safety aim for any nuclear facility should be an inherently safe design, consistent with the operational purposes of the facility.
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.
Engineering principles: Safety classification and standards		
ECS.2	Safety classification of structures, systems and components	Structures, systems and components that have to deliver safety functions should be identified and classified on the basis of those functions and their significance with regard to safety.
ECS.3	Standards	Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate standards.
ECS.4	Codes and standards	For structures, systems and components that are important to safety, for which there are no appropriate established codes or standards, an approach derived from existing codes or standards for similar equipment, in applications with similar safety significance, may be applied.
ECS.5	Use of experience, tests or analysis	In the absence of applicable or relevant codes and standards, the results of experience, tests, analysis, or a combination thereof, should be applied to demonstrate that the item will perform its safety function(s) to a level commensurate with its classification.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
Engineering principles: Ageing and degradation		
EAD.1	Safe working life	The safe working life of structures, systems and components that are important to safety should be evaluated and defined at the design stage.
EAD.2	Lifetime margins	Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components that are important to safety.
EAD.3	Periodic measurement of material properties	Where material properties could change with time and affect safety, provision should be made for periodic measurement of the properties.
EAD.4	Periodic measurement of parameters	Where parameters relevant to the design of plant could change with time and affect safety, provision should be made for their periodic measurement.
Engineering principles: Pressure systems		
EPS.2	Flow limitation	Flow limiting devices should be provided to piping systems that are connected to or form branches from a main pressure circuit, to minimise the consequences of postulated breaches.
EPS.5	Discharge routes	Pressure discharge routes should be provided with suitable means to ensure that any release of radioactivity from the facility to the environment is minimised.
Engineering principles: Integrity of metal components and structures		
EMC.2	Use of scientific and technical issues	The safety case and its assessment should include a comprehensive examination of relevant scientific and technical issues, taking account of precedent when available.
EMC.16	Contamination	The potential for contamination of materials during manufacture and installation should be controlled to ensure the integrity of components and structures is not compromised.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
EMC.21	Safe operating envelope	Throughout their operating life, safety-related components and structures should be operated and controlled within defined limits consistent with the safe operating envelope defined in the safety case.
Engineering principles: Safety systems		
ESS.1	Requirement for safety systems	All nuclear facilities should be provided with safety systems that reduce the frequency or limit the consequences of fault sequences, and that achieve and maintain a defined safe state.
ESS.2	Determination of safety system requirements	The extent of safety system provisions, their functions, levels of protection necessary to achieve defence in depth and required reliabilities should be determined.
ESS.3	Monitoring of plant safety	Adequate provisions should be made to enable the monitoring of the plant state in relation to safety and to enable the taking of any necessary safety actions.
ESS.4	Adequacy of initiating variables	Variables used to initiate a safety system action should be identified and shown to be sufficient for the purpose of protecting the facility.
ESS.16	No dependency on external sources of energy	Where practicable, following a safety system action, maintaining a safe facility state should not depend on an external source of energy.
Engineering principles: Control and instrumentation of safety-related systems		
ESR.8	Monitoring of radioactive substances	Instrumentation should be provided to enable monitoring of the locations and quantities of radioactive substances that may escape from their engineered environment.
Engineering principles: Control of nuclear matter		
ENM.1	Strategies for nuclear matter	A strategy (or strategies) should be made and implemented for the management of nuclear matter.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
ENM.2	Provisions for nuclear matter brought onto, or generated on, the site	Nuclear matter should not be generated on the site, or brought onto the site, unless sufficient and suitable arrangements are available for its safe management.
ENM.3	Transfers and accumulation of nuclear matter	Unnecessary or unintended generation, transfer or accumulation of nuclear matter should be avoided.
ENM.4	Control and accountancy of nuclear matter	Nuclear matter should be appropriately controlled and accounted for at all times.
ENM.5	Characterisation and segregation	Nuclear matter should be characterised and segregated to facilitate its safe management.
ENM.6	Storage in a condition of passive safety	When nuclear matter is to be stored on site for a significant period of time it should be stored in a condition of passive safety and in accordance with good engineering practice.
ENM.7	Retrieval and inspection of stored nuclear matter	Storage of nuclear matter should be in a form and manner that allows it to be retrieved and, where appropriate, inspected.
Engineering principles: Containment and ventilation		
ECV.1	Prevention of leakage	Radioactive substances should be contained and the generation of radioactive waste through the spread of contamination by leakage should be prevented.
ECV.2	Minimisation of releases	Nuclear containment and associated systems should be designed to minimise radioactive releases to the environment in normal operation, fault and accident conditions.
ECV.3	Means of confinement	The primary means of confining radioactive substance should be by the provision of passive sealed containment systems and intrinsic safety features, in preference to the use of active dynamic systems and components.
ECV.6	Monitoring devices	Suitable monitoring devices with alarms and provisions for sampling should be provided to detect and assess changes in the stored radioactive substances or changes in the radioactivity of the materials within the containment.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
ECV.7	Leakage monitoring	Appropriate sampling and monitoring systems and other provisions should be provided outside the containment to detect, locate, quantify and monitor leakages of nuclear matter from the containment boundaries under normal and accident conditions.
Engineering principles: Reactor core		
ERC.1	Design and operation of reactors	The design and operation of the reactor should ensure the fundamental safety functions are delivered with an appropriate degree of confidence for permitted operating modes of the reactor.
ERC.4	Monitoring of safety-related parameters	The core should be designed so that safety-related parameters and conditions can be monitored in all operational and design basis fault conditions and appropriate recovery actions taken in the event of adverse conditions being detected.
Engineering principles: Heat transport systems		
EHT.1	Design	Heat transport systems should be designed so that heat can be removed or added as required.
EHT.2	Coolant inventory and flow	Sufficient coolant inventory and flow should be provided to maintain cooling within the safety limits for operational states and design basis fault conditions.
EHT.4	Failure of heat transport system	Provisions should be made in the design to prevent failure of the heat transport system that could adversely affect the heat transfer process, or safeguards should be available to maintain the facility in a safe condition and prevent any release in excess of safe limits.
EHT.5	Minimisation of radiological doses	The heat transport system should be designed to minimise radiological doses.
Fault analysis		
FA.2	Identification of initiation faults	Fault analysis should identify all initiating faults having the potential to lead to any person receiving a significant dose of radiation, or to a significant quantity of radioactive material escaping from its designated place of residence or confinement.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 4)

SAP No.	SAP Title	Description
FA.18	Calculation methods	Calculation methods used for the analyses should adequately represent the physical and chemical processes taking place.

Table 2

Relevant Technical Assessment Guides for Reactor Chemistry Considered During Step 4

Reference	Issue	Title	Ref.
T/AST/051	01	Guidance on the purpose, scope and content of nuclear safety cases	82
T/AST/007	01	Severe accident analysis	83
T/AST/037	01	Heat transport systems	84
T/AST/005	04	ND guidance on the demonstration of ALARP (as low as reasonably practicable)	85
T/AST/014	01	Internal hazards	86
T/AST/023	01	Control of processes involving nuclear matter	87
T/AST/016	02	Integrity of metal components and structures	88
T/AST/021	01	Containment: chemical plants	89
T/AST/022	01	Ventilation	90

Table 3

Step 4 Reactor Chemistry Assessment Topics (Ref. 1)

	Area	Topic	Assessment Objective	Relevant section(s) in this report
01	Standards	Application	Identify detailed application of CREDO and its development into a standard for UK EPR	4.2.10
02	Start-up and Shutdown	Primary	Identify current approach and expectations for start-up and shutdown, including Hot Functional Testing; applications of good practice in primary and secondary circuits	4.2.11 and 4.2.12
03		Secondary		4.4.5
04	Primary Circuit	Chemical Control	Demonstrate the system performance and reliability requirements of the CVCS and associated systems are substantiated by the detailed engineering design	4.2.2
05		Radioactivity	Demonstrate primary circuit radioactivity has been reduced SFAIRP	4.2.3
06		Integrity	Demonstrate chemistry maintains pressure boundary and key component integrity	4.2.4
07		Fuel	Demonstrate chemistry maintains cladding integrity and minimises crud formation SFAIRP	4.2.5
08		Zinc	Demonstrate zinc addition is beneficial and waste is reduced SFAIRP	4.2.6
09		Hydrogen	Demonstrate hydrogen levels, dosing and controls are adequate for safe plant operation	4.2.7
10		Safety Systems	Demonstrate chemical conditions are maintained in safety circuits	4.2.8
11		Sampling	Demonstrate sampling systems provide adequate control for chemistry and sampling activities are safe	4.2.9
12		Holistic View	Demonstrate chemistry needs of Occupational Radiation Exposure (ORE), circuit and fuel integrity and waste production are balanced	4.2.10
13	Secondary Circuit	Chemistry and Materials	Demonstrate chemistry needs of circuit materials, fouling and impurity control are adequately balanced	4.4.2
14		Integrity	Demonstrate chemistry maintains integrity of the pressure boundary and key components	4.4.3
15		Sampling	Demonstrate sampling systems provide adequate control for chemistry and sampling activities are safe	4.4.4

Table 3

Step 4 Reactor Chemistry Assessment Topics (Ref. 1)

	Area	Topic	Assessment Objective	Relevant section(s) in this report
16	Fuel Pool Systems	Spent Fuel Pool	Demonstrate requirements for normal operations, SFP faults and extended lifetime are adequate	4.3
17	Accident Chemistry	Source Terms	Demonstrate that chemistry is adequately accounted for in the accident source term	4.6.2.3, 4.6.3.2, 4.6.4.2 and 4.6.5
18		SGTR	Demonstrate underlying chemistry in SGTR faults is appropriately identified and applied	4.6.2
19		Hydrogen Control	Demonstrate the performance of hydrogen control systems would meet the demands placed upon it	4.6.3
20		FP Control	Demonstrate the performance of UK EPR systems are adequate to control Fission Product releases	4.6.4
21		Core Melt	Demonstrate key chemistry parameters are realistic, appropriate, included and transparent in the design	4.6.5
22	Ancillary Systems	Radwaste	Demonstrate appropriate conditioning and discharges are controlled for gaseous and liquid radwaste	4.5.1
23		Component Cooling	Demonstrate appropriate chemical control of component cooling water including segregation from other systems	4.5.2

Table 4

Conclusions from Step 3 Reactor Chemistry Assessment of UK EPR (Ref. 7)

No.	Text
1	Not all areas have been fully assessed within the current PCSR due to difficulties in separating out claims and arguments and EDF and AREVA are still developing arguments and evidence in a number of areas for Reactor Chemistry.
2	Most information of relevance to assessment of Reactor Chemistry was obtained in the form of documents completely outside the current PCSR suite of documentation. Even with these shortcomings the safety report provided for Step 3 was satisfactory as a starting point for the Reactor Chemistry assessment conducted.
3	The principal aspects of the presentation of safety that need improvement are: • EDF and AREVA have provided little information on the chemistry of boron in the primary circuit and chemical effects in the secondary circuit and its ancillaries, although we understand some analyses may have been undertaken. This approach is not consistent with current expectations for a complete safety design. • Although we were encouraged that EDF and AREVA appear to have given considerable thought to severe accident chemistry, the current PCSR presentation is lacking. There is a lack of information on how chemistry has been applied specifically to the UK EPR design in this area. • The presentation that has been made was largely based upon experience from older plants and not quantitative analyses. A more balanced approach would avoid difficulties associated with dataset selection, sample population and numerical limits. • A topic report or PCSR overview of chemistry (including boron chemistry and faults) will be needed during Step 4 or in Phase 2.
4	We were encouraged that EDF and AREVA has put effort into the chemistry of the UK EPR design: • If commissioned properly, the levels of ^{60}Co around the primary circuit should be low although we have minor concerns regarding the boron recovery area and potential ‘hot-spots’. • EDF and AREVA are making good progress in analysing the chemistry of faults. • Systems for processing wastes appear robust.
5	Chapter 17 of the PCSR summarizes the ALARP case for a selection of major hazards. No ALARP case was presented in issue 1 of the PCSR for routine radiation exposure, wastes or discharges to the environment. It is clear from discussions with RP staff that these factors were nevertheless considered, even if documentation is lacking. ND and EA have started to obtain improvements in this area during Step 3.
6	The RP is going through a process of developing and formalising commissioning and operating documentation for Reactor Chemistry. We are encouraged that this is being actively considered at this early stage.
7	EDF bases its own in-house chemistry standards on an amalgam of international practice and experience from its own stations. These are then approved by ASN for all the French fleet. Almost all US and UK water reactors follow EPRI guidelines, and German reactors follow VGB guidelines. The RP claims certain deviations from international practice are justified, but has not provided a justification in the PCSR.
8	UK EPR is a complex reactor and the possibility of changes to the detailed design for boronation, hydrogen or secondary circuits arising from assessments during Step 4 cannot be ruled out.
9	Assessment of the chemistry of accidents will be coordinated with equivalent fault studies planned to begin in Step 4. Standards for physico-chemical modelling techniques may be examined.

Table 4

Conclusions from Step 3 Reactor Chemistry Assessment of UK EPR (Ref. 7)

No.	Text
10	The EPR is currently undergoing certification in France, Finland and the US and some information on the progress of these assessments has been obtained. We hope to make use of assessments made overseas particularly for severe-accident analysis.
11	To meet the GDA deadlines and provide ND with information for use in our assessment of chemistry in UK EPR, we have engaged a number Technical Support Contractor(s) (TSC) to assist with the Reactor Chemistry assessment work. These programmes of work are just beginning. The programme of TSC support may include accident chemistry, cooling circuit corrosion, chemistry control, sampling and standards for PWRs.

Table 5

Step 4 PCSR Reactor Chemistry Content (Ref. 11)

Chapter	Title	Section(s)	Examples of relevant Reactor Chemistry content
1	Introduction and General Description	2, 3	General description of plant, comparison to similar reactors (especially ‘Konvoi’ and N4).
3	General design and Safety Aspects	1	General description of plant, design of structures, components, equipment and systems. Containment philosophy.
4	Reactor and Core Design	1, 3, 5	Reactor core outline, fuel design, reactivity control functions.
5	Reactor Cooling system and Associated Systems	0, 2, 4	Safety Requirements (Functional), Coolant Pressure Boundary Integrity, General Description of Cooling Systems
6	Containment and Safeguard Systems	1, 2, 3, 6, 7	Materials, Hydrogen and Core Catcher, Auxiliary Services to Primary Circuit, Emergency Feedwater System, Extra Boration System
7	Instrumentation and Control	5	Flow, level, boron and temperature measurements.
9	Auxiliary systems	1 , 2 , 3	Auxiliary Buildings including CVCS, Ponds, Water Systems, Main Steam and Feedwater Lines
10	Main Steam and Feedwater Lines	1, 3, 4	Secondary Cooling, Steam Generator Blowdown System, Main Feedwater System, Overview of Waste Handling
11	Discharges and Waste – Chemical and Radiological	1, 2, 3	Waste Fluid Sources; ^{16}N, ^{58}Co etc, Effluent Management – principles. Lithium control.
14	Design Basis Faults	2	LOCA and Reactivity Insertion Accidents. SGTR.
16	Risk Reduction and Severe Accident Analyses	1, 2, 3, 4, Appendix 16A	Risk reduction and severe accident analyses including containment bypass and H_2. Computer codes used in analysis.
17	ALARP	2, 3, 4, 5, 6	Design features in UK EPR. Optioneering. Conclusions from the ALARP Assessment

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-01	The Licensee shall specify the normal operating chemistry regimes for the primary, secondary and auxiliary circuits of UK EPR. The specifications should be comprehensive and incorporate evidence for all modes of operation. The regimes should be consistent with the plant safety case, particularly the limits and conditions required by AF-UKEPR-RC-02.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Cold Ops.
AF-UKEPR-RC-02	The Licensee shall specify in the safety case all chemistry limits and conditions, including radiochemistry parameters, that have an impact on safety including ORE, wastes, combustion hazards, maintenance and testing. Limits and conditions for all modes of operation should be stated. The justification and classification for the limits should be made clear. Where appropriate, the nature and timescale of any corrective action should be justified.	This Assessment Finding should be completed before the first stages of commissioning are undertaken and such limits or conditions may be needed. Target milestone – Cold Ops.
AF-UKEPR-RC-03	The Licensee shall specify detailed chemistry related requirements for all phases of construction and commissioning through to normal operations.	This Assessment Finding will be staged throughout the new build project, but should begin with the production of a plan for developing appropriate documentation. The main stages will include delivery to site of major equipment (such as the RPV) and subsequent commissioning. Requirements should be set before delivery to site of major equipment. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-UKEPR-RC-04	The Licensee shall generate a detailed risk analysis, fully justifying the boron strategy to be applied. This should include commissioning, the fuel management and chemistry requirements, necessary control actions and effects from evaporation on radioactivity and impurity accumulation.	This Assessment Finding should be completed before the first fuel is brought onto site to ensure rigorous control of borated coolant used for reactivity control. Target milestone - Fuel on-site.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-05	The Licensee shall clearly identify the boron metering system used for safety and specify procedures that ensure common-mode calibration errors do not arise.	This Assessment Finding should be completed before the first fuel is brought onto site to ensure rigorous control of borated coolant used for reactivity control. Target milestone - Fuel on-site.
AF-UKEPR-RC-06	The licensee shall implement appropriate controls over the specifications for filters, resins and other consumables used within nuclear applications. The specifications should include purity and cleanliness requirements, take account of minor inconsistencies noted in this assessment regarding filter and resin aging and replacement and consider conversion of French specifications for materials and consumables to UK requirements.	This Assessment Finding should be completed before the first use of such consumables on site. Target milestone - Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-07	The Licensee shall ensure that a complete and unambiguous specification exists for all the materials to be used in UK EPR that could contact primary coolant. This should include trace elements prone to activation and be sufficiently detailed to allow sound procurement specifications to be produced.	This Assessment Finding should be completed before such materials are delivered to site, but certain aspects may need earlier consideration, for example, to ensure rigorous control during procurement activities. Target milestone – Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-UKEPR-RC-08	The Licensee shall ensure there is sufficient control over fabricators and operators that install, commission and maintain any hard-facing materials, including lapping, that may give rise to ^{60}Co dose.	This Assessment Finding should be completed before operations creating loose cobalt may take place on site, but certain parts may be necessary earlier, for example during component manufacture. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-09	The Licensee shall review and consider alternative materials to Stellite^{TM} for applications within UK EPR, and ensure that the final selection of materials is ALARP in this respect.	This Assessment Finding should be completed before such materials are delivered to site for installation. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-UKEPR-RC-10	The Licensee shall keep the specification of secondary neutron sources under review and consider suitable alternatives.	This Assessment Finding should be completed before nuclear operations, as this is when the source becomes activated. Target milestone – Initial criticality.
AF-UKEPR-RC-11	The licensee shall define a surveillance programme for control rods and secondary neutron sources. The programme shall prevent the release of materials such as tritium or silver before there is significant contamination of vessels or pipework.	This Assessment Finding should be completed before nuclear operations, to prevent the release of activatable material. Target milestone – Initial criticality.
AF-UKEPR-RC-12	The Licensee shall generate evidence to support the lifetime behaviour of the nickel plating to be adopted for the pressuriser heaters in UK EPR. This should include consideration of material losses from the plating on radioactivity.	This Assessment Finding should be completed before installation of the pressuriser is complete. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-13	The Licensee shall conduct sensitivity analysis for fuel crud formation in UK EPR. This should be used to demonstrate that levels of crud can be controlled and reduced So Far As Is Reasonably Practicable (SFAIRP) in UK EPR and should be based upon the detailed operating chemistry and core design for the UK EPR reactor. These calculations should provide balanced predictions of activity levels that allow the assessment of control measures including boiling patterns and Stellite^{TM} replacements, as well as the management of significant chemicals and radionuclides. The licensee shall conduct analyses of sensitivity to factors such as pH, zinc, boiling and dissolved corrosion products on crud build-up. The analysis should be used to justify related limits, conditions and criteria.	This Assessment Finding should be completed before nuclear operations, as this is when fuel crud is formed. This Assessment Finding is also closely linked to findings AF-UKEPR-RC-01 and AF-UKEPR-RC-02. Target milestone – Initial criticality.
AF-UKEPR-RC-14	The licensee shall justify limits for silica, iron and nickel in the primary circuit of UK EPR which prevent zinc dosing and include evidence for their adequacy.	This Assessment Finding should be completed before zinc is applied to the reactor with nuclear fuel present. Target milestone – Initial criticality.
AF-UKEPR-RC-15	The Licensee shall generate evidence for the optimum band for hydrogen concentration in a reactor with Inconel 690 steam generators. Such reactors normally operate within a narrower band of about 30 to 40 cc kg^{-1} and there appears to be little data to justify concentrations below around 25 cc kg^{-1}. The analysis should include a fuller analysis of the effects of hydrogen levels on Inconel 690 and stainless steels in UK EPR specifically.	This Assessment Finding should be completed before hydrogen is first applied to the reactor. Target milestone – Hot Ops.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-16	The Licensee shall review the provision of a pressuriser vapour space sampling capability.	This Assessment Finding should be completed before such facilities would be needed for nuclear safety but certain aspects may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-17	The Licensee shall consider the need for isokinetic type sampling as part of the corrosion product sampling capabilities in the nuclear sampling system.	This Assessment Finding should be completed before Hot Functional Testing commences as such capabilities would be needed during these activities, but may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Hot Ops.
AF-UKEPR-RC-18	The Licensee shall demonstrate the adequacy of the post accident sampling capabilities in UK EPR.	This Assessment Finding should be completed before such facilities would be needed for nuclear safety but certain aspects may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Fuel load.
AF-UKEPR-RC-19	The Licensee shall include procedures for correcting off-specification chemistry in plant operating procedures.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Cold Ops.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-20	The Licensee shall review whether to add zinc or not during Hot Functional Testing (HFT) and generate evidence to justify this decision.	This Assessment Finding should be completed before HFT procedures are applied to the reactor. Target milestone – Hot Ops.
AF-UKEPR-RC-21	The Licensee shall specify suitable procedures for Hot Functional Testing (HFT), building upon the evidence presented for GDA and including further knowledge and experience particularly from other EPR units commissioned prior to any UK new build. The documentation should justify the controls during HFT of UK EPR, particularly related to hold points, chemistry measurements and target levels, together with their justification.	This Assessment Finding should be completed before HFT procedures are applied to the reactor. Target milestone – Hot Ops.
AF-UKEPR-RC-22	The Licensee shall consider the risks posed by accidental over-cooling of the UK EPR spent fuel pool (SFP). The consequences of this should be documented and recognised in the safety case. Reasonably practicable design changes to mitigate this effect should be considered, if appropriate.	This Assessment Finding should be completed before operation of the spent fuel pool systems. Target milestone – Cold Ops.
AF-UKEPR-RC-23	The Licensee shall include the safety aspects of the spent fuel pool (SFP) operating chemistry in the safety case.	This Assessment Finding should be completed before operation of the spent fuel pool systems. Target milestone – Cold Ops.
AF-UKEPR-RC-24	The Licensee shall review the surface finish to be applied to areas of the spent fuel pool (SFP) subject to level oscillations and generate evidence for the suitability of the surface finish chosen.	This Assessment Finding should be completed before fuel is delivered to site, but may need to be considered earlier, for example, prior to procurement of the affected equipment. Target milestone – Fuel on-site.
AF-UKEPR-RC-25	The Licensee shall specify the acceptable level for tritium in the spent fuel pool and connected systems, including the IRWST. This should include evidence that operator radiation exposure and discharges have been considered.	This Assessment Finding should be completed before nuclear operations, as this is when tritium will be first generated. Target milestone – Initial Criticality.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-26	The Licensee shall develop the controls required to ensure that spent fuel can be successfully exported from the UK EPR fuel pond following storage.	This Assessment Finding should be completed before nuclear operations, as prior to this the fuel export facilities will not be needed. Target milestone – Initial Criticality.
AF-UKEPR-RC-27	The Licensee shall conduct a design review, justification and analysis for the secondary circuit considering the operating regime, material choices, corrosion threats and plant design amongst others. This will input into the secondary chemistry optimisation. This should consider all of the major secondary circuit systems, including many of those not included within the GDA scope.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-28	The Licensee shall generate an assessment of the consequences of introducing Emergency Feedwater into the SG with elevated dissolved oxygen levels.	This Assessment Finding should be completed before operation of the steam generators at temperatures above 120°C, as risks below this temperature are low. Target milestone – Hot Ops.
AF-UKEPR-RC-29	The licensee shall update the safety case documentation to reflect the defined secondary chemistry regime.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-30	The Licensee shall review and justify the limitation on nitrogenous discharges from UK EPR on a site specific basis in consultation with the relevant regulatory bodies. This information should feed into a site specific secondary chemistry optimisation and analysis.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-31	The Licensee shall review and justify the plant specific technical strategy for the Steam Generator Blowdown System ion exchange resin beds, in conjunction with the plant specific chemistry optimisation and analysis.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-32	The Licensee shall review the requirements for automatic actions in case of significant ingress of impurities that could damage Steam Generator tubing or other components needed for nuclear safety. Documentation of the review should include evidence that the adopted site-specific strategy is appropriate.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-33	The Licensee shall generate evidence that the monitoring and surveillance programme for flow accelerated corrosion around the secondary circuit will be adequate.	This Assessment Finding should be completed before plant operations at elevated temperatures, but certain aspects may need consideration earlier, for example, to facilitate inspection provisions in the design. Target milestone – Hot Ops.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-34	The Licensee shall review the case for using a different material for the Nuclear Island (NI) sections of the feedwater piping and generate evidence for the suitability of the material used.	This Assessment Finding should be completed before such components are delivered to site, to ensure appropriate design choices are made. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-UKEPR-RC-35	The Licensee shall review the implications for organic acid impurities in the secondary circuit based upon the operating chemistry and document their justification for any limits specified.	This Assessment Finding should be completed before hot operation of the secondary side of the plant. Target milestone – Hot ops.
AF-UKEPR-RC-36	The Licensee shall specify the dry lay-up chemistry requirements for the secondary circuit of UK EPR. This should include all stages of installation, commissioning and operations with evidence of their suitability.	This Assessment Finding should be completed before delivery to site of the secondary circuit equipment, but certain aspects may need consideration earlier, for example, during component manufacture. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-UKEPR-RC-37	The Licensee shall generate a justification for limits and conditions associated with activity in the Gaseous Waste Processing System (GWPS). This should consider all forms of activity and associated maintenance and testing of the GWPS.	This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated, however consideration should be given earlier to ensure the design is adequate to support the limits and conditions. Target milestone – Initial Criticality.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-38	The Licensee shall generate further details and evidence to support the operation of the Liquid Waste Processing System (LWPS) evaporator, including consideration of chemical effects in operation, such as boron crystallisation, activity accumulation or precipitate generation, as noted in this assessment report. .	This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated, however certain aspects may require earlier consideration, for example, during procurement. Target milestone – Initial Criticality.
AF-UKEPR-RC-39	The Licensee shall include the safety aspects of the Component Cooling Water System (CCWS) chemistry in the safety case. This should include specifications for the detailed CCWS chemistry, including evidence that the chosen regime is adequate.	This Assessment Finding should be completed before initial plant operations. Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-UKEPR-RC-40	The Licensee shall update the safety analysis for Steam Generator Tube Rupture (SGTR) events presented in the safety case to be a clear and consistent safety justification for such events, based upon a single set of underlying assumptions. The chemistry aspects of the safety analysis should be consistent with current experimental data and knowledge on iodine chemistry. The assumptions used should be clearly linked to the supporting transient analysis and the behaviour of the plant systems and where bounding assumptions are used these should be demonstrably so.	This Assessment Finding should be completed before first active operation of the plant.Target Milestone – Initial criticality.
AF-UKEPR-RC-41	The Licensee shall consider the impact of the proposed design change (CMF22) on the Steam Generator Tube Rupture (SGTR) chemistry assumptions used in the safety analysis presented in the safety case.	This Assessment Finding should be completed before first active operation of the plant. Target Milestone – Initial criticality.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-42	The Licensee shall undertake UK EPR specific analysis to support the Combustible Gas Control System design for UK EPR. This analysis should adequately cover all phenomena that may occur during such accident sequences. This analysis should cover the effects of B_4C control rods in the UK EPR design and include demonstration of the long-term plant behaviour post accident.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-43	The Licensee shall review and document the examination, maintenance, inspection and testing arrangements for the (Passive Autocatalytic Recombiners) PARs. This should include consideration of Operational Experience Feedback and the protection requirements during non-power operations.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-44	The Licensee shall demonstrate that the experimental testing of the PARs matches the boundary conditions used in the safety analysis, including under representative severe accident conditions.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-45	The Licensee shall review the influence of CO and CO_2 on fast deflagration and DDT (Deflagration to Detonation Transition) combustion analysis in terms of the most recent experimental work and incorporate this into the plant analysis as appropriate.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-46	The Licensee shall demonstrate that the release fractions for plutonium and strontium in a severe accident, and their longer-term consequences are appropriate for the UK EPR.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-47	The Licensee shall quantify the proportions of gaseous elements contributing to the public consequences in the acute and longer timescales of an accident, so that evidence for the proportion of organic iodine can be generated if significant. An alternative analysis may be agreed with the regulator.	This Assessment Finding should be completed before the POSR is effective.Target Milestone – Fuel load.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-48	The Licensee shall demonstrate that the source term takes account of other sources, such as plant rooms, painted surfaces and the spreading compartment, at different times and examine the sensitivity of their existing analyses to re-release of captured iodine.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-49	The Licensee shall ensure that equilibrium levels of airborne fission-products within the containment are calculated and verified both for prolonged transients and events over longer timescales.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.
AF-UKEPR-RC-50	The Licensee shall estimate the quantities of all possible chemical species that could degrade the performance of the IRWST and analyze their downstream effects on cooling and radioactive release. Possible sources from different events include acidic fumes from radiolysis or pyrolysis, working materials introduced during shutdowns and leaching from solid materials trapped in the strainers. Each of these could reduce the quality of the water in the IRWST and impair heat transfer or iodine retention.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – Fuel load.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-51	The Licensee shall generate evidence for the relative timings of the melt ejection and concrete ablation/plug failure (i.e. the factors affecting the retention time in the pit) and taking account of the following: i) The rate of ablation of the haematite-based sacrificial concrete in the axial and radial directions relative to the timescales for the complete ejection of melt from the RPV. ii) The differences in the rates of ablation between the mixed and the layered condition. iii) The ablation rate for the condition with a metal layer in contact with the concrete. iv) Experimental data for the improvement in flow characteristics for FeO1-x containing melts. v) Thermal stability of the Al-Mg gate (loss of mechanical strength with temperature).	This Assessment Finding should be completed before the POSR is effective.Target Milestone – Fuel load.
AF-UKEPR-RC-52	The Licensee shall review and justify the activatable content of the sacrificial concrete used in the reactor pit and specify low trace element content where appropriate.	This Assessment Finding should be completed before the plant is operated , but should be considered before the acrificial concrete is poured. Target Milestone – Initial criticality.
AF-UKEPR-RC-53	The Licensee shall analyse the effect of additional heat input from the exothermic chemical reaction between the corium and water on the energy released when they interact. Documentation for this effect should include the justification for any assumptions made.	This Assessment Finding should be completed before first nuclear operations with the reactor. Target milestone – Initial criticality.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – UK EPR

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-UKEPR-RC-54	The Licensee shall repeat the analysis of re-criticality in the corium, in more detail to include effects such as boron mixing and volatility.	This Assessment Finding should be completed before first active operation of the plant. Target Milestone – Initial criticality.
AF-UKEPR-RC-55	The Licensee shall compare the results from equivalent analyses generated by the MAAP and COSACO computer codes to confirm the bounding results have been used to examine the consequences of severe accident, over the period where their scope overlaps.	This Assessment Finding should be completed before the POSR is effective. Target Milestone – 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 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 Issues – Reactor Chemistry – UK EPR

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

Technical Area		**REACTOR CHEMISTRY**	
Related Technical Areas		Severe Accident	
GDA Issue Reference	**GI-UKEPR-RC-01**	**GDA Issue Action Reference**	**GI-UKEPR-RC-01.A1**
GDA Issue	Impact of Passive Autocatalytic Recombiners during accidents		
GDA Issue Action	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.		

Annex 2

EDF AND AREVA UK EPR GENERIC DESIGN ASSESSMENT

GDA ISSUE

COMBUSTIBLE GAS CONTROL SYSTEMS

GI-UKEPR-RC-01 REVISION 1

Technical Area	**REACTOR CHEMISTRY**		
Related Technical Areas	Severe Accident		
GDA Issue Reference	**GI-UKEPR-RC-01**	**GDA Issue Action Reference**	**GI-UKEPR-RC-01.A2**
GDA Issue Action	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.		

Annex 2

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

Technical Area		**REACTOR CHEMISTRY**	
Related Technical Areas		Severe Accident	
GDA Issue Reference	**GI-UKEPR-RC-01**	**GDA Issue Action Reference**	**GI-UKEPR-RC-01.A3**
GDA Issue Action	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.		

Annex 2

EDF AND AREVA UK EPR GENERIC DESIGN ASSESSMENT
GDA ISSUE
CONTROL AND MINIMISATION OF EX-CORE RADIATION
GI-UKEPR-RC-02 REVISION 0

Technical Area		**REACTOR CHEMISTRY**	
Related Technical Areas		Radiation Protection Fuel Design Waste and Decommissioning	
GDA Issue Reference	**GI-UKEPR-RC-02**	**GDA Issue Action Reference**	**GI-UKEPR-RC-02.A1**
GDA Issue	EDF and AREVA to demonstrate that ex-core radiation levels in UK EPR are minimised so far as is reasonably practicable and can be controlled.		
GDA Issue Action	EDF and AREVA to provide calculations, or alternative evidence agreed by the regulator, which demonstrate that the control of corrosion products (fuel crud) and other radioactivity (excluding tritium) in safety systems in the UK EPR and outside of the primary reactor cooling circuit are minimised so far as is reasonable practicable and are controlled. The safety systems considered should include all of those inside the Nuclear Island which are routinely expected to handle radioactive materials, including the Spent Fuel Pool, In-containment Refuelling Water Storage Tank and the Residual Heat Removal System. Activation of the reactor vessel itself need not be included in the response. Such evidence should be based upon the expected plant operating procedures, particularly relating to shutdown, head-lift criteria and operation of the boron recycle system and should be compatible with the expected plant limits and conditions. With agreement from the Regulator this action may be completed by alternative means.		

Further explanatory / background information on the GDA Issues for this topic area can be found at:	
GI-UKEPR-RC-01 Revision 1	Ref. 198.
GI-UKEPR-RC-02 Revision 0	Ref. 199.