Office for Nuclear Regulation
An agency of HSE

Generic Design Assessment – New Civil Reactor Build

Step 4 Reactor Chemistry Assessment of the Westinghouse AP1000$^{®}$ Reactor

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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 Westinghouse relating to the AP1000® reactor design, were established prior to the events at Fukushima, Japan. Therefore, this report makes no reference to Fukushima in any of it's findings or conclusions. However, ONR has raised a GDA Issue which requires Westinghouse 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 Westinghouse AP1000® reactor.

EXECUTIVE SUMMARY

This report presents the findings of the Reactor Chemistry assessment of the AP1000 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 December 2009 Pre-construction Safety Report (PCSR) and supporting documentation submitted by Westinghouse 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 Westinghouse were examined.

The scope of the Step 4 assessment was to review the safety aspects of the AP1000 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 focused on obtaining further evidence from Westinghouse and assessing the chemistry of:

- The Westinghouse 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.

A number of items have been agreed with Westinghouse 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:

- Westinghouse has been continuously developing the design of AP1000 throughout the GDA assessment. While this has caused questions to be raised regarding design definition and the cohesiveness of the safety case, a number of positive design changes have been incorporated which have allayed many of my concerns in the original design.
- Westinghouse has struggled to meet my expectations in regard to defining and limiting the chemistry required for safe operation of AP1000. As a plant vendor, Westinghouse do not specify the operational chemistry regimes for AP1000, referring instead to industry guidelines which, in some cases, allow the operator a degree of freedom. Westinghouse also does not propose limits and conditions related to the vast majority of chemical or radiochemical parameters. This latter case is a significant shortfall and will need to be addressed before nuclear safety-related construction and is the subject of a cross-cutting GDA Issue.
- I have assessed the major chemistry systems which allow the operator to control, monitor and change the primary chemistry, including those that are used during accidents. The AP1000 has a number of systems for these aspects which have been simplified and made passive, in line with the overall plant design philosophy, but are functionally very similar to existing PWRs in a number of regards. I have assessed the Chemical and Volume Control System (CVS) in some detail as part of my assessment. This system is novel in a number of aspects but I am content that an adequate case has been made from a Reactor Chemistry perspective for this system, with the exception of the hydrogen dosing control, which I have raised as a GDA Issue which requires resolution. Similarly, sampling of the primary coolant is an important chemistry function allowing the operator to maintain control. Despite a positive design change made late in Step 4 I have still not been convinced that the design of the AP1000 is adequate in this regard and has been shown to meet relevant good practice. I have raised this as a GDA Issue.
- The Westinghouse case for materials in AP1000 is well reasoned and sound, both from a radioactivity and corrosion prevention perspective. Westinghouse have engineered many known ‘problem’ alloys out of the AP1000 design entirely, have reduced many to levels consistent with ALARP as well as demonstrating an appropriate level of control over aspects such as surface finishing and fabrication. Westinghouse has proposed to electropolish the steam-generator channel heads.
- Westinghouse proposes to add zinc to the primary coolant of AP1000 to further reduce the plant dose rates. Based on the evidence presented to me I consider that zinc addition is justified for AP1000 and the use of zinc during commissioning appears to be a welcome addition, provided the depleted form is chosen by the Licensee.
- Estimates of the radioactive materials such as tritium and cobalt isotopes that would be produced by AP1000, have been provided by Westinghouse based on a standard US method. These estimates took no account of different management schemes for AP1000, nor some specifics of the design. I commissioned independent analysis which showed that AP1000 may produce more of the cobalt isotopes that some current PWRs for a comparable power output. Westinghouse also predict some tolerable fuel crud generation. I consider that AP1000 may be more prone to the development of fuel crud and production of cobalt isotopes although this could be manageable provided robust and strict controls, limits and conditions are put in place by the Licensee.
- Despite Westinghouse identifying all aspects of the secondary circuit as being in the scope of the GDA assessment, a number of the important chemistry systems are not yet fully designed. Despite these gaps I have assessed a number of aspects of the design including principal material choices, corrosion threats, chemistry control and tolerance of abnormal chemistry. At a high level it is apparent that Westinghouse has incorporated operating experience and feedback into the design and main material choices for AP1000. A number of detailed material choices, and the operating chemistry, are not yet decided and will only be defined by the

eventual Licensee. A novel design choice for the AP1000 secondary circuit is the use of Electrodeionisation (EDI) for purification of the steam generator blowdown. I have assessed a number of features of this design in detail and have been satisfied with the responses from Westinghouse for the most part, with some areas requiring further work. Thus while reasonable arguments have been made by Westinghouse in these areas, the principal deficiency is that a holistic assessment for the secondary circuit, considering chemistry and material choices, is not yet available, although I am content that there should be no fundamental hindrances to safe operation of the plant.

- The AP1000 Spent Fuel Pool (SFP) safety case related to criticality and loss of cooling events relates to Reactor Chemistry in a number of areas including boron control and the potential for radioactive releases. This has been a cross-cutting area during GDA. In response to our assessment, Westinghouse has proposed a number of design improvements to the SFP and associated systems and has revised the safety case in a number of areas. Whilst broadly in line with my expectations, these were received late in GDA and will need further assessment. A cross-cutting GDA Issue has been raised in this area, which also needs to be satisfactorily resolved before an adequate Reactor Chemistry safety case can be made.
- The AP1000 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 Westinghouse case for chemistry during accidents is acceptable for GDA. The main exception to this is for the control of fission products in an accident. While the containment of AP1000 has been designed to retain radioactive material in an accident, which simplifies the management of radioiodine, AP1000 does not include a recirculating, pH buffered spray system for fission product control as in many PWRs, instead relying on passive deposition mechanism driven by external cooling supplemented by a spray if necessary. The chemistry aspects of this case were presented to ND late in GDA and I have not yet completed my assessment in this important area. I have raised this as a GDA Issue.
- As a result of the GDA assessments, the consolidated PCSR for AP1000 has been updated and now includes a 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. As the Step 4 PCSR contained no chemistry chapter, and this chapter was issued during March 2011, I have not yet fully assessed this document. I have raised this as part of a cross-cutting GDA Issue.

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 conclusions 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 an AP1000 reactor in the UK. These are identified in this report as GDA Issues are formally defined in Annex 2 of this report. In summary these relate to:

> ***GI-AP1000-RC-01*** *- Westinghouse need to provide further evidence that the source term for severe accident release has been appropriately applied for the AP1000 design, including fractions and timing of release in both the short and long term.*
>
> ***GI-AP1000-RC-02*** *- Further justification, potentially including further design changes, will be needed for the primary circuit sampling systems to meet UK expectations.*

> ***GI-AP1000-RC-03*** *- Westinghouse will need to provide further evidence to support the design of the primary circuit hydrogen injection system.*

In addition, there are cross-cutting Issues relating to assessment of the consolidated GDA PCSR (**GI-AP1000-CC-01**), operating limits and conditions (**GI-AP1000-CC-02**) and the spent fuel pool (**GI-AP1000-FS-01**), which require a satisfactory resolution before an adequate Reactor Chemistry safety case can be made.

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 AP1000 reactor design. The AP1000 reactor is therefore suitable for construction in the UK, subject to satisfactory progression and resolution of 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

AC	Alternating Current
ADS	Automatic Depressurisation System
AICC	Adiabatic Isochoric Complete Combustion
ALARP	As Low As Reasonably Practicable (see also SFAIRP)
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASN	L’Autorité de sûreté nucléaire (Nuclear Safety Authority, France)
ASTM	American Society for Testing and Materials
AVT	All Volatile Treatment
BAST	Boric Acid Storage Tank
BDBA	Beyond Design Basis Analysis
BDS	Steam Generator Blowdown System
BMS	(ND) Business Management System
BOA	Boron Offset Anomaly
BWR	Boiling Water Reactor
CANDU	CANada Deuterium-Uranium reactor
CCS	Component Cooling Water System
CDS	Condensate System
CFR	(US) Code of Federal Regulations
CFS	(Turbine Island) Chemical Feed System
CHF	Critical Heat Flux
CILC	Crud-Induced Localised Corrosion
CIPS	Crud-Induced Power Shift
CL	Cold Leg (of RCS)
CMT	Core Make-up Tank
CORS	Catalytic Oxygen Reduction System
CoSHH	Control of Substances Hazardous to Health (Regulations)
CP	Corrosion Product
CPP	Condensate Polishing Plant (see also CPS)
CPS	Condensate Polishing System
CPVC	Chlorinated PolyVinyl Chloride
CRDM	Control Rod Drive Mechanism
CSS	Containment Spray System
CST	Condensate Storage Tank
CVS	Chemical and Volume Control System

LIST OF ABBREVIATIONS

CWS	Circulating Water System
DBA	Design Basis Analysis
DCD	Design Control Document
DCH	Direct Containment Heating
DCP	Design Change Proposal
DDT	Deflagration to Detonation Transition
DE	Dose Equivalent
DSEAR	Dangerous Substances and Explosive Atmosphere Regulations
DTS	Demineralised Water Treatment System
DWS	Demineralised Water Storage and Transfer System
DWST	Demineralised Water Storage Tank
EDCD	European Design Control Document
EDI	Electrodeionisation
EMIT	Examination, Maintenance, Inspection and Testing
EPRI	Electric Power Research Institute (US)
EU	European Union
FAC	Flow Accelerated Corrosion
FHA	Fuel Handling Area
FP	Fission Product
FPS	Fire Protection System
FRI	Fuel Reliability Index
FW	FeedWater
FWS	Feed Water System
GDA	Generic Design Assessment
GSP	Grab sample Panel
HDS	Heater Drain System
HEPA	High Efficiency Particulate Air
HFT	Hot Functional Testing
HL	Hol Leg (of RCS)
HOR	Hide Out Return
HP	High Pressure
HPME	High Pressure Melt Ejection
HSE	(The) Health and Safety Executive
HVAC	Heating, Ventilation and Air Conditioning
HX	Heat Exchanger
IAEA	The International Atomic Energy Agency
IASCC	Irradiation Assisted Stress Corrosion Cracking

LIST OF ABBREVIATIONS

IGA	Inter-granular Attack
IGSCC	Inter-granular Stress Corrosion Cracking
IHST	Integrated Head Storage Tank
IRWST	In-containment Refuelling Water Storage Tank, part of the PXS
IVR	In-Vessel Retention
LB	Large Break
LOCA	Loss of Coolant Accident
LP	Low Pressure
LTCP	Low-Temperature Crack Propagation
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Programme
MATPRO	MATerial PROperties (database)
MCCI	Molten Core-Concrete Interaction
MCR	Main Control Room
MFCV	Main Feedwater Control Valve
MFIV	Main Feedwater Isolation Valve
MSL	Master Submission List
MSLB	Main Steam Line Break
MSR	Moisture Separator Reheater
MSS	Main Steam System
MTS	Main Turbine System
ND	(HSE) Nuclear Directorate
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission (US)
OECD	Organisation for Economic Co-ordination and Development
OEF	Operational Experience Feedback
ORE	Operator Radiation Exposure
PAR	Passive Autocatalytic Recombiner
PASS	Post-Accident Sampling System
PCCWST	Passive Containment Cooling Water Storage Tank
PCS	Passive (containment) Cooling System
PCSR	Pre-construction Safety Report
PLS	Plant Control System
PORV	Power Operated Relief Valve
PRA	Probabilistic Risk Assessment (see also PSA)
PRHR	Passive Residual Heat Removal system, part of the PXS
PSA	Probabilistic Safety Analysis (see also PRA)

LIST OF ABBREVIATIONS

PSS	Primary (circuit) Sampling System
PWR	Pressurised Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
PXS	Passive Core Cooling System
PZR	Pressuriser
QOTTC	Quick Operating Transfer Tube Closure
RCDT	Reactor Coolant Drain Tank
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RI	Regulatory Issue
RIA	Regulatory Issue Action
RMCS	Reactor Make-up Control System
RNS	Normal Residual Heat Removal System
RO	Regulatory Observation
ROA	Regulatory Observation Action
RPV	Reactor Pressure Vessel
RSG	Recirculatory Steam Generator
SA	Severe Accident (see also BDBA)
SAMG	Severe Accident Management Guideline(s)
SAP	Safety Assessment Principle
SCC	Stress Corrosion Cracking
SFCV	Start-up Feedwater Control Valves
SFAIRP	So Far as is Reasonably Practicable (see also ALARP)
SFP	Spent Fuel Pool, part of the SFS
SFS	Spent Fuel Pool Cooling System
SG	Steam Generator
SGS	Steam Generator System
SGTR	Steam Generator Tube Rupture
SINCAD	SIlver-INdium-CADmium alloy
SODA	Statement of Design Acceptability (from EA)
SSC	System, Structure or Component
SSD	System Specification Document
SSER	Safety, Security and Environmental Report
SSS	Secondary (circuit) Sampling System
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority, Finland)
SWS	Service Water System
TCS	Turbine Building Closed Cooling Water System

LIST OF ABBREVIATIONS

TDS	Turbine Drains System
TQ	Technical Query
TSC	Technical Support Contractor
TSP	Tube Support Plate (in SG)
TSoP	Trisodium Phosphate
UK	United Kingdom
UN	United Nations
URD	Utility Requirements Document
US	United States (of America)
USA	United States of America
VAS	Fuel Handling Area HVAC System
VCT	Volume Control Tank
VFS	Containment Ventilation System
VGB	Verenigate Grosskraftwerke Betreiber (Federation of Large Power Station Operators, Germany)
VKS	Containment Ventilation System
VLS	Containment Hydrogen Control System
VTS	Turbine Building Ventilation System
VVER	Vodo-Vodyanoi Energetichesky Reactor (Water-Water Energetic Reactor - a Russian PWR)
VWS	Central Chilled Water System
WENRA	The Western European Nuclear Regulators' Association
WGS	Gaseous Radwaste System
WLS	Liquid Radwaste System
WWS	Waste Water System
ZIRLO®	ZIRconium Low Oxidation alloy

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1 INTRODUCTION

1 This report presents the findings of the Step 4 Reactor Chemistry assessment of the December 2009 AP1000 reactor Pre-construction Safety Report (PCSR) (Ref. 1) and supporting documentation provided by Westinghouse 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 Master Submission List (Ref. 240), 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 (SAP) (Ref. 3) 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 Westinghouse 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 Westinghouse 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. 4), 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 Party (RP) 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. 1) 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. 5) 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 As stated previously (para. 4) this report has been prepared in accordance with relevant ND guidance (Refs 2 and 6), 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. 5).

10 The Step 4 assessment process consists of examining the evidence to support the claims and arguments in the Westinghouse AP1000 PCSR (Ref. 1) 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 Westinghouse'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. 4); raising and issuing of Technical Queries (TQ), Regulatory Observations (RO) and Regulatory Issues (RI), as appropriate, followed by assessment of Westinghouse 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 Westinghouse AP1000, 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 2.5.3 of this report.

2.3 Assessment Approach

13 As identified in Ref. 5, in addition to the Step 4 AP1000 safety case produced at the end of 2009 (Ref. 1), assessment included four principal mechanisms to form a regulatory position on the adequacy of the Westinghouse AP1000 safety case during Step 4. These were:

- Assessment of the outputs produced by Westinghouse in response to the Regulatory Observations Actions (ROA) raised at the end of Step 3 and during Step 4.
- Assessment of the responses to Technical Queries (TQ) produced during Step 4.
- Technical meetings held with Westinghouse 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 Westinghouse 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. None the less, 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 Observations

16 The Regulatory Observations (RO) and associated Actions (ROA) raised with Westinghouse during Step 4 are given in Reference 7.

17 Three ROs were produced and issued in the Reactor Chemistry area at the end of Step 3, which contained a total of 11 ROAs. Although these were issued at the end of Step 3, these were not acknowledged by Westinghouse until May 2010, so could be considered as Step 4 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 one action was raised under one of these existing ROs.

18 One further RO, covering radioactivity in the nuclear island was issued during Step 4. This observation carried a further three actions.

19 Overall Reactor Chemistry issued four ROs and 15 ROAs during GDA, in addition to several joint or cross-cutting ROs with other assessment areas.

20 The deliverables provided by Westinghouse 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 Westinghouse to these actions supplied a number of deliverables which contribute significantly to the overall Reactor Chemistry Safety Case for AP1000.

2.3.2 Technical Queries

21 A total of 127 Technical Queries (TQ) were raised with Westinghouse for the Reactor Chemistry assessment, 116 during Step 4. Refer to Reference 8.

22 The responses provided by Westinghouse 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 Westinghouse to these actions supplied further evidence supporting the overall Reactor Chemistry Safety Case for AP1000.

2.3.3 Technical Meetings

23 As part of the Step 4 planning process a series of technical meetings were arranged with Westinghouse. These meetings occurred at regular intervals throughout 2010 when most of the Step 4 assessment took place. A total of 22 days of main technical exchange meetings were undertaken during Step 4, in addition to numerous teleconferences and smaller meetings, as necessary.

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

25 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

26 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 AP1000 undertaken by ND and are an input into the conclusions of this report.

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

2.4 Standards and Criteria

28 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

29 Of all of the standards and criteria that inform the assessment, it is the selection of the relevant Safety Assessment Principles (SAP) (Ref. 3) 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

30 Assessment was conducted to relevant ND internal standards and guidance (Refs 2 and 6 and Table 2).

2.4.3 External Standards and Guidance

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

32 The International Atomic Energy Authority (IAEA) has prepared a standard on Reactor Chemistry (Ref. 9). 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. 10), and as such is only suitable as advisory guidance. Similar guidance is also available for the Spent Fuel Pool (Ref. 11), containment systems (Ref. 12) and for defining limits and conditions of operation (Ref. 13) and these were similarly used as advisory during the assessment.

33 As part of the GDA Step 2 assessment, HSE requested that IAEA undertake a technical review of AP1000 against the relevant IAEA standards (Ref. 14). IAEA did not reveal any fundamental safety problems with the AP1000, but indicated a number of areas where further assessment work may be required, particularly in areas that are novel or technically complex. The findings from the IAEA technical review have been taken into account by ND during our own assessments.

34 A large number of operating Pressurised Water Reactors (PWR) worldwide base their chemical specifications on standards and guidance produced by industry bodies like the Electric Power Research Institute (EPRI) (Refs 15 and 16) and the German Federation of Large Power Station Operators (VGB Powertech) (Ref. 17). 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.

35 A review of WENRA (Western European Nuclear Regulators' Association) levels (Ref. 18) found none specific to Reactor Chemistry, but there are some relevant to some aspects of the assessment, such as Limits and Conditions. Again, these have been used as advisory during the assessment.

2.5 Assessment Scope

36 Historically, Reactor Chemistry was poorly controlled in early Pressurised Water Reactors (PWR) which gave rise to great variability and 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 each of these aspects and controls are available to limit their occurrence.

37 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 accident analysis.

38 Due to the nature of the GDA process, it was not considered feasible or realistic for Westinghouse 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 Westinghouse to precisely define every aspect of AP1000 chemistry at this stage due to the likely changes in relevant ‘good’ practice that may occur between GDA and operation of any reactor. However, the Step 4 assessment was based on what the ‘expected’ AP1000 chemistry regimes would be (i.e. a baseline case), with Licensee specific development required during Phase 2 (licensing). This is in line with the approach taken by Westinghouse in its safety submissions. The Step 4 assessment also included the provision to identify a range around this ‘baseline’ such that potential ‘cliff edge’ effects are avoided.

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

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

2.5.1 Assessment Topics

41 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.

42 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 AP1000 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 Westinghouse. This original intent was found to be adequate and the originally identified topics were those assessed during Step 4.

43 These were assessed; according to the assessment plan (Ref. 5) 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 Westinghouse.

2.5.2 Findings from GDA Step 3

44 The Step 3 Reactor Chemistry Assessment Report (Ref. 19) conclusions are given in Table 4.

45 Overall the arguments presented during Step 3 were reasonable; however they were generally at a high level. As stated in the Step 3 Assessment Report (Ref. 19) the Step 3 PCSR (Ref. 20) makes extensive use of the European Design Control Document (EDCD) (Ref. 21) in providing the bulk of the safety case information. However, even in combination these two documents did not provide a complete ‘claims – arguments - evidence’ submission; specifically some of the ‘evidence’ that would be required for Reactor Chemistry assessment in Step 4 was lacking in a number of key areas.

46 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

47 Assessment during Step 4 largely followed up the Step 3 Assessment Report (Ref. 19). No additional technical areas, outside those examined during Step 3, were assessed during Step 4.

2.5.4 Use of Technical Support Contractors

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

49 In general the TSCs were contracted to undertake detailed technical reviews of Westinghouse 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 Westinghouse 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. 5). Collectively, our TSC generated over 1500 pages of reports, summarising various aspects of the design of AP1000.

50 While the TSC provide an input into the Step 4 assessment, the regulatory judgment on the adequacy or otherwise of the AP1000 Reactor Chemistry Safety Case was made exclusively by ND. The TSC outputs were used as an input to this decision making process.

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

52 Visibility of TSC work and feedback on progress and outcomes of TSC work was provided to Westinghouse throughout Step 4.

2.5.5 Cross-cutting Topics

53 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
- Categorisation and Classification
- Limits and Conditions
- Design Reference
- Definition of Scope
- Boron Dilution
- Smart Instruments
- Source Terms

54 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

55 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 was proportionate and targeted. The Step 4 Assessment Plan (Ref. 5) contains a matrix that captures areas for assessment co-ordination during Step 4 of the GDA process.

2.5.7 Out of Scope Items

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

- The definition of operating chemistry regimes for the primary, secondary and ancillary circuits.
- Detailed site specific aspects; which include construction, commissioning and site-specific operational matters such as marine fouling.
- Seawater cooling implications and design provisions.
- The implications for routine load-following.

- Use of Mixed Oxide (MOX) fuel.
- Use of control rods based on tungsten.
- 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 WESTINGHOUSE’S SAFETY CASE

57 The Westinghouse Safety Case for AP1000 is based around a Pre-construction Safety Report (PCSR) and supporting documentation, as identified in the Master Submission List (MSL) (Ref. 240).

58 Westinghouse submitted two updates to the Step 3 PCSR (Ref. 20) for the AP1000 during Step 4. The safety case used as the basis of the Step 4 assessments was that issued in December 2009 (Ref. 1). This was the first update and was a revision to the Step 3 PCSR which Westinghouse claimed had been completely restructured to accommodate ND comments on claims, arguments and evidence and to reflect new documents (particularly the AP1000 UK safety categorization and classification of structures systems and components), external hazards, a revised European Design Control Document (EDCD) and a revised environment report.

59 Despite the changes made to the PCSR for Step 4, the EDCD remained a key part of the safety case for AP1000 (Ref. 22). As part of the Step 4 PCSR update a revised EDCD was issued. The EDCD had been revised to include changes to AP1000 as a result of Westinghouse design finalisation reviews, US Nuclear Regulatory Commission (US NRC) review and specific changes identified for a European AP1000 plant. The principal ‘European plant’ changes included the provision of additional redundancy and separation to the AP1000 Normal Residual Heat Removal System (RNS), Component Cooling Water System (CCS), Service Water System (SWS), Spent Fuel Pool (SFP) cooling, increasing of power of Main feedwater pumps and a change of Reactor Coolant Pump (RCP) vendor. The EDCD aligns more closely with revision 18 of the US DCD.

60 During Step 4 Westinghouse undertook a complete revision to the PCSR for GDA, which included the addition of a specific Reactor Chemistry chapter, amongst other significant changes. This draft revision of the chemistry chapter was issued in December 2010 (Ref. 23) and was not updated until the consolidated GDA submission, including an updated PCSR (Ref. 105), was produced in March 2011. As such, neither the December 2010 draft nor the March 2011 issue formed the basis for the Step 4 assessment.

61 Due to its delivery late in the GDA process, and the significant changes undertaken by Westinghouse, I have not assessed the final consolidated GDA submission (March 2011) from Westinghouse during Step 4. As this is an important aspect of the Reactor Chemistry assessment of AP1000, I will support the cross-cutting GDA Issue in this area **GI-AP1000-CC-02** (see Ref. 237). I have reviewed an early draft of the PCSR Reactor Chemistry chapter during Step 4 (December 2010) and on this basis do not expect there to be significant shortfalls (over and above those identified in the draft) in the consolidated submission, but this needs to be confirmed.

3.1 Step 4 Submission (December 2009)

62 The following commentary is based on the Step 4 submissions only; the PCSR (Ref. 1) and the EDCD (Ref. 22). 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.

3.1.1 Structure

63 The UK AP1000 PCSR is described as the ‘top-tier’ document within the Westinghouse safety submission for GDA. The PCSR claims that the overarching safety claims for AP1000 are presented in the PCSR, while most of the evidence for the claims and arguments can be found within the EDCD and other supporting documents and technical reports. Westinghouse acknowledge that the EDCD and supporting documentation are prepared from a US regulatory background and the PCSR (and specific topic reports) act as ‘head documents’ linking these to the demonstration of safety expected in the UK.

64 Although a number of other documents are present in the Westinghouse submission, and do contain useful information, as for Step 3, together the PCSR and EDCD represent the bulk of the safety case. While improved from that presented during Step 3, the structure of the PCSR still does not relate directly to the corresponding structure of the EDCD and as such it is not straightforward to transfer directly between the two documents.

65 Neither the PCSR nor the EDCD contained detailed information on the Reactor Chemistry of AP1000. 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 presented for Step 4. The omission of much chemistry related information from the PCSR is a clear failure to meet my expectations for a UK safety case. It should, however, be noted that a Chemistry chapter has been included in the March 2011 revision of the PCSR, which I have yet to assess.

66 As such the most significant evidence lies in documents outside the PCSR and EDCD 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 Westinghouse.

3.1.2 Content

67 Neither the PCSR nor the EDCD contain any main sections which deal with Reactor Chemistry for the design. This is perhaps not unexpected, due to the nature of Reactor Chemistry and the many interactions it has with systems, structures and components throughout the entire plant. Instead Reactor Chemistry is detailed within the text for specific individual systems, principally within the EDCD. This is exemplified in Table 5 which details the sections of the PCSR and EDCD relevant to Reactor Chemistry. For the significant systems of interest to the Reactor Chemistry assessment, information is scattered widely throughout the PCSR and EDCD.

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

- The overall claims-argument-evidence structure of the PCSR is lacking. It should be recognised that the PCSR and EDCD together do not represent a complete safety case in a UK context, especially from a Reactor Chemistry perspective. Further documentation is required to fully substantiate the ‘evidence’ stage of the assessment. By their very nature these documents may not form part of a PCSR directly, but should be referenced as appropriate as they are an important part of the overall safety case. Despite repackaging the DCD to an EDCD, due to its origin as a means of demonstrating to the US Nuclear Regulatory Commission (US NRC) compliance with US requirements, the EDCD does not present a claims-argument-evidence structure in a manner compatible with UK expectations. Most claims in the EDCD are made implicitly and there is little argument or evidence from a Reactor Chemistry perspective.

- Westinghouse bases many of its arguments for chemistry on experience with other reactors and not on theoretical or quantitative analyses. The lack of theoretical or quantitative analyses weakens some arguments, especially where AP1000 is novel. Further evidence in this area is needed as part of the safety case development.
- As originally provided, the Classification and Categorisation presented in the safety case did not align with the UK requirements. During 2009, Westinghouse updated their classification and categorisation of the Safety Systems, Structures and Components in AP1000 to align with the UK guidance in SAPs ECS.1 to ECS.5, Ref. 3. The revised scheme for AP1000 was delivered in late 2010. While this has not hindered the Step 4 Reactor Chemistry assessment, and has not been a feature of my assessment, it should be recognised that consequential changes, for instance to identify safety limits for newly classified systems, have yet to be made.
- Westinghouse 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 PCSR contains very little information on the chemistry associated with many other safety relevant systems in the AP1000 design including:
    i) Secondary circuit chemistry
    ii) Component Cooling Water System (CCS)
    iii) Chemistry requirements associated with the Spent Fuel Pool (SFP) and connected systems, such as the In-containment Refuelling Water Storage Tank (IRWST)
- The analysis of design basis faults contains little information on the underlying chemical processes which occur. The assumptions made in these areas can influence the consequences of such events and should be justified as part of the safety case.
- Similarly, while Westinghouse appears to have invested considerable effort in severe accident chemistry, the presentation of chemistry related information in these areas is lacking. There is a deficit of information on how chemistry has been applied specifically to the AP1000 design and the chemistry assumptions used are not transparent and presented in many cases.
- The safety case presents no, or very limited information on chemistry related limits or conditions for the safe operation of the plant. This is particularly relevant to those parameters which affect radwaste, occupational exposure or have long-term effects on plant safety.

3.1.3 Summary

69 Overall, the Step 4 submissions were only marginally improved over those presented for Step 3. 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.

3.2 Draft PCSR Reactor Chemistry Chapter (December 2010)

70 Westinghouse submitted a “*preliminary*” draft of the PCSR chapter in response to RO-AP1000-55.A1 and RO-AP1000-55.A9 (Ref. 7) in September 2010. These ROAs requested a primary chemistry “*topic report*” and draft PCSR section(s) respectively. I reviewed and returned comments to Westinghouse on this ‘preliminary’ draft (Ref. 127) in letter WEC70267R (Ref. 129).

71 The following section describes the “*preliminary*” draft PCSR Chemistry chapter which preceded the PCSR submitted in December 2010 (Ref. 23), itself a draft for the consolidated GDA submission, see Section 3.3 below.

3.2.1 Structure

72 It is apparent from the draft PCSR Chemistry chapter that the Consolidated PCSR will contain a dedicated Chapter (21) on Reactor Chemistry. This chapter provides coverage of the main areas where chemistry affects safety, including primary, secondary and auxiliary circuit chemistry, accident chemistry and covers related issues such as operational strategies and construction and commissioning. Many of the sections link to other chapters of the PCSR for complete coverage, for example to the fault studies section to detail boron dilution controls. This is an immediate and significant improvement in the safety case assessed during Step 4, where significant portions of the plant chemistry were deficient or absent.

3.2.2 Content

73 The draft PCSR chapter contains information on the chemistry functions, safety requirements and system descriptions of the major plant systems affected by chemistry. Westinghouse defines the safety requirements for the various AP1000 systems on the basis of “*adherence to a number of involatile principles*” defined earlier in the overall PCSR. While I have not reviewed all of this earlier list, as it was not presented in the draft Chemistry chapter, it is evident from the Chemistry chapter that this includes high-level safety requirements such as “*reactivity control*”, “*maintenance of integrity*” and “*minimisation of ORE* [Operational Radiation Exposure]”, which are consistent with the main high level safety requirements I would expect to see in a PCSR from a chemistry perspective.

74 As for the Step 4 submissions, some general comments can be made on the draft PCSR Chemistry chapter. These comments have been shared with Westinghouse (Ref. 129):

- The overall claims-argument-evidence structure is much improved. The reliance on the EDCD to provide the evidence is greatly diminished compared to the Step 4 PCSR (Ref. 1). Much more relevant information is contained in specific Westinghouse or relevant EPRI documents, although many of these are not specific to AP1000 and are guidance documents only.
- The chapter contains lots of background information, which although useful, may not be appropriate for a PCSR at the level of detail currently presented. For example, there are many pages related to data on Inconel 600, which is hardly used in AP1000, material properties (stress, strain) which are not directly relevant to chemistry, detailed system descriptions or extensive technical background. While the intention is understood in terms of presenting the narrative which explains why and how the design, materials and chemistry for AP1000 have evolved from previous experience,

there needs to be a balance struck between what is presented in the main PCSR and elsewhere; the fundamental principle should be to link the operating chemistry with safety. The overall impression is that metallurgical effects are heavily presented in the chapter and it would benefit from being more tightly focussed on chemistry in the safety case for AP1000 specifically. As currently presented the chapter is weaker in presenting this fundamental arrangement and as a result, some of the relevance of chemistry to overall safety is opaque.

- Due to the Westinghouse position of not specifying precise chemistry regimes (see out of scope items (Section 2.5.7) and Section 4.1 for a fuller description) the draft PCSR chapter encompasses the often quite wide range of possibilities offered by the various referenced guidelines. For example, Section 21.5.6 of the draft PCSR states that the build-up of primary circuit radioactivity is minimised by "*maintaining* pH_{Tav} *within the range* [redacted]". Whilst this is consistent with EPRI guidelines (Ref. 15) and the AP1000 "*chemistry manual*" (Ref. 25), this range is broad and operation at the extremities within this range would not be suitable for AP1000, see Section 4.2.10. Thus, the chemistry elements of the draft PCSR chapter represent a safety case for a PWR (Pressurised Water Reactor), but not demonstrably so for AP1000 specifically.
- The section describing "*Operational Strategies in the AP1000 Design*" (21.8) does not consider systems outside of the primary circuit.
- The sections dealing with accident chemistry (either design basis or severe accidents) appear to provide only a summary, without clear safety claims and assumption for the chemistry, and only provide a summary of the areas discussed with Westinghouse during GDA (i.e. they do not present the safety case as a whole). They might be better suited to the relevant faults studies or PSA (Probabilistic Safety Assessment) chapters as appropriate.
- The chapter fails to present information on chemistry related limits or conditions for the safe operation of the plant, other than general descriptions given as part of the "*technical basis*". A summary section identifying key chemical parameters and activities needing control either through Westinghouse, EPRI or other equivalent guidance, would help to identify the importance of the various chemical parameters to safety.
- Many of the sections refer to analysis, calculations or design improvements that are still on-going. The chapter lists relevant ROs and TQs, when these should be incorporated in the main text, as appropriate. As such the chapter does not yet fully represent the final position at the end of GDA.

3.2.3 Summary

75 Overall, the draft chapter is much improved on the Step 4 submissions and Westinghouse should take credit for the significant improvement to the AP1000 safety case for Reactor Chemistry that this represents. This is the first inclusion of such a chapter in the Safety Case for AP1000 and I have provided Westinghouse with written feedback. This has become part of the consolidated PCSR, which will be assessed as part of the cross-cutting GDA Issue, **GI-AP1000-CC-02** (see Ref. 237), see the following section.

3.3 Consolidated GDA submission (March 2011)

76 The following section describes the consolidated PCSR submissions submitted in March 2011 (Ref. 105).

77 Westinghouse submitted a consolidated PCSR to ND in letter UN REG WEC 000536 (Ref. 130). Due to the delivery date for the consolidated PCSR I have not assessed it during GDA. Westinghouse states there are "*no significant changes*" to the Chemistry chapter since the December 2010 draft revision, although many other related sections, such as fault studies, categorisation and classification and operating limits and conditions have been changed. The nature of the general comments made in Section 3.2 above, and the changes made to the overall PCSR for AP1000 mean that I consider that a detailed review of the consolidated PCSR is necessary in the Reactor Chemistry area, before I can be satisfied that it adequately represents the final position for GDA. This is the basis for the cross-cutting GDA Issue, **GI-AP1000-CC-02** (Ref. 237).

3.4 Assessment Findings

78 I have identified no general Reactor Chemistry Assessment Findings for the AP1000 safety case overview.

3.5 GDA Issues

79 Based upon the assessment of the AP1000 safety case as described in Section 3 above, I support the cross-cutting GDA Issue on Operating Limits and Conditions, described in Section 4.2 and the following cross-cutting GDA issue on the safety case itself, which requires resolution before an adequate Reactor Chemistry safety case can be made for AP1000 (see Ref. 237):

> ***GI-AP1000-CC-02*** *– PCSR to Support GDA - Westinghouse to submit a safety case to support the GDA Design Reference and then to control, maintain and develop the GDA submission documentation, including the SSER, the MSL and design reference document and deliver final consolidated versions of these as the key references to any DAC/SODA the ONR or the Environment Agency (the joint Regulators) may issue at the end of GDA.*

4 GDA STEP 4 NUCLEAR DIRECTORATE ASSESSMENT FOR REACTOR CHEMISTRY

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

81 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 principle 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

82 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 and standards, such as the EPRI (Refs 15 and 16) or VGB guidelines (Ref. 17), in determining the most appropriate chemical regime.

83 As indicated in Section 2.5, it was not the aim of the GDA assessment to compel Westinghouse to devise and detail the exact AP1000 chemistry regime 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 an acceptable chemical regime.

84 Some 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.

85 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 Westinghouse approach to Reactor Chemistry in this important cross-cutting topic is also discussed in this section.

4.1.2 Assessment – Chemistry Standards

86 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, particularly where the design of AP1000 is novel or differs from progenitor PWR designs. Based upon TQ responses and discussions at the time, it became apparent that Westinghouse recommend following current US practice with the AP1000, namely adherence to EPRI standards and guidance (Refs 15 and 16), although they do produce supplementary, more restrictive guidance

where a particular requirement (especially for the fuel) is not met within the EPRI documents. Westinghouse believe that the EPRI guidelines are often more prescriptive than others and as such should represent a bounding case. This forms the basis of their case for GDA.

87 Overall, at the end of Step 3 I was satisfied that this was a reasonable approach, at a high level, although I noted that the EPRI material are guidelines, not standards and only propose a methodology for optimising the plant chemistry in certain instances. It was also unclear how design differences in AP1000 would affect this approach and these areas were assessed further during Step 4. This was exacerbated by the PCSR (Ref. 1) not containing any substantive information on Reactor Chemistry and the information in the EDCD (Ref. 22) on occasion suggesting controls that were dated. Similarly, what was not apparent during Step 3 was the link between the chemistry regime and the AP1000 safety case for chemistry and this was a key line of enquiry which was explored with Westinghouse during Step 4.

88 TQ-AP1000-534 (Ref. 8) queried a number of points related to the development of chemistry standards for AP1000. The response confirmed that Westinghouse expect Licensees to follow the EPRI guidelines to develop plant specific standards. This is the reason that “*definition of operating chemistry regimes for the primary, secondary and auxiliary circuits*” is listed as an out of scope item for the GDA assessment of AP1000; in essence Westinghouse has not defined the precise operating chemistry for AP1000, only a tolerable range, which in some instances is relatively large. As a result the Licensee of any UK AP1000 will be required to document and justify the operating chemistry regimes for the primary, secondary and auxiliary circuits. The regimes selected should be consistent with the plant safety case, particularly the limits and conditions required for safe operation. Included in the documentation should be an ALARP (As Low As Reasonably Practicable) case for the plant operating chemistry which should demonstrate that concerns such as integrity, ORE and wastes have been adequately weighted in defining the optimised regime. The evidence provided during GDA could be used as a basis; including further knowledge and experience particularly from other AP1000 units commissioned and operated prior to any UK new build. I consider this to be an Assessment Finding, **AF-AP1000-RC-01**.

89 On the whole, while the Westinghouse approach is reasonable for GDA, I found this a surprising argument to make, firstly because clearly some assumptions on the chemistry will be made in the safety case assessments and secondly, as the designer of the plant, Westinghouse are potentially best placed to define the chemistry as they have the intimate knowledge of the systems and processes. Westinghouse has indicated they could help a Licensee in this respect, but this would be subject to commercial agreement. If not, the arrangements for transfer of knowledge to the Licensee would be vital. The details regarding this arrangement would be expected to be part of the work necessary to address Assessment Finding, **AF-AP1000-RC-01**.

90 A TSC contract (Ref. 24) 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.

91 The response to TQ-AP1000-534 also provided information on the involvement of Westinghouse in the development of EPRI guidelines. It is notable that Westinghouse also recognised the generic nature of the EPRI guidelines and indicates that several AP1000 design features, such as direct hydrogen injection and lack of a Volume Control Tank (VCT), may mean that specific guidance may be required in these areas. At the

time of the response (June 2010) Westinghouse were developing three documents which would provide further guidance to potential Licensees in this area, namely:

- The AP1000 "*Chemistry Manual*" (Ref. 25)
- The Westinghouse supplemental guidance to the EPRI primary guidelines, specific to AP1000 (Ref. 26)
- An updated PCSR, including a specific chemistry chapter (Refs 23 and 105)

92 These documents were made available to ND from summer 2010 onwards and are discussed further below. My expectations were that these documents would provide suitable and sufficient guidance to any potential operator on the relative importance and derivation of chemistry standards specific to the AP1000 design. 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, my expectations were for the AP1000 safety case to demonstrate that all safety significant chemistry parameters had been captured and the relative importance of these to plant safety were presented or could be inferred by a potential Licensee from the suite of documentation.

93 TQ-AP1000-593 (Ref. 8) queried how chemistry related conclusions from the safety case would be transferred to an operational AP1000. The response suggested that the updated PCSR Chemistry chapter would provide the link between the chemistry parameters and safety.

94 As Westinghouse make claims that the design of AP1000 will allow equivalent or better control over chemistry parameters compared to existing reactors, TQ-AP1000-713 (Ref. 8) was raised to understand if any modifications were anticipated on the historically used 'action level' boundaries specifically for AP1000 based upon OEF (Operational Experience Feedback) (i.e. evidence of learning from experience in defining chemistry standards). The response indicated that Westinghouse do not have access to this information for operating plants. While this may be acceptable in a generic sense for application of EPRI guidelines, it does mean that Westinghouse cannot confirm if the action levels and controls have been sufficient on existing plants. This will have to be undertaken and justified by the Licensee. I consider this to be an Assessment Finding, **AF-AP1000-RC-02**.

95 As the AP1000 safety case was subject to on-going development throughout Step 4, I queried what safety case documentation Westinghouse see as defining the operational chemistry for AP1000 in TQ-AP1000-1240 (Ref. 8). I was particularly interested in how AP1000 design specifics were handled. This response represents the final position for the GDA assessment of AP1000. The response provides a comprehensive and structured description of the AP1000 case in this area, citing many documents. The principal Westinghouse documents which define the chemistry standards are considered to be the "*chemistry manual*", the Westinghouse AP1000 supplemental guidelines, the PCSR and the relevant system manuals, as described below.

96 The AP1000 "*chemistry manual*" (Ref. 25) is a high level guidance document providing information on how a site specific chemistry programme could be developed. This

document can be considered the 'head document' referencing the EPRI (Refs 15 and 16) or Westinghouse supplemental guidance (Ref. 26) as appropriate. The overall document is comprehensive, covering primary, secondary and many auxiliary systems during various operational states such as start-up and shutdown. This document is a valuable addition to the safety case, although it is notable that the *"chemistry manual"* does not reference the PCSR and as such does not link the chemistry back to the safety case. As guidance, the manual references out to the EPRI primary (Ref. 15) and secondary guidelines (Ref. 16); in most instances this does not lead to precise standards, with the *"chemistry manual"* referring to the EPRI guidelines, and the EPRI guidelines referring to the need for a plant specific optimisation. In effect, this leaves the definition of chemistry to the Licensee, within the broad constraints specified by EPRI and Westinghouse. The effect of this on the main primary and secondary chemistry regimes is different:

- Primary chemistry is, by default, much more specific in the chemical additives than secondary chemistry but the effects of smaller differences in parameters can be significant. An example is the primary coolant pH_T value. The AP1000 *"chemistry manual"* allows this to be defined by the Operator/Utility within the constraints of pH_T between [redacted], with lithium less than [redacted] mg kg^{-1}. As discussed in Section 4.2.10, this could affect many safety issues such as integrity, ORE and wastes and does not allow an ALARP claim to be made.
- For secondary chemistry, where chemical additive choices are influenced by both materials and design of a range of (site specific) systems, this means that a coordinated assessment of secondary side corrosion and chemistry risks cannot be undertaken at this time. Similarly, material choices for the secondary side are also often influenced by operational chemistry. The implications of this for secondary side chemistry are discussed more in Section 4.4.2.

97 Westinghouse provides guidance on the expected values for various species in the primary coolant in the '*Westinghouse Supplement to EPRI PWR Primary Water Chemistry Guidelines Rev. 6 for the AP1000™ Standard Plant*' (Ref. 26). This guidance is considered mandatory and supersedes any EPRI or other guidance referenced by Westinghouse.

98 As described in Section 3.1, the revised draft PCSR for AP1000 (Ref. 23), including the Chemistry chapter, was delivered to ND in December 2010. This was also requested in RO-AP1000-55.A9 (Ref. 7) and was delivered in response to RO-AP1000-55.A1 (Ref. 7) in relation to primary chemistry. This was not formally issued until March 2011. A commentary on the draft and consolidated GDA submissions is provided in Section 3.2, including the PCSR Chemistry chapter.

99 Various AP1000 design documents (System Specification Documents (SSD)), Design Change Proposals (DCP) and operating procedures are cited to provide guidance to the operator on the intended operation of the plant. Many of those most relevant to chemistry are not yet complete and hence have not been assessed during GDA. The most relevant are discussed in the assessment sections that follow.

100 In '*Safe and Simple: The genesis and process of the AP1000 Design*' (Ref. 27), Westinghouse identifies a number of design features of AP600/1000 that are different from other non-passive PWRs.

101 Overall, Westinghouse provides much guidance and information to prospective Licensees on their expectations for chemistry control in AP1000, albeit within broad constraints. This is a positive position and credit should be given to Westinghouse on this approach. However, as described in para. 91, I assessed how AP1000 specific differences had

been captured. I do not yet believe that the safety case yet adequately explains how many of the chemistry related differences are covered by the documentation. These need to be more formally documented and presented as part of the supporting documentation to the AP1000 safety case. For example, certain features of the use of a high pressure Chemical and Volume Control System (CVS), direct hydrogen injection, use of Electrodeionisation (EDI) etc. as described later in this report. I consider this to be an Assessment Finding, **AF-AP1000-RC-03**.

4.1.2.1 Summary

102 Based upon the evidence presented during GDA, the main conclusion I draw for the assessment of chemistry standards in AP1000 are:

- Westinghouse has described the proposed basis for developing chemistry standards for AP1000. While I am satisfied that a suitably competent and experienced Licensee should be able to define adequate operating chemistry regimes for an AP1000 this will need to done at a later stage of licensing, including ALARP justifications. I have raised Assessment Findings to cover the points related to this approach. I am satisfied these can be resolved post GDA.
- Westinghouse have made some positive steps in producing guidance for AP1000, particularly the "*chemistry manual*" and supplementary guidance, which could be used by a Licensee to help with developing and justifying the operating chemistry. The Licensee can use these as a basis for further development as the safety case is supplemented with additional information and evolves through licensing.

103 On balance, I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.1.2.2 Assessment Findings

104 Based upon the assessment of chemistry standards in AP1000 described in Section 4.1.2 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-AP1000-RC-01*** *– The Licensee shall specify the normal operating chemistry regimes for the primary, secondary and auxiliary circuits of UK AP1000. The specifications should be comprehensive and incorporate evidence for all modes of operation. This Assessment Finding should be completed before plant operations using the intended operating chemistry commence; Target milestone – Cold Ops.*
>
> ***AF-AP1000-RC-02*** *– The Licensee shall specify the chemistry-related action level boundaries that are appropriate for AP1000. The documentation shall include evidence that the boundaries are appropriate and a demonstration that Operational Experience Feedback (OEF) has been used in their development. This Assessment Finding should be completed before plant operations using the intended operating chemistry commence; Target milestone – Cold Ops.*
>
> ***AF-AP1000-RC-03*** *– The Licensee shall generate evidence that operating chemistry regimes, including limits/conditions and action levels/corrective actions, do reflect the design of UK AP1000 given its difference to existing PWRs. 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

105 Based upon the assessment of chemistry standards in AP1000 described in Section 4.1.2 above, I have identified no reactor chemistry GDA Issues in this area. However this area does closely relate to the cross-cutting GDA Issue on limits and conditions, **GI-AP1000-CC-01**, described below.

4.1.3 Assessment – Limits and Conditions

106 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 stay within them. From a Reactor Chemistry perspective this should limit the operational chemistry.

107 The PCSR (Ref. 1) provides little discussion of limits and conditions. Westinghouse define limits and conditions to only include those parameters that:

- Bound the conditions assumed by the transient analysis for each fault in the DBA (Design Basis Analysis) fault schedule.
- Place conditions on the availability of protective safety measures, based on the required reliability of providing the nuclear safety function, given the postulated frequency and consequences of each fault.

108 The technical specifications for the AP1000, which are presented in Chapter 16 of the EDCD (Ref. 22), set out the operational limits and conditions needed by the design basis safety case. It is notable that some of the most important chemistry parameters, for example primary circuit lithium, are not included in these. This is a function of the US regulatory system, whereby many chemistry parameters are not included in the highest level "*technical specifications*". However, this is a European DCD so it should address such matters in a manner consistent with European, rather than US, expectations.

109 RO-AP1000-94 (Ref. 7) was issued to Westinghouse as a cross-cutting RO requesting evidence of how limits and conditions specific to AP1000 would be developed. The RO specifically made reference to chemistry related parameters. A summary of my assessment of this response, as applicable to Reactor Chemistry, is provided in the following paragraphs. Note that I consider radiochemical parameters to be part of the chemistry in this discussion. I also commissioned an independent TSC review of the Westinghouse response to RO-AP1000-94 (Ref. 106), the conclusions of which are consistent with the assessment that follows (Ref. 230).

110 The RO response (Ref. 106) described how Westinghouse would approach the development of limits and conditions for a UK AP1000. The response defines the concept of "*Technical Specifications*" and divides these into two categories, "*operating rules*" and "*availability controls*", however the document fails to outline which parameters are within this remit and where the division between these two classes lies. As described previously, Westinghouse relies heavily on the EPRI guidelines which outline suggested action levels and related allowable out-of-specification times. Based on the description

provided in the response Westinghouse sees most of the chemistry parameters at a lower level than 'technical specifications'.

111 While the response attempted to 'classify' the limits and conditions based upon their respective hazard, an approach based mainly on the DBA analysis potentially neglects limits and conditions associated with other parts of the safety case. The response did not provide the links between the limits and conditions and the AP1000 safety case presented for GDA and did not indicate which chemistry parameters Westinghouse expect to be part of the plant limits and conditions. It is notable that throughout the document Westinghouse imply that the derivation and production of limits and conditions are the responsibility of the Licensee. This is similar to many of the TQ and RO responses I have received as part of the Chemistry assessment during Step 4; see for example, Section 4.3.2.3 and the discussion of the response to RO-AP1000-84 (Ref. 7). I agree that this approach is adequate for GDA, but my expectation is that Westinghouse will provide the information and guidance necessary to enable a Licensee to fully develop their plant specific limits and conditions, building on those derived from the GDA safety case (as developed by Westinghouse). While the definition of precise values, actions and timescales resides with the Licensee, I would expect Westinghouse to be able to identify those parameters which are already included within the safety case at this stage of licensing, 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. The response to RO-AP1000-94 does not allow this.

112 Much of the response describes the methodology used by Westinghouse in meeting US regulations, so may not be applicable in the UK, and is based upon information provided in the EDCD. It is also notable that the limits and conditions given in the PCSR and EDCD do not take account of the changes to the AP1000 safety case for the UK. Westinghouse does not provide feedback from operators of their experience with keeping to action levels; see TQ-AP1000-713 (Ref. 8).

113 The response does not provide an adequate definition or evidence for how chemistry related plant limits and conditions can be derived from the safety case made in the GDA PCSR. On the basis of the response as presented, Westinghouse have not identified any chemistry related limits and conditions. This is a significant departure from my expectations for GDA, where I would expect Westinghouse to identify which chemistry parameters are important to safety and therefore should form part of any Licensee derived set of limits and conditions. I consider this to be a part of the cross-cutting GDA Issue, **GI-AP1000-CC-01**. As this is a subject affecting many assessment areas, I will support this cross-cutting GDA Issue. I judge that this Issue is resolvable from a Reactor Chemistry perspective, but will need to be satisfactorily resolved before an adequate Reactor Chemistry safety case for AP1000 can be made.

114 Overall, I am content that a competent and experienced Licensee should be capable of developing suitable chemistry standards for AP1000, based on the guidance provided by Westinghouse. Optimisation of the plant operating chemistry based upon the Westinghouse and EPRI guidelines should result in adequate safety control, but this will need to be optimised for other concerns such as ORE and wastes and consider ALARP. As Westinghouse has chosen not to address these during GDA, these aspects will need to be addressed by the Licensee during later stages of licensing. This will be required as part of Assessment Finding **AF-AP1000-RC-01**, see Section 4.1.2.

115 As described in para. 96, Westinghouse has taken a positive step in producing a "*chemistry manual*" specific to AP1000 (Ref. 25). During construction and commissioning

of any UK AP1000, a detailed chemistry document, containing the basis and description of the chemistry requirements for the various Systems, Structures and Components (SSC) through all phases of operation, for example, purity, cleanliness or material compatibility, would be a valuable document. In this way the chemistry in the various systems is transparent to all involved and early resolution of any problems can be aided. The current "*chemistry manual*" is a useful starting point for this type of documentation. Production of this type of documentation can be pursued at a later stage in Licensing and I consider this to be an Assessment Finding, **AF-AP1000-RC-04**.

4.1.3.1 Summary

116 Based upon the evidence presented during GDA, the main conclusion I draw for the assessment of limits and conditions in AP1000 are:

- In line with the decision not to define a precise operating chemistry for AP1000, Westinghouse has not yet provided sufficient information on limits and conditions required in the interest of safety. Such limits and conditions are a fundamental part of any nuclear safety case and I expect Westinghouse to be able to identify those chemistry parameters which are related to safety. This will need to be addressed before nuclear safety-related construction can begin and I support the cross-cutting GDA Issue on Limits and Conditions in this area, **GI-AP1000-CC-01**.

117 On balance, I judge that further work is required by Westinghouse on the claims, arguments and evidence as presented in this area but believe that Westinghouse can make an adequate case to support GDA, provided the cross-cutting Issue identified can be adequately resolved.

4.1.3.2 Assessment Findings

118 Based upon the assessment of limits and conditions in AP1000 described in Section 4.1.3 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, by the Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-04*** *– 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.*

4.1.3.3 GDA Issues

119 Based upon the assessment of limits and conditions in AP1000 described in Section 4.1.3 above, I support the following cross-cutting GDA Issue on Limits and Conditions, which requires a satisfactory resolution before an adequate safety case can be made from a Reactor Chemistry perspective:

> ***GI-AP1000-CC-01*** *– Limits and Conditions - In respect of any operation that may affect safety, Westinghouse should have arrangements to identify and advise the future Licensee of the conditions and limits necessary in the interests of safety.*

> *These arrangements need to ensure that there is an appropriate link between the analysis documented in its safety case and the associated operational limits and conditions derived from the safety case, such that the Licensee can operate in accordance with the safety case.*

4.2 Primary Circuit

4.2.1 Overview

120 The principal system in the primary circuit is the Reactor Coolant System (RCS). The AP1000 RCS is described in detail in the PCSR (Ref. 1, Section 5). The AP1000 RCS configuration is an unconventional two-loop design. 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 two loops before returning to the core, cooler after the transfer of heat to the secondary coolant via the Steam Generators (SG). Each loop comprises a hot leg pipe, Steam Generator (SG), Reactor Coolant Pump (RCP) and two cold leg pipes. 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 in the following figure (Ref. 1).

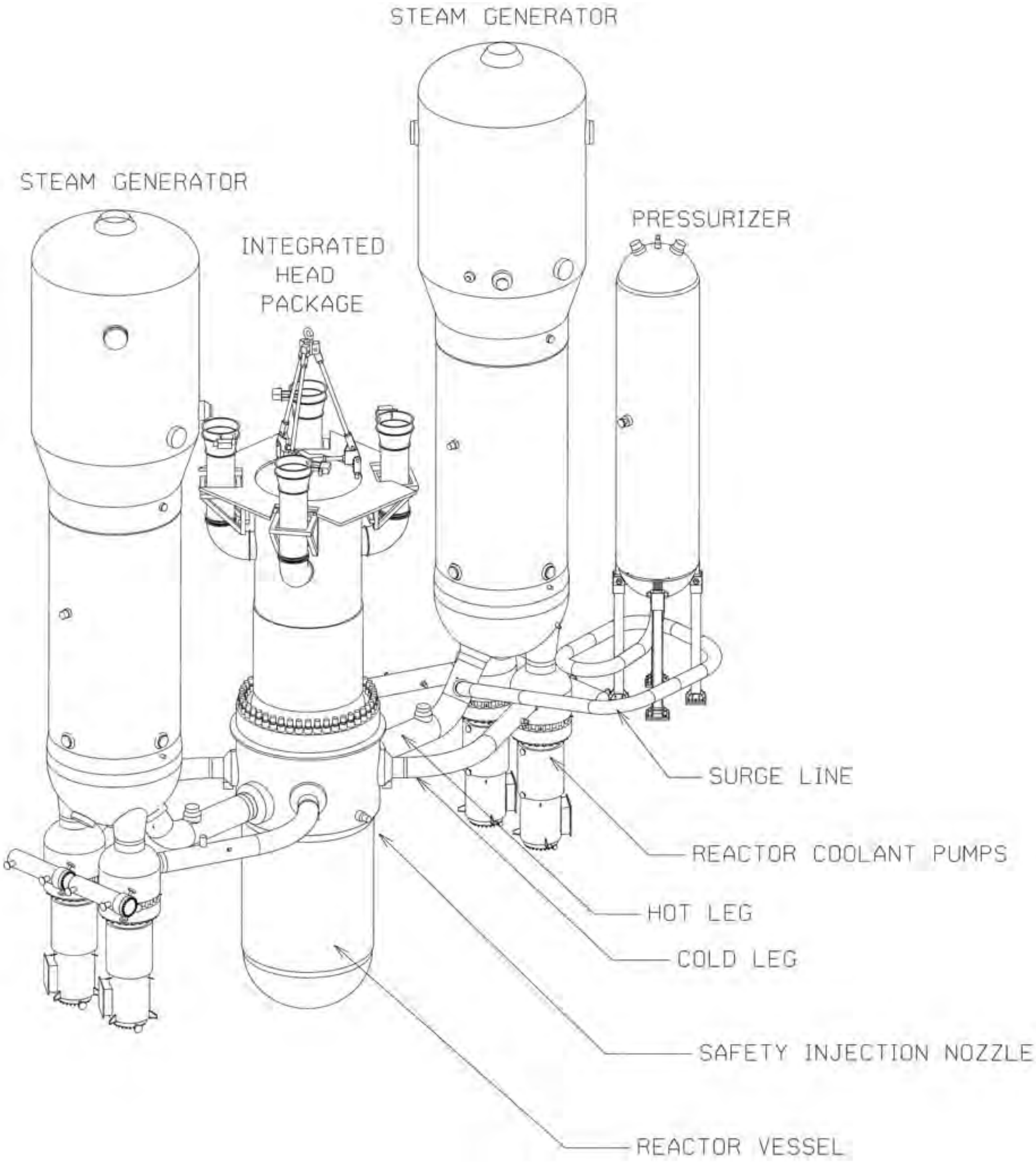

Figure 1: AP1000 Reactor Coolant System

121 Many of the main components used in the AP1000 RCS have been used in previous Westinghouse designed PWRs, with adaptations for the specific design of AP1000.

122 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, including those that operate at above ambient temperatures and pressures. 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 affects but inadvertent 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.

123 The primary coolant chemistry in AP1000, 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_T to alkaline, mitigating these effects. However, too much lithium can adversely affect the fuel cladding by enhancing corrosion rates. Lithium is also a source of 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, Westinghouse proposes to add soluble zinc to the coolant in AP1000 to reduce corrosion rates and the propensity for fuel crud deposits.

124 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 CVS. In addition to the RCS and CVS, other systems on which the primary coolant could have an effect in normal operation include the RNS (Normal Residual Heat Removal System) and PXS (Passive Core Cooling System, which includes the IRWST) and these in turn can affect successful cooling. The largest surface area of any single metal is the nickel based alloy from which the SG heat transfer tubes are constructed. The second largest surface is the zirconium based cladding of the fuel and this barrier retains more than 99% of the radioactivity in the reactor. With due care, modern SG tube alloys and fuel cladding materials can now be produced with such low corrosion rates that the stainless steels which make up much of the remainder of the surface area of the circuit are becoming increasingly important to control.

125 In AP1000, a number of systems are connected to the RCS, which support chemical control, sampling and safety functions of the primary circuit, including:

- The Chemical and Volume Control System (CVS).
- The Primary Sampling System (PSS).
- The Normal Residual Heat Removal System (RNS).
- The Passive Core Cooling System (PXS), which includes the Accumulators and Core Make-up Tanks (CMT).

126 The main system that controls the coolant chemistry are the Chemical and Volume Control System (CVS, Section 4.2.2)) supported by the Primary Sampling System (PSS, Section 4.2.9) and the water make-up systems (DTS and DWS, Section 4.4.2.1.8), all of

which are assessed in this report. While the functions of the safety systems are assessed elsewhere (mainly, Ref. 67) their impacts on plant chemistry are assessed in this report.

127 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 Westinghouse approach and expectations for primary circuit chemistry in AP1000, 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

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

4.2.2 Assessment – Chemical Control

129 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 described earlier (para. 126) the main system which controls the primary coolant chemistry in AP1000 is the CVS, 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 CVS to support refuelling operations (Sections 4.2.8 and 4.3).

130 Assessment of the CVS in AP1000 began 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. 186). The assessment that follows is consistent with this contractor review. During Step 3, I was broadly satisfied with the overall claims and arguments presented by Westinghouse for the AP1000 CVS, noting several features and potential improvements the design offered over existing comparable systems:

- Virtual elimination of the possibility of a CVS leak by-passing containment.
- Simplification, meaning less valves, piping and components.
- Dedicated zinc dosing system.

- Larger capacity ion-exchange.

131 However, it was recognised that the overall simplification was potentially double-edged and questions were raised to assess differences from more conventional CVS designs including:

- How the purification ion-exchange units perform at full system pressure.
- Whether hydrogen addition would be effective and controllable.
- If the offline degasifier made up for the lack of a Volume Control Tank (VCT).
- The impact of the in-containment location (for example for maintenance, filter change etc.).

132 My assessment also covered boron control and material choices for the CVS valves and other components in contact with the coolant. The use of high cobalt alloys (Stellites^{TM}) particularly required clarification and justification.

133 Although Westinghouse claim that the AP1000 has been designed to permit load following, which would put further demands on the CVS, ND is not assessing load following in GDA, as this is out of scope (Section 2.5.7).

4.2.2.1 Chemical and Volume Control System Overview

134 The CVS is described in the PCSR (Ref. 1, Section 6.5.1) and in the System Specification Document (SSD) (Ref. 189). Westinghouse identified several "*safety functions*" for the CVS (in the PCSR) as given below:

- Containment isolation of CVS lines penetrating containment
- Preservation of the RCS pressure boundary including isolation of normal CVS letdown from the RCS
- Isolation of makeup on the steam generator or pressuriser high level signal
- Termination of inadvertent RCS boron dilution

135 Westinghouse also claim in the PCSR (Ref. 1) that there is no safety-related functional requirement to supply coolant in a small LOCA (Loss of Coolant Accident) and, due to the use of a high pressure CVS, they have also placed a higher demand on the CVS isolation valves achieving their stated functions to prevent leakage from the CVS.

136 As for the AP1000 in general, these safety functions were based upon the US definition of "*safety functions*", which is not entirely consistent with UK expectations. Westinghouse revised their safety categorisation and classification methodology throughout Step 4, and the consolidated GDA PCSR submission (March 2011, Ref. 105), identified the following revised safety functions for the CVS, which can be summarised as:

- The four "*safety functions*" identified in para. 134 have been classified as Category A safety functions by Westinghouse.
- Westinghouse has specified the CVS as a "*Class 2 Systems, Structures, and Components Providing Category A Safety Functions*":
  i) The CVS provides defence in depth for small LOCAs and, on this basis, the CVS make-up pumps are designated as Class 2. Westinghouse claim that one make-up pump is capable of maintaining normal RCS inventory following an RCS leak of up to 9.5 mm inside diameter without actuation of the PXS safety injection systems

ii) The CVS provides means of controlling boron concentrations in the primary circuit during normal operation

iii) The CVS provides back-up boration capability to the PXS in fault conditions

137 As described in Section 3.3, I have not assessed the consolidated GDA PCSR (Ref. 105) during Step 4 and hence have not assessed the adequacy or otherwise of these safety functions. This will form part of the cross-cutting GDA Issue **GI-AP1000-CC-02**, described in Section 3.5.

138 As well as providing safety functions the system also performs the following important operational functions, relevant to chemistry:

- Continuous control of the RCS water inventory during all normal plant operating conditions utilising the make-up 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.
- Provide primary coolant chemical control by interfacing with the coolant waste treatment, degasification and boron / water make-up systems.
- Supplying and control of zinc acetate to the coolant.
- 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.
- Supply of treated coolant to other connected systems such as the RNS
- Supply of auxiliary pressuriser spray.

139 The CVS adds the chemicals required to control the primary circuit chemistry and removes impurities such as fission products from tramp uranium or defective fuel rods and activated corrosion products. The CVS is also used for controlling the chemistry, purity and inventory within a number of related auxiliary systems, notably the accumulators, In-containment Refuelling Water Storage Tank (IRWST) and Spent Fuel Pool (SFP).

140 The AP1000 CVS design is shown below (Ref. 189). Note that this schematic includes the late design change to separate and move the zinc and hydrogen addition points (Ref. 192), described later in Section 4.2.2.2.3 (and 4.2.6, 4.2.7) of this assessment report.

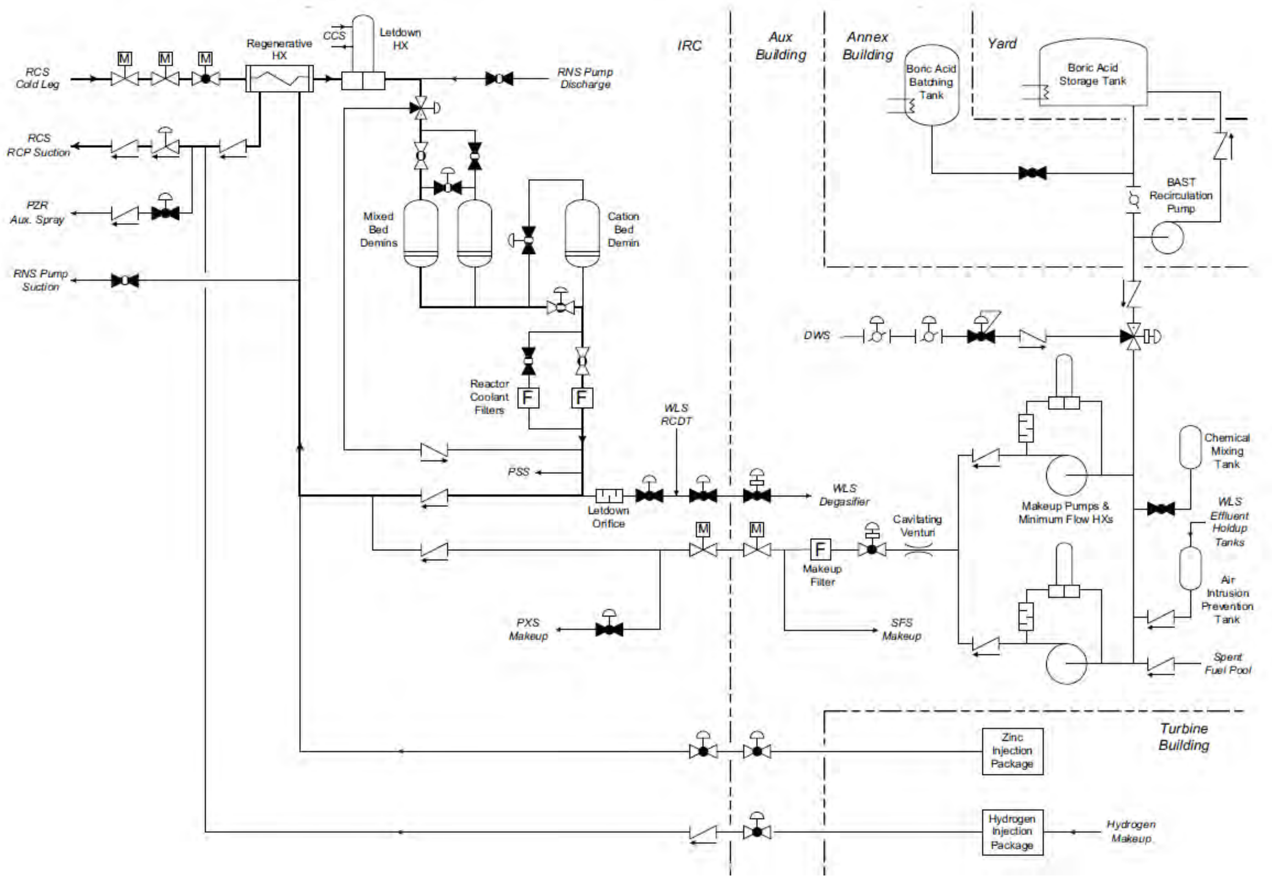

Figure 2:AP1000 Chemical and Volume Control System

141 Coolant flows in and out of the CVS through separate letdown and make-up lines via one regenerative heat-exchanger, a single let-down heat exchanger (cooled by the Component Cooling Water System (CCS)) and a series of isolating valves. The let down line is taken from the RCS cold leg line 1B (shared with the pressuriser spray) and due to the operation at full RCS pressure does not include let-down orifices as in conventional designs. The return line normally returns to the RCP (Reactor Coolant Pump) suction of both pumps on SG 1 but can also provide coolant to the auxiliary pressuriser sprays. There is no requirement for the CVS to provide seal water because the main coolant pumps are canned. The normal treatment path for the coolant is through the purification sub-system, which is a simple system, comprising three ion-exchange beds and two parallel filters. The normal flow path will be through one mixed resin ion-exchange bed and one filter. The first two ion-exchange beds are parallel duplicate mixed beds, while the third cation bed is in series and intended to be used mainly during shutdowns for corrosion product removal. The cation bed demineraliser can also be used intermittently for purification as required during normal power operations. The filters are duplicates providing back-up capability. The CVS in AP1000 has no need for its own pumps in clean-up or letdown modes with the driving flow provided by the pressure difference across the RCPs in normal operations or the RNS pumps during shutdowns. High-pressure pumps are provided for make-up when boric acid, water or other chemicals need to be added to the system. It has a two-way connection through the containment to the waste-treatment system which contains the degasifier.

142 Once purified, additions can be made to the coolant before it is returned to the RCS. Continuous additions will include hydrogen and zinc (acetate). Other additions, such as lithium hydroxide, boric acid, hydrazine or hydrogen peroxide, can be added as required. The design and positions of the zinc and hydrogen injection points, downstream of the regenerative heat exchanger were changed by Westinghouse during my assessment, Ref. 192. In summary, the single hydrogen and zinc injection line was separated to add zinc before and hydrogen after the regenerative heat exchanger. Additional changes were made to the method of hydrogen addition, as discussed later in this report (Sections 4.2.2.2.3 and 4.2.7).

143 The make-up sub-system includes a bulk boric acid storage tank (at around 4,375 mg kg^{-1} boron) and a boric acid batching tank, both of which are heated to prevent freezing and promote dissolution respectively. Connections are provided to the demineralised water supply and a small chemical addition tank where additional chemicals (for example hydrogen peroxide) can be prepared before addition to the RCS. Connections are provided to other served systems, such as the Spent Fuel Pool (SFP). The AP1000 design feature two high pressure make-up pumps which provide around 30 or 40 m^3 hr^{-1} make-up depending upon the number of operating pumps (total flow is limited by a venturi device).

144 The CVS is the interface between the high pressure RCS and the low pressure systems outside containment. The CVS provides a flow path for the continuous letdown and charging of RCS water and maintains the RCS water inventory at the desired level (as specified via the Pressuriser (PZR) level control system) and provides auxiliary spray for PZR cool down. The purification part of 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).

145 The systems and components to which the CVS is connected in AP1000 include the:

- Normal Residual Heat Removal System (RNS).
- Liquid Radwaste System (WLS).
- Spent Fuel Pool Cooling System (SFS) including the Spent Fuel Pool (SFP).
- Demineralised Water Supply (DTS and DWS).
- Emergency coolant reservoirs, such as the accumulators and Core Make-up Tanks (CMT) in the Passive Core Cooling System (PXS).

146 As described in para. 130, there are a number of design differences in the AP1000 CVS from more established designs and the PCSR and other supporting documentation does not provide an adequate explanation for the impact of these choices. The main design choice is the operation of the system at full RCS pressures, although it is notable that a similar system has been in use in VVER (Russian designed PWR) reactors for many decades, and appears to work satisfactorily, although there are many other differences in these reactors so a direct comparison is not possible. As such, I raised RO-AP1000-55.A3 (Ref. 7) asking Westinghouse to justify the novel design of the CVS in AP1000. Westinghouse responses are Refs 188 to 191, with the main response given in Ref. 32.

147 On numerous occasions Westinghouse has stated that AP1000 has been designed to run under EPRI chemistry guidelines (Ref. 15). However, these guidelines were developed for other PWRs. Most PWR operate within similar broad parameters but the new and unusual CVS design for AP1000 means that some levels and recovery actions applicable

to older plant may not apply to AP1000. Throughout Step 4 I consistently asked Westinghouse to state clearly how and whether the standard guidelines apply to AP1000 and to document where any differences may lie. For instance, it is possible to change filters and resins at power in many reactors, but this would not normally be the case for AP1000. In response, Westinghouse provided a *“chemistry manual”* for use by operators during fabrication and commissioning and a supplement to the current version of the EPRI guidelines, Ref. 26, described in Section 4.1 of this report.

148 The following sections assess the main chemical functions provided by the AP1000 CVS in further detail.

4.2.2.2 Chemical Additions

149 This section describes the assessment of the capabilities of the AP1000 CVS to provide the chemical additions necessary to control the primary coolant chemistry. It 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

150 Boron is dissolved in the primary coolant to regulate rates of nuclear reaction at power and as a back-up 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 the 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.

151 The precise concentration of the boron required at any one time is 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 the control rods). Exercising this control is a normal activity for all PWR operators.

152 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 acidity 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 grey rods would permit a stable operating acidity to minimise effects from corrosion. During Step 4 I raised a number of further queries with Westinghouse on boron control in AP1000, particularly related to the capabilities of the CVS to deliver and control boron and the hazards posed by homogeneous boron dilutions, where the boron concentration is slowly diminished rather than rapidly removed or changed (heterogeneous dilution). The latter of these faults is assessed elsewhere (Ref. 67).

153 The make-up subsystem of the CVS, which delivers boron, is described in para 143. This arrangement is standard in many PWRs and AP1000 offers no novel features compared to many operational plants in this regard. The CVS in AP1000 can add boron at a rate sufficient to increase the concentration in the RCS by 350 mg kg^{-1} per hour, which greatly exceeds the reactivity increase caused by xenon decay, such as results from a sudden

reduction in power. Boric acid stocks would be stored outdoors at 4,375 mg kg^{-1}, as part of the make-up sub-system. Westinghouse has provided frost protection and believes trace heating is not required to keep all the boron dissolved in cold weather. The capacity of the Boric Acid Storage Tank (BAST) is sufficient to allow for one shutdown to cold shutdown followed by another shutdown for refuelling at the most limiting time in core life with the most reactive control rod withdrawn.

154 It is anticipated that AP1000 cores will be loaded with burnable poison, the effect of this on boron levels was assessed in my Step 3 report. Dependant upon the choice of burnable poisons used, the peak boron concentration may occur mid-cycle rather than at the beginning requiring a corresponding increase in coordinated lithium hydroxide to maintain the desired pH_T. In itself this is not novel to AP1000 and predicting and anticipating this will be part of the normal activities for operators in their planning for cycle specific chemistry control.

155 An important point to make regarding the design of AP1000 compared to other PWRs is the incorporation of a “*grey rod*” system which consists of control rods with limited neutron absorption capacity. While designed primarily to allow AP1000 to load follow without frequent boration and dilution events, they do allow AP1000 to operate with much reduced make-up requirements during normal power operations. The grey rods contain the equivalent of “*several hundred mg* kg^{-1} *of boron*”. Westinghouse claims that the make-up system will be used to dilute the boron “*once every 2 or 3 weeks*” depending upon the operating strategy.

156 AP1000 features an automatic system to control the boron concentration (and RCS volume) in the primary circuit, based upon measurements made during sampling; the Reactor Make-up Control System (RMCS). This is a C&I system operated via the Plant Control System (PLS). Westinghouse described this system to me in TQ-AP1000-1292 (Ref. 8). In normal operation, to dilute the coolant, two actions are required from the operator:

- Switch control of the make-up from the automatic make-up mode to the dilute mode.
- Start the CVS make-up pumps: One CVS make-up pump is started when the CVS is placed into dilute mode.

157 A number of status indicators are provided to advise the operator that dilution is taking place:

- Indication of the boric acid and blended flow rates.
- CVS make-up pumps status.
- Deviation alarms, if the boric acid or blended flow rates deviate by more than the specified tolerance from the preset values.
- When the reactor is subcritical there are four separate flux indicators.
- And when the reactor is critical there are two flux alarms, a control rod height alarm and a temperature alarm; these can be followed by reactor trips.

158 I raised numerous TQs related to boron control including TQ-AP1000-460 and 620 to 622 (Ref. 8). Westinghouse also presented a useful description of boron faults and the CVS in a technical meeting, subsequently provided in response to TQ-AP1000-1292 (Ref. 8). My assessment of the case presented by Westinghouse, including these responses, is described below. It is notable that the PCSR (Ref. 1) does not contain much discussion on these types of faults, nor does the EDCD (Ref. 22) or supporting documentation. The

draft PCSR chemistry chapter (See also Section 3.2, Ref. 23) contains limited summary information on these aspects, although it does reference other chapters of the consolidated PCSR which I have not assessed. Due to the importance of the control of boron, such faults warrant further prominence in the safety case than I have seen so far, but this may prove to be the case once the entire consolidated PCSR is assessed.

159 Homogeneous dilution events tend to be slow and are challenging because, if unchecked, they allow all of the coolant to reach the lower 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 AP1000. Conversely if detected early they allow the operator a period in which actions can be taken to restore correct control.

160 The UK fault schedule for AP1000 (Ref. 151) considers the relevant boron dilution faults in each mode of operation:

- During refuelling (Mode 6): Administrative controls require specified valves to be locked. Any make-up required during refuelling is made directly from the boric acid tank. I queried what these administrative controls were and was satisfied with the controls that Westinghouse identified in response to TQ-AP1000-671 and TQ-AP1000-1247 (Ref. 8) subject to their satisfactory implementation by the Licensee.

- During Cold Shutdown (Mode 5): At least one main coolant pump is normally running, keeping the coolant continuously mixed. The nuclear instrumentation detects changes in neutron flux and if a large flux increase is detected an alarm is sounded and the valves supplying water and coolant to the DWS and CVS make-up pumps are closed and the make-up pumps are tripped.

- During Safe Shutdown (Mode 4): Similar to above, the source of dilution is automatically isolated on detection of a neutron flux increase. No operator action is required.

- During Hot Standby (Mode 3): Similar to above, the source of dilution is automatically isolated on detection of a neutron flux increase. Westinghouse have identified in the AP1000 “*Technical Specifications*” that at least one main coolant pump is in operation in this mode, keeping the coolant well mixed.

- During Start-up (Mode 2): In this mode the plant is under manual control. In this mode the operator receives a signal giving permission to override a reactor trip. If a dilution takes place, a trip follows too rapidly for the operator to override it. The reactor trip causes the automatic isolation of the DWS thereby terminating the dilution. In addition the CVS make-up is automatically realigned to suction from the boric acid storage tank. After such a trip, the dilution would have to continue for approximately 283 minutes before the available shutdown margin was overcome.

- During Full Power Operation (Mode 1): At power the reactor can be either under manual or automatic control. If under manual control and the operator takes no action to terminate the dilution, it will cause the power and temperature to rise and the reactor to trip on high temperature. The trip will isolate the DWS and the CVS make-up is automatically realigned, as in Mode 2. In automatic rod control, the pressuriser level controller limits the dilution flow rate to the maximum letdown rate. If a dilution rate in excess of the letdown rate is present the pressuriser level controller throttles charging flow down to match the letdown rate. The increase in power from any dilution causes the rods to be inserted in an attempt to compensate. This prompts at least three alarms to the operator, two on rod height plus one flux alarm.

161 As can be seen from the above, much of the protection from boron dilution relies on isolation of potential dilution sources to the CVS. The DWS isolation valves will be manually locked closed during refuelling, TQ-AP1000-621 (Ref. 8), and they are designed to fail closed in other modes of operation. The motor-operated containment isolation valves on the make-up line fail "*as-is*", TQ-AP1000-620 (Ref. 8), and will only be open infrequently. I consider this is normal, since the make-up line also has several check valves in series with it.

162 I raised a number of queries about the range and choice of values for maximum CVS flow and flux-doubling times in TQ-AP1000-622 (Ref. 8), since there were apparent inconsistencies between various Westinghouse documents. Various maximum (run-out) CVS flow rates had been quoted by Westinghouse as the design of the CVS had evolved through 2009. This value is now fixed at 39.75 m^3 hr^{-1} and safety analyses dated since then should reflect the new value. Flux multipliers over 50 minutes of 3.0 and 2.2 have been quoted by Westinghouse; the difference is that one includes the measurement uncertainty. As the AP1000 documentation for dilution protection is still being consolidated, it needs to be consistent with the latest design and safety case. I consider the completion of this to be an Assessment Finding, **AF-AP1000-RC-05**.

163 I am content that Westinghouse has considered significant equipment faults that might lead to a boron dilution, including leakage from the letdown heat-exchanger, ion-exchange faults and effects of starting and stopping the main coolant pumps. However, Westinghouse has not considered several minor CVS feeds which are not automatically isolated. These include the zinc addition line and the water supply to the chemical addition and boric acid batching tanks. Many of these are low pressure, so are only relevant in refuelling. These should be covered by the operating documentation, and as part of Assessment Finding, **AF-AP1000-RC-01**.

164 As may be seen, there are many alarms and the inherent slow progression of dilution even at start of cycle, so the operator has over 5 hours from the rod insertion low-low limit until the shutdown margin is lost according to the Westinghouse analysis (Ref. 23). At the end of cycle, the time is much longer because the boron concentration is lower. Overall, I am content that the design of AP1000 is not unusually susceptible to homogenous dilution faults.

165 My assessment gave me confidence that homogeneous dilution from the CVS would not challenge the reactor and that the anti-dilution system outside of the CVS would protect against homogeneous dilutions which might originate within the CVS. Manual controls and physical security of boron stocks outside the building can be reviewed as part of normal regulation.

166 I note that the AP1000 does not include a boron monitor or similar device to indicate to the operators the actual coolant boron concentration. I consider this further under the Primary Sampling System, Section 4.2.9.

4.2.2.2.2 Lithium

167 Most PWR have safety limits and action levels associated with the primary coolant acidity. 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_T. As the boron concentration changes through the cycle, so must the lithium hydroxide concentration. Similarly lithium is produced during a cycle from the boron neutron absorption reaction. The normal maximum lithium level specified by EPRI is [redacted] mg kg^{-1} (Ref. 15). Westinghouse have provided a supplement to the EPRI guidelines (Ref. 26) confirming this value and

allowing some flexibility to go above this for a short time if required, as necessary at the start of cycle for xenon equilibrium.

168 Westinghouse has specified depleted lithium for use in AP1000 (PCSR, Ref. 1, Section 6.5.1). Since the ^{6}Li in natural lithium contributes to the production of tritium, Westinghouse is considering use of lithium depleted in ^{6}Li to at least 99.9 atomic % of ^{7}Li. I consider this to be a beneficial proposition and this is discussed further in Section 4.2.3.3.2.

169 The chemical addition tank is used to introduce the ^{7}LiOH solution to the primary coolant via the suction of the make-up pumps. The solution is poured into the chemical mixing tank and is then flushed to the suction manifold of the make-up pumps with demineralised water. A flow orifice is provided on the demineralised water inlet pipe to allow chemicals to be flushed into the RCS at acceptable concentrations. If the concentration exceeds the proper value, as it may during the early stages of core life when ^{7}Li is produced in the core at a relatively high rate (as the boron level is higher), the cation ion-exchange bed demineraliser is used to lower the ^{7}Li concentration. Since the build up of lithium is slow, the cation bed demineraliser is used only intermittently. When letdown is being diverted to the Liquid Radwaste System (WLS), the purification flow is routed through the cation bed demineraliser for removal of as much ^{7}Li and caesium as possible.

170 This is a simple and standard arrangement used in many PWRs. Commissioning tests for this system have yet to be specified, TQ-AP1000-459 (Ref. 8).

4.2.2.2.3 Hydrogen

171 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.

172 In most existing PWRs, the hydrogen is added through the VCT, where the cover gas above the coolant is used to control the concentration of dissolved hydrogen in the coolant according to Henry’s law. This is a simple and reliable system, but requires a large volume of hydrogen and produces large amounts of off-gas which must be treated by the Gaseous Radwaste Systems (WGS). As the AP1000 CVS is high pressure and does not include a VCT, Westinghouse opted for an in-line hydrogen addition system, injecting hydrogen directly into the pipework of the CVS with the intention of dissolving it quickly in the coolant flowing past and certainly before any un-dissolved gas reaches safety equipment. This is significantly safer for a high-pressure CVS, avoiding the use of a high-pressure hydrogen gas-filled vessel.

173 The design at the start of Step 4 was one whereby the hydrogen was added intermittently along with the zinc acetate solution. ND was provided with details, early in 2010, of the hydrogen addition system in Refs 189, 190 and 22 and TQ-AP1000-531 and 711 (Ref. 8) and these were also assessed by my technical support contractors (Refs 186 and 198). The hydrogen will be supplied from the Plant Gas System (PGS), but controlled independently in the CVS. My view was that the hydrogen levels may not be sufficiently well controlled by the Westinghouse design, a view shared by my TSC contractors, and I expressed my concerns to Westinghouse at our meeting on 6 May 2010. In response Westinghouse confirmed that a number of changes to the hydrogen (and zinc injection) system would be made to address my concerns and other identified deficiencies later in 2010. The changes were intended to prevent excessive fluctuation of hydrogen levels in the core and make various improvements to the zinc injection system.

174 Westinghouse supplemental guidelines for the AP1000 (Ref. 26) recognise that hydrogenation without a VCT may cause greater fluctuation in hydrogen levels. Westinghouse therefore recommends an increased sampling frequency [redacted] until experience of the design has been gained. It is UK practice to sample hydrogen continuously but this is difficult in the current design of AP1000. These points are taken up in Section 4.2.9 of this report, on sampling.

175 The Design Change Proposal (DCP) for the new hydrogenation and zinc injection system, Ref. 192, was received by ND in November 2010. Calculations summarised in the DCP confirmed that the original design could not adequately control the flow and other problems with two-phase flow. [redacted]. It (with the other changes for zinc) was given the highest UK Level 1 categorisation by Westinghouse following the ND categorisation scheme operating in GDA for UK AP1000. The change was intended to be standard for all AP1000 plant, worldwide. In summary, the single hydrogen and zinc injection line was separated to add zinc before and hydrogen after the regenerative heat exchanger.

176 The DCP (Ref. 192) presents reasons for the change and clearly identifies its impact in terms of fabrication. Analyses are presented demonstrating the problems with the old design but no assessment was presented for the new design and I advised Westinghouse of my reservations at our level 3 meeting on 11 Nov 2010.

177 Further information for the new design was requested in TQ-AP1000-1184 and 1230 (Ref. 8), the latter asking specifically for evidence that the proposed system would work as intended. Westinghouse responded to TQ-AP1000-1184 on 31 December 2010 and TQ-AP1000-1230 on 18 March 2011. Neither response fully justified the design of the revised hydrogen injection system, nor provided the expected level of evidence to support the approach taken. For example, TQ-AP1000-1230 (Ref. 8) requested an analysis of the potential faults with the revised design; the response contains a (brief) list of faults but no analysis to support the overall conclusion that they are controlled. As an important chemical parameter, often found within the highest level of limits and conditions, I expect a higher degree of substantiation and supporting evidence than has been provided by Westinghouse to date.

178 I concluded from Ref. 192 and the responses to TQ-AP1000-1184 and 1230 (Ref. 8) that insufficient evidence had been provided that the new system would actually work as required for a Category 1 safety change.

179 Due to the timing of the design changes and the on-going CVS development by Westinghouse during Step 4, the safety case and evidence for the safety for these are not yet complete and a number of concerns remain. Specifically the response to TQ-AP1000-1184 and 1230 (Ref. 8) contain arguments but incomplete evidence to support the AP1000 hydrogen dosing system design. Westinghouse themselves state in the response to TQ-AP1000-1230; *"There is no known commercial operational experience for nuclear power; reliance on direct injection for the AP1000® Plant is a first of a kind approach."*

180 Overall while the design changes can be considered improvements, to date Westinghouse has not presented a consistent and structured safety case containing sufficient evidence to support the AP1000 hydrogen addition method, specifically:

- Evidence to support the addition system (e.g. testing, use in other applications, calculations etc.).
- Impact of anticipated transient conditions (e.g. during start-up periods, RCS letdown/make-up etc.).
- Fault analysis and controls.

181 Due to the importance of this parameter and control systems this will be required before acceptance of the design can be considered and for this reason I consider this to be a GDA Issue, **GI-AP1000-RC-03**.

182 Hydrogen is used in all PWRs and some of the hazards associated with the production and use of hydrogen are assessed in Sections 4.2.2.3.3, 4.2.8.1.5 and Section 4.2.11 of this report.

4.2.2.2.4 Zinc

183 Westinghouse proposes to add zinc to the primary coolant of AP1000, in the form of zinc acetate solution. The effects of zinc addition are assessed further in Section 4.2.6.

184 As with hydrogen addition, the zinc addition system was subject to a design change during Step 4 (Ref. 192), however unlike the hydrogen addition system this change did not alter the method by which the additions are made, which remain as a low flow addition to the CVS after the purification ion-exchange beds. The DCP provides a useful summary of the main reasons for the design change, including calculations which show the problems with the original arrangement. The DCP did alter the location of addition to a cooler part of the CVS due to concerns regarding precipitation and solubility of the zinc solution (which has a negative temperature solubility relationship).

185 The zinc addition system consists of a conical bottom tank, a high head positive displacement pump and the 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 CVS pipework where it mixes (but not mechanically (i.e. via a mixing device)) with the CVS flow. This is a simple system, similar to many that have been retro-fitted to operating plants. The zinc addition equipment is located away from the CVS, in the Turbine building. The addition line features check and control valves to stop inadvertent reverse transfer of RCS liquid to the zinc addition equipment.

186 I am content that the zinc addition system in AP1000 is adequate. The addition of an engineered means of addition is a positive step.

4.2.2.3 Chemical Purification

187 The following section describes the assessment of the AP1000 CVS chemical purification systems. A large part of the Regulatory Observation RO-AP1000-55.A3 (Ref. 7) dealt with the effectiveness of purification in the novel CVS, see Ref. 32. In addition to requesting evidence for the performance of the purification processes under normal (pressurised) operating conditions, particular attention was given to the question of whether the ion exchange resin or the filter cartridges might need replacement or changing during the fuel cycle and might require person access to the containment at power.

188 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 CVS purification systems is at its highest, is described in Section 4.2.11.

4.2.2.3.1 Ion Exchange

189 The CVS in AP1000 has been designed with three identical ion-exchange vessels; two intended for mixed beds and one for use as a cation exchanger. They are each 2 m^3 volume, with 1.4 m^3 of resin, and also act as "*pre-filters*" since the beds precede the filters in AP1000. Westinghouse expects that the mixed bed ion exchange units will contain resins to remove ionic corrosion products and certain ionic fission products. One mixed bed unit is in service with a second available as back-up. The precise operating strategy for the resin beds will be developed by the Licensee, however Westinghouse expect that the cation resin in both mixed beds will be in the ^{7}Li form to avoid de-lithiation of the coolant. The anion resin will initially be loaded in the hydroxide form and while the operating bed will rapidly saturate with boron the back-up bed is intended to be used to de-borate at the end of cycle and could be used to reduce the amount of liquid radwaste associated with boron dilution. The third unit is a cation bed to remove caesium in the event of fuel clad defects and to control lithium concentration during power operations. This third cation bed will also be used during shutdowns to increase the purification capacity for corrosion products. This resin will initially be in the hydrogen form. All 3 beds have been sized for 24 months operation, providing capacity for at least 1 full fuel cycle.

190 In reality the CVS of any PWR is not particularly efficient at clean-up, and is only really intended to maintain low levels which have been achieved through rigorous purity controls and minimisation of adventitious impurities; gross impurity would have to be removed by letdown and make-up. I note that ion-exchange will not remove fluoride or silica and high-purity water make-up is still required, as in any PWR. The main radioactivity that can be efficiently removed is particulate activity, via filtration. The mixed bed can trap 90% of passing radioiodine and the cation bed is even less efficient for ^{137}Cs. Combined with the low letdown rate from the primary circuit, this means that radiological clean-up will be slow and this is typical of PWRs.

191 Because of the novel design of the AP1000 CVS, I queried the sensitivity of these beds to pressure fluctuations, poor temperature control and channelling in RO-AP1000-55.A3 (Ref. 7). The response provides reasonable arguments to support the AP1000 design, as summarised below.

192 There should be no technical reason to suspect the high pressure would adversely affect the AP1000 ion exchange beds directly, despite operating at 15.4 MPa compared to around 1 MPa in low pressure CVS applications. Boiling Water Reactor (BWR) condensate polishers operate at up to 6 MPa without problems. VVER reactors (V213 units) operate with two primary circuit purification loops filled with ion exchange resins and operate at full RCS pressure, 12 MPa, driven by the RCP pressure differential at flows of around 25 m^3 hr^{-1} per loop (Ref. 132). This lends confidence that there is no fundamental issue with the operation of such a system in AP1000, from a chemistry perspective.

193 Such systems are however sensitive to pressure differentials across the bed, with moderate drops leading to resin compression and ultimately damage. Due to the design of AP1000, the pressure difference across the CVS is low and operating instructions for AP1000, Ref. 214, additionally specify a low CVS flowrate. In the CVS SSD (Ref. 189) Westinghouse indicate that there is a possibility of fouling of the resin beds leading to

reduced CVS flow and increased pressure drop. In the response to RO-AP1000-55.A3 (Ref. 32) Westinghouse claim that calculations with removal of 100% of the allowable suspended solids concentration (10 μg kg^{-1}) would not result in reaching the pressure drop limit of 0.34 MPa in an 18 month fuel cycle, although they do not state the impact on CVS flow. In such instances the back-up bed would be put into service, if available. The decision to change before this "*limit*" will be complex and based on many factors, both technical and economic.

194 The response to RO-AP1000-55.A3 (Ref. 32) also considers operational pressure transients, such as during start-up and shutdown, concluding no negative impact on the AP1000 CVS performance. I was content with these responses. Therefore I do not expect pressure transients to disrupt the beds, which were described by my TSC (Ref. 186) as "*reacting like wet sand*".

195 I also queried if flow channelling could occur in the AP1000 design. Under these circumstances some of the flow through the bed would preferentially pass through a "*path of least resistance*" without contacting the ion exchange resins fully, resulting in by-passing and reduced performance. I am content that AP1000 should not be more prone to this feature than other lower pressure systems.

196 Excessive low temperature can remove additional boron, but not exceptionally so. High temperatures can physically damage some resins. The Westinghouse responses with RO-AP1000-55.A3 (Ref. 32) and TQ-AP1000-457 (Ref. 8) described the temperature cut-outs to prevent excessively high or low temperature coolant reaching the resins in AP1000. The letdown flow to the CVS is cooled, partly because the mixed bed ion exchange resins are sensitive to temperatures above 60°C, TQ-AP1000-457 (Ref. 8). Westinghouse considered temperature transients in the response to RO-AP1000-55.A3 (Ref. 32), but concentrated on reducing rather than increasing the temperature. Operating procedures associated with controlling the resin temperature are yet to be written.

197 One consequence of thermal and some other types of resin damage is to increase the volume of solid radwaste, per Becquerel. AP1000 will operate at 54 °C compared to 45 °C in current operating plants, and Westinghouse themselves agree that this will result in an additional radwaste of up to 10% over 18 months. However, the total system capacity is over twice that in many current operating plants when calculated for each hot RCS mass, and the total volumes involved are small, hence the additional losses should not be important.

198 The higher temperature does reduce the margin available before more significant damage to the resins could occur. Whilst not expected, significant resin damage would result in a build-up of sulphates and other damaging impurities in the rest of the circuit.

199 There is some capacity in the system to operate at lower temperatures and the Licensee may consider operating at lower temperatures or consider one of the more robust types of resin. It is recommended that the Licensee reviews these aspects of the CVS in AP1000. This is part of Assessment Finding **AF-AP1000-RC-26**, described in Section 4.2.11.

200 The protection of the beds from peroxides and hydrazine is covered in Section 4.2.11.

201 I had a number of questions about the capacity of the beds in stretch-out operation, TQ-AP1000-772 (Ref. 8). Stretch-out is an extended period of reduced power operation sometimes at the end of a cycle, undertaken to improve economic performance of some reactors. This type of operation would test the capacity of resin beds and perhaps demand operator intervention within containment at power. My questions included:

- The capacity of the beds, particularly if zinc was being added.
- The requirement for deboration by the resin.

202 Westinghouse replied that zinc addition, at the levels they specify ([redacted] μg kg^{-1}), would consume 8% of the resin capacity over a normal cycle. Operation at much higher levels, up to 60 μg kg^{-1} would consume 50%. A single bed could just cope with stretch-out provided there had been no other operational disturbance. The back-up bed is capable of adjusting boron by up to 70 mg kg^{-1} and therefore is just sufficient for end of cycle deboration. A small concentration of zinc can have such a large effect because it is being added all the time. Additional unplanned shutdown and restarts at the end of cycle or in stretch-out would generate a lot of waste coolant. However, the alternative would be to oversize the beds, which might lead to creating more radwaste in the longer term so can be considered a reasonable approach.

203 From an operational perspective, one of the most important features of the AP1000 CVS design is the location of the ion-exchange beds within containment. As AP1000 is designed to allow containment entry at power only under exceptional circumstances, this immediately limits the access to manage or change the ion exchange beds should this be required at power; for example due to blockage of failure. In RO-AP1000-55.A3 (Ref. 32), Westinghouse argues that the duplicate operational beds and filters provide provisions which should eliminate a single purification component failure leading to containment entry. As described above, the capacity of the ion-exchange beds appears to have sufficient margin over that estimated for a full 18 month cycle, barring major operational transients.

204 If an operator did need to change a demineraliser at power, the doses would exceed 1 mSv shared between 3 operators, higher than doses in a normal shutdown for the same operation; TQ-AP1000-458 (Ref. 8). The response to RO-AP1000-55.A3 (Ref. 32) states that "*The at-power changeout is estimated to produce an operator exposure of 0.34 mSv, while the same operation during shutdown is estimated to yield an operator exposure of 0.19 mSv.*" No further details are provided of these estimates, although clearly different assumptions are used for the two estimates and an at-power change is much more dose intensive. As this is not a Reactor Chemistry related concern I shared this information with my Radiation Protection assessment colleague. This is related to Assessment Finding **AF-AP1000-RC-26**, described in Section 4.2.11.5, but is less relevant to normal power operations where the chance of an at-power change appears to be small, but not zero.

205 In order to change the resins, there is a demineralised water supply provided to flush the resin beds, and I raised two TQs covering faults this might initiate. TQ-AP1000-790 (Ref. 8) concerned isolation of the DWS supply to prevent boron dilution, and is discussed in Section 4.2.2.2.1; the Westinghouse response to this specified manual lock-out controls. TQ-AP1000-1257 (Ref. 8) covered controls that prevent the demineralised water flushing resin back into the primary circuit, as happened at Fessenheim in 2004 (Ref. 133). I raised TQ-AP1000-1256 (Ref. 8) to cover reverse flow through the beds under certain accident conditions. I was content with the responses to these TQs provided by Westinghouse, which suggested such faults were controlled.

206 Overall, Westinghouse proposals for the ion-exchange equipment in AP1000 appear reasonable. The beds seem well-sized and Westinghouse has begun to think about the types of operations needed, however due to the in-containment design the Licensee will have to fully define the procedures and controls on the ion-exchange sub-system.

4.2.2.3.2 Filtration

207 In RO-AP1000-55.A3 (Ref. 7) I asked Westinghouse to justify the filtration provisions in AP1000, particularly the performance and the lack of filtration before the ion-exchange beds, as is common in many PWRs.

208 In the response (Ref. 32) Westinghouse describes the filtration arrangements. The filters are designed to retain resin particles that leave the demineraliser beds and other particulate matter down to 0.1 μm, with Westinghouse recommending a filter mesh size of 25 μm initially with the option to decrease this upon gaining operational experience. Higher flow rates will be experienced with the CVS under RNS flow, during a shutdown. As for the ion-exchange vessels, Westinghouse claim that the filters are sized based on OEF to achieve a 24 month operating period. Duplicate filters are provided. As noted in Section 4.2.2.3.1, Westinghouse claim the ion exchange beds as the main source of particulate removal in AP1000.

209 As for the ion-exchange resins, the in-containment location make filter changes difficult. I asked Westinghouse whether the filter capacity would be sufficient to avoid the need for operator access to the reactor at power. The response (Ref. 32) summarises several references which include OEF surveys and concludes that any pre-filtration capability before ion-exchange only serves to marginally increase the bed operating life, potentially allowing multi-cycle operation. However no such benefits have been experienced as the ion-exchange resin is routinely charged every cycle due to other factors such as operating capacity. In the TQ-AP1000-458 response (Ref. 8) Westinghouse replied that operators could specify coarse filters during the early operation of AP1000 to avoid the need for change at power. I am satisfied that the filtration capacity of the demineraliser beds should be sufficient to make this unnecessary, although Westinghouse state in the RO-AP1000-55.A3 response (Ref. 8) that “*an at-power filter changeout would result in a doseage increase of 100mSv as compared to filter changeout at shutdown*”; similarly I have shared this with the Radiation Protection inspector. Commissioning tests have been specified by Westinghouse to ensure filter performance is as expected, TQ-AP1000-459 (Ref. 8). Westinghouse does state that filters may need to be changed during shutdowns, depending upon the cycle history and usage; see Section 4.2.11.

210 Some reactors use filters containing glass-fibre. I was encouraged that metallic filters were specified for AP1000, TQ-AP1000-671 (Ref. 8). This removes one potential source of contamination by silica. Excessive silica in primary coolant would potentially deposit on fuel, increasing the surface temperature and hence failure probability by a small amount.

211 Overall, I was content with the arguments presented by Westinghouse for the CVS filtration capabilities, from a chemistry perspective.

4.2.2.3.3 Degasification

212 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.

213 There are a number of design features which mean that AP1000 may be more prone to gas accumulation in the RCS:

- In other PWR designs which have a low-pressure CVS, the VCT acts as a break in the circuit and some of the gases which accumulate in the coolant are removed by the headspace purge in this vessel. AP1000 has no VCT.
- Additionally some gases accumulate within the pressuriser vapour phase. At the start of Step 4, the AP1000 did not have a system to allow purging of the pressuriser vapour.
- The treatment systems for the demineralised water supply, as described in Section 4.4.2.1.8, utilise Catalytic Oxygen Reduction Systems (CORS) to remove dissolved oxygen. These will not remove other dissolved gases (for example nitrogen) and hence more may be transferred to the primary coolant of AP1000 compared to other PWRs which use thermal or mechanical degasification.
- The Reactor Coolant Drain Tank (RCDT) in the Liquid Radwaste System (WLS) is maintained under a nitrogen atmosphere, potentially affecting dissolved nitrogen concentrations in the stored coolant. However the coolant in this tank is not expected to be routinely returned to the RCS.

214 During a shutdown it is necessary to remove the hydrogen from the coolant in order to prevent a flammable hazard, See Section 4.2.11 for an assessment of the start-up and shutdown chemistry of AP1000. In order to do this some of the primary coolant can be redirected to the Waste Liquid System (WLS) degasifier for treatment, before return to the RCS. AP1000 will also use this device during normal operations, as necessary and when available. The WLS system is assessed in Section 4.5.1.2. This offers the capability to remove gases from the circulating coolant.

215 During Step 4, partly in response to our queries, Westinghouse proposed a design change (Ref. 30) to include a pressuriser vent line into AP1000. This modification allows the operator to direct a low flow purge from the pressuriser to the Reactor Coolant Drain Tank (RCDT), where it is subsequently treated via the Gaseous Radwaste System (WGS), see Section 4.5.1.1. I consider this to be an important modification to the design from a reactor chemistry perspective and was satisfied that Westinghouse had implemented a solution to remove gases from the pressuriser, should this be necessary. I note however, that the AP1000 does not have a means of sampling the pressuriser vapour phase directly, although indirect indications of non-condensable gas accumulation in the pressuriser may be available. Similarly the ability to monitor the coolant for dissolved gases is discussed further in Section 4.2.9.

216 In the response (Ref. 32) to RO-AP1000-55.A3 (Ref. 7) Westinghouse describe consideration given to gas accumulation in the primary circuit of AP1000, including provisions for vent and drain lines and use of OEF. Section 1.9 of the EDCD (Ref. 22) contains information related to US NRC requirements, including gas intrusions.

217 The response to TQ-AP1000-1229 (Ref. 8) provides a useful summary of the evaluations and consideration given to gas accumulation in the primary circuit of AP1000. The principal mitigation is the use of high point vents which feature instrumentation and alarms (void and temperature) to alert to operator to gas accumulation which can be rectified by manual venting (to the containment). While clearly an undesirable option, Westinghouse do not consider such features will be necessary. The majority of the response does consider gross gas intrusions; however these are not within the Reactor Chemistry assessment remit. What was not apparent in the documentation supplied by Westinghouse was evidence that consideration had been given to the design specifics of AP1000 (see the bulleted list above, for example) in these evaluations. As such I cannot conclude that adequate consideration has been given to these effects, especially for the

potential effects of the slower and less detectable accumulation of gases within the coolant. I do not believe these effects will have immediate or fast acting safety concerns, but will need to be considered and monitored at least until operational experience is gained. This is part of Assessment Finding **AF-AP1000-RC-03**.

218 Overall, Westinghouse has improved the degasification capabilities of AP1000 and in doing so have addressed a number of concerns I had in this area. While the systems for degasification appear reasonable it is less clear that any assessment of the specific AP1000 features has been undertaken and this will need to be resolved by a future Licensee to ensure that the plant operating procedures and limits and conditions are appropriate.

4.2.2.4 Summary

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

- The AP1000 CVS design is different from most PWRs in a number of ways. Westinghouse has adequately explained the rationale for these differences, many of which could offer potential advantages for Reactor Chemistry, but assessments of the consequences of these differences did not appear in the PCSR, for instance:
    i) It will not be possible to hold a fresh resin bed in reserve for shutdown use, if the same bed has to be used for deboration and cannot routinely be changed.
    ii) The Fault Schedule did not list all possible water injection lines.
    iii) The beds and filters operate at full system pressure.
- The AP1000 CVS has been demonstrated to be adequate to control the boron concentration in the RCS during a normal fuel cycle. Homogeneous dilution from the CVS would not challenge the reactor and that the anti-dilution system outside of the CVS would protect against homogeneous dilutions which might originate within the CVS. Much of the Boron make-up system is ‘standard’ to PWRs and may be used less frequently in AP1000 due to the grey rod system.
- The systems for the addition of lithium hydroxide and zinc are reasonable and should provide adequate control. The hydrogen addition system is novel and was subject to a design change late in GDA. Westinghouse has not yet demonstrated that this revised design is adequate and I have raised this as a GDA Issue, **GI-AP1000-RC-03**.
- The purification systems in AP1000 have been demonstrated to be adequate, despite operations at high pressures. The ion-exchange system should be the principal export route for radiocobalt to solid radwaste from AP1000. The in-containment location of these systems has highlighted concerns regarding ORE should replacement or maintenance of these systems be required with the reactor at power. Westinghouse argue that this is unlikely due to redundancy and capacity in the design and I am content that such activities should not be routine.
- Westinghouse has improved the degasification facilities in AP1000, by the addition of a pressuriser vent modification. This, in conjunction with the existing design features, should reduce the likelihood of gas accumulation in AP1000.
- The definition of Examination, Maintenance, Inspection and Testing required for new components, with particular attention given to their early operation if OEF in this application is not available, would be normal business for the Licensee.

220 When taken as a collective answer, the TQ responses under this area add significantly to the AP1000 safety case for CVS. With the exception of the GDA Issue on the design of the hydrogen addition system, I judge that the claims, arguments and evidence as presented in this area are reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.2.2.5 Assessment Findings

221 Based upon the assessment of chemistry control in AP1000 described in Section 4.2.2 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, by the Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-05*** *– The licensee shall update the safety case to include a more detailed consideration of homogeneous boron dilution events, including sources, mitigation and consequences and review operating procedures for dilution control in the Chemical and Volume Control System (CVS). 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.*

4.2.2.6 GDA Issues

222 Based upon the assessment of chemistry control in AP1000 described in Section 4.2.2 above, I have identified the following GDA Issue which requires resolution :

> ***GI-AP1000-RC-03*** *– Hydrogen Dosing System - Demonstrate that the hydrogen dosing system in AP1000 has the capacity and capability to provide suitable control over the primary coolant hydrogen concentration during all operating modes and potential faults.*

4.2.3 Assessment – Materials, Chemistry and Radioactivity

223 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, Ref. 31, and the major source of this is fuel crud. Unlike many other source terms (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.

224 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 corrosion and 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 nickel or cobalt released either via general corrosion or wear of the RCS materials in contact with the coolant. The table in Section 4.2.3.2 summarizes the main nuclear transformations. 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.

225 Historically there has been a great variation in levels of radioactivity generated by different PWRs. The figures below illustrate average annual worker doses (in man.Sv) per PWR in different countries (Ref. 232). While it is difficult to directly compare results of this nature, due to factors such as plant design, numbers of plants or cycle history, these graphs do exemplify the general trend towards lower ORE seen in recent years for PWRs.

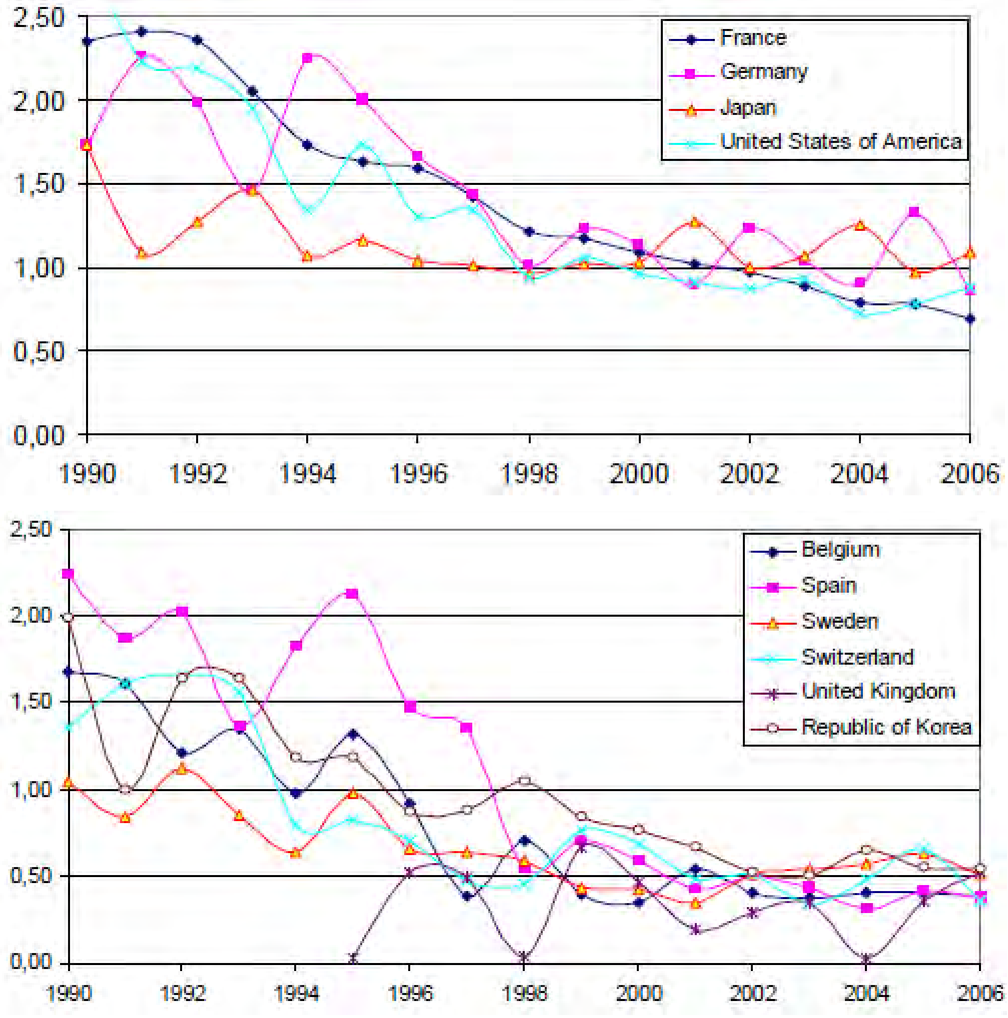

Figure 3: Evolution of Average PWR Collective Radiation Exposure by Country

226 One of the main reasons for this 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 minimize 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_T, levels of zinc and oxygen
- Using the CVS clean-up system to try and remove as many of the precursors and radioactive products as possible
- Maintain high purity in make-up sources and avoid adventitious impurities

227 The influence of material choices in AP1000 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 AP1000, based upon both the chemistry and material choices. The following sections describe my assessment of the effects of primary circuit chemistry and materials on radioactivity in AP1000. The assessment of zinc addition, including the potential for radioactive source term reduction, is described in Section 4.2.6.

4.2.3.1 Overview

228 Westinghouse base their analysis of the normal levels of radioactivity in AP1000 (Ref. 31) on the American National Standard Institute method (ANSI 18.1) in Ref. 158. This takes account of the rating of the reactor and its principal dimensions and is primarily used for assessments of long-term radwaste production. This method does not take account of detailed CVS performance or the materials of the reactor, so Westinghouse extended their assessment to include shorter lived nuclides from corrosion, such as ^{60}Co, based on average performance from about 70 US reactors. Whilst reasonable, this approach did not take account of certain AP1000 specifics, such as the proportion of Stellite^{TM} in the reactor and the boiling rate of the core. Radioactivity can be sensitive to a number of such factors, meaning that such estimations may or may not be pessimistic for AP1000 (Ref. 162).

229 Information on the basis for the AP1000 radiation analysis is provided in the following documents:

- Information on source terms for normal and post accident conditions: AP1000 Radiation Analysis Design Manual (Ref. 31) (APP-GW-N1-021).
- Expected corrosion product sources: AP1000 Corrosion Product Sources (Ref. 135) (APP-RCS-N2C-002).
- Determination of the expected primary coolant activities: AP1000 Normal Source Terms (Ref. 170) (APP-SSAR-GSC-118).
- AP1000 Expected Production and Release Rates for ^{14}C (APP-WLS-M3C-056) (Ref. 179).

230 I also raised RO-AP1000-57 (Ref. 7) with two actions requesting Westinghouse to present evidence that radioactivity in AP1000 would be reduced So Far As Is Reasonably Practicable (SFAIRP), based on the materials of construction in the reactor (Action 1) and on the chemistry (Action 2). This was supplemented by TQ-AP1000-710 (Ref. 8), requesting a full material schedule, amongst other TQs (455, 530, 671, 979 and 980 (Ref. 8)). I also commissioned TSC support to review the materials of construction of AP1000 and chemistry of the primary circuit (Ref. 164). The assessment that follows is consistent with this TSC review. The information in these responses is summarised below.

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

- Westinghouse 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 dose but are accumulated and discharged in radwaste of various types. These are covered in Sections 4.2.3.3.2 and 4.2.3.3.3 of my report.
- Most of the other radioactive fission products and actinides generated in AP1000 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 minimizes crud build-up on fuel helps to maintain fuel integrity 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 Sections 4.2.2 and 4.5.1 of this report.
- My assessment of the radioactive source term (mainly iodine) in accidents is presented in Section 4.6.

232 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

233 Some of the more significant nuclides produced from the RCS materials in current PWRs are given below;

Nuclide	Production	Approximate half life (days)	Main RCS sources
^{60}Co	$^{59}Co\ (n,\gamma)\ ^{60}Co$	1925	Stainless steels, Co alloys, Inconels
^{58}Co	$^{58}Ni\ (n,p)\ ^{58}Co$	71	Inconels
^{59}Fe	$^{58}Fe\ (n,\gamma)\ ^{59}Fe$	45	Stainless and mild steels
^{51}Cr	$^{50}Cr\ (n,\gamma)\ ^{51}Cr$	28	Chromium steels
^{95}Nb	$^{94}Zr\ (n,\gamma)\ ^{95}Zr \rightarrow \beta^- \rightarrow\ ^{95}Nb$	35	Zirconium (also fission product)
^{110m}Ag	$^{109}Ag\ (n,\gamma)\ ^{110m}Ag$	250	Control rods
^{122}Sb	$^{121}Sb\ (n,\gamma)\ ^{122}Sb$	2.7	Seals and bearings
^{124}Sb	$^{123}Sb\ (n,\gamma)\ ^{124}Sb$	60	Seals and bearings

Table 6: Significant Radionuclides Produced from RCS Materials

234 The amount of corrosion that affects radiation production is very small and often invisible to the naked eye. 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 principal 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.

235 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. 159. 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.

236 I raised RO-AP1000-57.A1 (Ref. 7) requesting evidence from Westinghouse that the materials in AP1000 had been selected so as to reduce levels of radioactivity SFAIRP. In Ref. 165, they outlined the selection of bulk materials, cobalt alloys and other materials for AP1000. Many components would be made entirely from stainless or nickel-based alloys that have a high degree of corrosion resistance. These alloys would also be used to clad the ferritic alloys used to make the RPV and other components requiring great strength. Ferritic alloys are stronger but have lower corrosion resistance. All the wetted surfaces would be made from these alloys except the fuel and small areas where special materials are needed. An important design choice, from the Reactor Chemistry perspective, for the AP1000 RCS is the use of Inconel 690 in the thermally treated state for the tube material in the SGs. A number of other alloys, which are important from a radiation field and ORE perspective, are also included but their surface areas are smaller (Ref. 162). The arguments presented by Westinghouse in Ref. 165 are summarized below.

237 Low-cobalt alloys with a very small surface area should make little contribution to activity build-up. Conversely, high cobalt alloys (Stellites^{TM}) with low surface areas and large surfaces like the SG tubes will have a bigger effect. In general, the information provided by Westinghouse was well-organised and comprehensive. I requested further evidence of cobalt in wetted materials, TQ-AP1000-671 (Ref. 8), and for certain hard facings in TQ-AP1000-979 (Ref. 8). My assessment of these material choices appears in the following sections.

4.2.3.2.1 High Cobalt Alloy Inventory

238 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.

239 High cobalt alloys have particular use as hard wearing alloys and are commonly used in PWR components such as Control Rod Drive Mechanisms (CRDM), 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 (principally Stellites^{TM}) have contributed much of the cobalt which caused significant radioactivity in older PWRs (Refs 134 and 160). It is not certain precisely 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 sufficient instructions for fabricators and operators to install, commission and maintain any hard-facing materials that may give rise to ^{60}Co dose. I consider this to be an Assessment Finding **AF-AP1000-RC-06**.

240 Once Stellites^{TM} were identified as significant, much work was undertaken, principally with the 'Konvoi' reactors in Germany, progressively to eliminate Stellite^{TM} from various components, Ref. 160. The reduction in ORE reached a plateau at around 2m^2 of remaining Stellite^{TM} even though the reduction programme continued until there was only 0.17m^2 in the core, excluding the CRDMs, which are very similar in AP1000. It is important when considering any Stellite^{TM} replacement that the alternative is not actually worse in terms of either its mechanical safety or the corrosion of other elements in the alloy. The Mechanical Engineering aspects of Stellite^{TM} use are assessed elsewhere (Ref. 136).

241 The response to RO-AP1000-57.A1 (Ref. 165) states that the "*worst case*" Stellite^{TM} use in AP1000 corresponds to 34.7 m^2, with "*worst case*" assuming load following. This figure comes from Ref. 135, which calculates the Stellite^{TM} inventory for use in the CORA code to determine corrosion product inventories in the primary coolant. This figure is not the true Stellite^{TM} inventory in AP1000, but has been increased to provide the expected input of cobalt for the code calculations as CORA only considers corrosion and not wear mechanisms. The true Stellite^{TM} inventory in AP1000 is actually closer to 2 m^2, excluding the CRDMs (additional 5.9 m^2), which demonstrates the dominating contribution wear is expected to play in the release. This compares favourably with what was undertaken in Germany and elsewhere regarding Stellite^{TM} reduction.

242 Westinghouse is conducting an extensive programme of development, reviewing the use of Stellites^{TM} in CRDMs, the remaining valves and other components. Westinghouse has tested [redacted] as a replacement for the Stellites^{TM} latch and link in the CRDM. The [redacted] latch arms, and the drive rod paired to them, showed significantly less wear than the Stellites^{TM} assemblies. However, the Stellite^{TM} pins used with the [redacted] latches produced more wear than the Stellite^{TM} only assemblies. A latching mechanism with both components made of [redacted] tended to bind. Westinghouse takes a guarded approach to replacement materials and the reference design of the CRDM still contains Stellite^{TM} (Ref. 165).

243 Stellite^{TM} will be used for the main coolant pump bearings, and for some keys in the core of the reactor. The coolant pump bearings in AP1000 are fully submerged in the primary coolant and I asked Westinghouse to consider the loss of cobalt from these bearings in TQ-AP1000-979 (Ref. 8). In reply, Westinghouse said KSB pumps had hydrodynamic bearings that are not normally subject to wear. The bearings have also been subject to extensive testing. In their reply, Westinghouse quoted tests over 3525 start/stop cycles that resulted in 7 µm of wear over the bearing surface. Any release of cobalt will result in more ^{60}Co, but it would be difficult for Westinghouse to reduce this level of wear in the coolant pump still further. This source of cobalt is outside the core and other chemistry measures, such as CVS purification and addition of zinc can be used to optimise cobalt removal.

244 Older reactors tended to contain large numbers of isolation valves which had Stellite^{TM} hard-facings. Westinghouse was keen to point out that the design of AP1000 includes fewer valves than a conventional PWR, and therefore starts from a position of containing less cobalt. In the responses to TQ-AP1000-454 and 677 (Ref. 8) Westinghouse provided a list of valves (mainly in the CVS) which contain, or are allowed to contain by virtue of

their specification, Stellite^{TM}. Westinghouse make the claim (in RO-AP1000-57.A1 (Ref. 165)) that the simplification of AP1000 means less valves and hence less Stellite^{TM}, however this does not consider some valves as more prone to release or wear than others. For example, large pressure drop valves have large flows and more wear or some valves may be subject to greater maintenance, while replacement materials are more suited to low temperature applications.

245 Westinghouse takes a guarded and sensible approach to Stellite^{TM} replacement, by specifying components in three ways; those that must contain Stellite^{TM}, those which must not, and those "optional" components where a Licensee could choose, when fully justifiable on nuclear safety grounds. Therefore, I expect a Licensee to further justify which valves could be subject to Stellite^{TM} replacement, especially those which are "*optional*". I consider this to be an Assessment Finding, **AF-AP1000-RC-07**.

246 Overall, Westinghouse has made reasonable arguments to support the claim that the high cobalt alloy inventory in AP1000 has been reduced SFAIRP, based upon the current knowledge in this field. I am satisfied that Westinghouse has done a lot of development work to review and minimize use of hard-facing cobalt alloys in the generic AP1000. Currently some use of cobalt alloys seems unavoidable and other chemistry measures outlined in this report can be optimised to make ^{60}Co releases ALARP. Since a Licensee would effectively be specifying components, such as valves, and materials are an on-going area of research, a future Licensee for UK AP1000 should ensure no suitable alternative to Stellite^{TM} exists before acquiring significant equipment containing hard-facings in contact with primary coolant. I consider this to be an Assessment Finding, **AF-AP1000-RC-08**.

4.2.3.2.2 Trace Elements

247 In addition to the cobalt in Stellite^{TM}, there may be trace levels of cobalt or other elements in the other materials used to construct the reactor. High levels of cobalt impurity in structural metals are associated with higher ^{60}Co levels. Cobalt in other alloys or other trace-elements also have effects. Westinghouse controls alloy compositions for AP1000 mainly through application of the ASME (American Society of Mechanical Engineers) metallurgical codes, but there are additional restrictions applied in component specifications.

248 Westinghouse provided information on Cobalt impurity limits applied to AP1000 in the response to RO-AP1000-57.A1 (Ref. 165). In summary, some of the most important of these are:

Location	Co maximum / wt. %
SG tubes	[redacted]
Inconel and stainless steel in fuel components; Outside of active core but subject to high neutron flux; auxiliary heat exchangers exposed to primary coolant; primary components and weld clad surfaces	[redacted]
SG surfaces other than tubing	[redacted]
Reactor internal bolting; other small components in high flux areas	[redacted]
Bearings and hard facings	[redacted]

Location	Co maximum / wt. %
Others	[redacted]

Table 7: AP1000 Cobalt Impurity Limits in Primary Circuit Materials

249 It is not practicable (or even possible) to completely eliminate cobalt from metals but for the AP1000 design Westinghouse have specified tight controls to limit cobalt in SG tubing [redacted], stainless steels subject to neutron irradiation [redacted] and stainless steels not subject to neutron irradiation [redacted]. This emphasis reflects the relative areas of these metals and their significance in cobalt production, TQ-AP1000-671 (Ref. 8). Of particular importance, as reflected in the impurity limits above are the cobalt levels in Inconel 690 which are determined by the original ores and would be difficult to reduce further. Westinghouse expects 40% of the total activity to be ^{60}Co with ^{58}Co, iron and manganese providing the balance.

250 Westinghouse makes reasonable arguments that these values can be considered ALARP.

251 The presence of other trace-elements in metals, such as sulphur and phosphorus, impacts on other properties of the metal, including corrosion. In Ref. 165 Westinghouse states 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. 137).

252 Antimony, tungsten and silver are covered in Section 4.2.3.2.4 below.

253 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 Westinghouse are appropriate 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 Westinghouse have adequately demonstrated how this would be done for AP1000.

4.2.3.2.3 Bulk Materials

254 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, particularly in the Steam Generators. Alloy 800 is not an Inconel and could be a replacement, but Westinghouse has no experience of fabrication with this alloy and 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 around 70% 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-life.

255 To minimize 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 AP1000 has much

higher chromium content which helps to stabilize the grain boundaries. Steam-generator tubing, tube divider plates and some radial supports and nozzles in the reactor head will all be made of Inconel 690.

256 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.

257 Radiation fields at Sizewell B are low, partly as a result of the use of Inconel 690 (Ref. 159). Many other PWRs using Inconel 690 have also benefitted from low radiation fields. 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 reasons for this are now believed to relate to the finishing treatments applied to metal components by their manufacturers and to the commissioning carried out. Passivation prior to nuclear operations, by Hot Functional Testing (HFT), is assessed in Section 4.2.12 of this report.

258 In order to minimise general corrosion Westinghouse are improving methods of finishing and conditioning surfaces, particularly of SG tubing, and by electropolishing the channel heads and water-chambers in the SGs. These are positive developments which should help with reducing the radiation levels.

259 Westinghouse has specified austenitic stainless steel for the main pipework, which is normal practice in a PWR. This material is resistant to general corrosion and erosion by primary coolant. The flow rates in the reactor are significantly below the threshold value for erosion by single-phase flow, Ref. 164.

260 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. Westinghouse presented and described their processes for tubing manufacture in Ref. 142. Westinghouse has provided comprehensive descriptions for the materials and fabrication procedures and I am content that these will be adequate for the control of cobalt production. My assessment of these follows.

Conditioning and Inspection

261 The surface treatment of alloys used to construct AP1000 will also have an effect on corrosion rates and activity pick-up (Ref. 213). 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. 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.

262 Westinghouse has not specified which of the three main suppliers would be used for SG tubing. Based on historical performance Sandvik and Valourec tubing is known to passivate well. It is believed that Sumitomo is developing a new oxidising stage in manufacture to lay down a thick protective chromium oxide layer.

263 In my meetings with Westinghouse, I made clear the importance of adequate control over all phases of manufacture, particularly SG tubing, to ensure radioactivity build-up was minimised SFAIRP. This included surface finishing. In TQ-AP1000-530 (Ref. 8), Westinghouse outlined the manufacturing steps that would be used to ensure a high-quality of Inconel 690 tubing. This was a comprehensive answer and provided me with

confidence that Westinghouse understand the importance of adequately preparing the SG tubing.

264 Responding to TQ-AP1000-1235 (Ref. 8) Westinghouse said EPRI guidelines recommend an inner surface roughness limit for all of the tubes of [redacted] µm whereas Westinghouse impose a 1.0 µm limit. A further limit of 0.5 µm for 90% of the tubes is applied [redacted].

265 Of the numerous processes applied to Inconel tubing, there is evidence that bright annealing after manufacture reduces corrosion. To be effective, the process should use pure hydrogen with a low dew point. See Ref. 161. Standards for tubing finish have been defined by Westinghouse which refines the specifications provided by ASTM (American Society for Testing and Materials), EPRI and other bodies, Ref. 142.

266 Electropolishing can reduce the accumulation of radioactivity on out of core surfaces. Westinghouse considered electropolishing the channel heads and water-chambers in the SGs was justified in AP1000 and electropolishing of the pools in the CA module as not justified, Ref. 71. This demonstrates an ALARP approach to dose-reduction in the design of AP1000, Ref. 161.

267 Westinghouse provided additional specifications to safety-grade pipework, welds and components, controlling heat treatments, welding processes, consumables, testing, cutting, cold-work and inspection in TQ-AP1000-1235 and Ref. 167. Careful attention is paid to avoid sensitization of stainless steels. I was content with the adequacy of these arrangements for GDA from a chemistry perspective.

268 Several surfaces in the reactor are built up by cladding tough ferritic structural steel with a corrosion-proof cladding. The chemistry aspects of this are covered in section 4.2.4.1 of my report.

269 From my sample assessment of surface conditioning for the control of radioactivity, I conclude that adequate controls have been defined by Westinghouse for the present stage.

Surface Cleanliness

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

271 Westinghouse has addressed general materials in Chapter 13 of the *"chemistry manual"*, in the tubing specification and supplemental guidelines (Refs 167 and 25). In this, foreign material is defined as undesirable material in or near a component which would not normally be present as part of the AP1000 design. Foreign material may be introduced as a result of operations such as manufacturing, installation, repair, maintenance, inspections, or other procedural processes. 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 by Westinghouse during any activity where foreign material may be introduced.

272 Sulphur, lead, copper, mercury, aluminium, antimony, arsenic, and other low-melting-point elements and their alloys and compounds are 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 is prohibited.

273 Westinghouse provided a general specification for concentrations of detrimental material applicable to different alloys. Possible sources of detrimental materials are also listed. Requirements 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 apply at all stages of fabrication and operation. These requirements are applicable to all surfaces that contact the operating fluid or maintain the integrity of the pressure boundary.

274 Westinghouse documentation for Surface Cleanliness control is comprehensive.

4.2.3.2.4 Other Materials - Antimony, Silver and Tungsten

275 Any silver lost by materials in the reactor would be activated to ^{110m}Ag in the core; similarly any antimony would be activated to nuclides such as ^{124}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 PWRs historically. Naturally-occurring tungsten contains several isotopes which can capture neutrons to produce radioactive products. Tungsten is not a common PWR material but will be used in the main pump flywheels of AP1000.

276 I queried the potential use of silver and antimony in the CVS of AP1000 in TQ-AP1000-461 (Ref. 8). Westinghouse replied with comprehensive specifications for control of materials and cleanliness, with which I was satisfied. See Section 4.2.4.1.1.

277 The conventional design of control-rod used for adjustment of reactor power is made from a Silver-INdium-CADmium (SINCAD) alloy. Like all PWR control rods these will have a defined service life and potentially suffer from swelling. The management of control rods to ensure replacement before material is released should be part of the normal licensee activities. In the response to RO-AP1000-57.A1 (Ref. 165), Westinghouse has specified a chromium plating process for the control rods to minimise wear and corrosion product deposition. While it is recognised this may marginally increase the ^{51}Cr levels in the coolant, the benefit is a reduced contamination of the rods themselves by factors of 5 to 30. It is not clear if a specification for cobalt content in the plating is given, but this is expected to be consistent with those given in Section 4.2.3.2.2.

278 Antimony is used within the secondary neutron sources specified for AP1000. While these are encased and not expected to be exposed to the primary coolant any leaks in the cases will result in dissolution and transfer of antimony to the coolant (Ref. 152). 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-AP1000-RC-09**. This is also a radwaste question, since the disposal of a used neutron source can be difficult.

279 To improve passive safety, the main coolant pumps in AP1000 are canned, which means the flywheel is entirely submerged in coolant. In discussions, Westinghouse advise the tungsten flywheel is encased for life inside a shell of alloy 625. Gross failure of the flywheel casing would be a major fault and is not assessed here. Westinghouse has specified liquid-penetrant testing of the casing welds and other in-process controls to ensure flywheel tungsten do not come into contact with the coolant, Ref. 164.

280 A new type of grey control-rod is being developed by Westinghouse, which utilizes tungsten for the control material, Refs 166 and 164. Tungsten control-rods are out of scope for GDA. It is noted that the corrosion product source report (Ref. 135) does not consider tungsten. Since the AP1000 contains a significant quantity of tungsten and its use can increase, this analysis should be updated to include the effects of tungsten. The

canned main-coolant pumps of the AP1000 have a number of advantages, but the likelihood and effect of porosity in the flywheel casing and bearing wear should be monitored.

281 Preventative surveillance of control rods, flywheels and secondary neutron sources should therefore be reviewed and justified by the Licensee. I consider this to be an Assessment Finding, **AF-AP1000-RC-10**.

4.2.3.3 Water Chemistry

282 In RO-AP1000-57.A2 (Ref. 7), I asked Westinghouse to provide evidence that the chemistry of the primary coolant would be controlled so as to reduce levels of radioactivity SFAIRP. Their response (Ref. 165) outlined the chemistry needed to minimize the concentration of corrosion products in the coolant and minimize their deposition on fuel cladding and limit accumulation on out-of-core surfaces. In general terms this can be achieved by controlling the pH_T 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. Identification of the chemistry environment in contact with circuit materials during all stages of operation was reviewed for ND in Ref. 168 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 flux of the core and so increase the quantity of activated products. Minimising such deposition is a major objective of primary coolant chemistry control.

283 Reduction of the rate of metal release from primary circuit materials as a consequence of general corrosion is a prime coolant chemistry control objective. 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 (CVS) as the plant is shut down, see Section 4.2.11 and Ref. 159.

284 In addition the water and the species added to the coolant to control the chemistry environment are themselves subject to the neutron flux and can produce activated species. Many 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 listed in the table below:

Nuclide	Production	Approximate half life	Production Source
^{3}H	$^{10}B\ (n,2\alpha)\ ^{3}H$	12.3 years	Boric acid
	$^{6}Li\ (n,\alpha)\ ^{3}H$		Lithium hydroxide
	$^{7}Li\ (n,n\alpha)\ ^{3}H$		Lithium hydroxide
^{7}Li	$^{10}B\ (n,\alpha)\ ^{7}Li$	stable	Lithium hydroxide
^{14}C	$^{17}O\ (n,\alpha)\ ^{14}C$	5730 years	Water

Nuclide	Production	Approximate half life	Production Source
	^{14}N (n,p) ^{14}C		Dissolved nitrogen gas
^{16}N	^{16}O (n,p) ^{16}N	7.1 seconds	Water
^{32}P	^{35}Cl (n,α) ^{32}P	14.3 days	Contamination
	^{32}S (n,p) ^{32}P		Contamination
	^{31}P (n,p) ^{32}P		Contamination
^{35}S	^{35}Cl (n,p) ^{35}S	87.5 days	Contamination
^{41}Ar	^{40}Ar (n,γ) ^{41}Ar	1.8 hours	Argon in air

Table 8: Significant Radionuclides Produced from RCS Chemical Additions and Impurities

285 The principal products of these are tritium (^3H) and ^{14}C, which are discussed further in Sections 4.2.3.4.2 and 4.2.3.4.3, 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 flux) 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, manly chloride and phosphorus via the reactions given above. These nuclides are present as phosphate and sulphate in the RCS and as such are removed on the CVS 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

286 In the AP1000 Environmental Report (Ref. 92) Westinghouse describe the primary coolant chemistry controls which are used to minimise radioactivity, namely control of pH_T and addition of hydrazine at start-up, hydrogen and zinc. No indication of levels or limits is provided.

287 The Reactor Coolant Water Chemistry Specification provided in the original European Design Control Document (Ref. 21) (EDCD) was derived from US NRC requirements concerned with controlling the use of sensitised stainless steels and extended to include limitations aimed at reducing the risk of deposition on fuel cladding. This is less restrictive than the EPRI Guidelines (Ref. 15) that Westinghouse recommends for plant operations and the Westinghouse supplemental guidelines (Ref. 26).

288 One significant parameter controlling corrosion is the pH_T, a measure of the acidity of the coolant at operating temperature. Values of pH_T should always be slightly alkaline during normal operations. As described more fully in Section 4.2.10, the original Westinghouse recommendations for the AP1000 for normal operation were as follows:

- Maintain alkaline pH_T of [redacted] at 300°C with as high a pH_T as practical, while remaining below [redacted] mg kg^{-1} lithium limit for the fuel.

- Maintain a reducing environment with 25 to 50 cc kg^{-1} hydrogen, assessed in Section 4.2.7 (note that cc 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).
- Add zinc acetate to achieve [redacted] μg kg^{-1} zinc, assessed in Section 4.2.6.
- Minimize impurities including chloride, fluoride, sulphate, suspended solids, silica, calcium, aluminium and magnesium. Focus on obtaining high purity of the make-up water and other feed streams.

289 The minimum recommended pH$_T$ was subsequently increased to [redacted] by EPRI in their report 'Fuel Reliability Guidelines: PWR Fuel Cladding Corrosion and Crud' (Ref. 235) which may still be too low for AP1000, I believe. Westinghouse considers application or otherwise of this increase to be part of the Licensees responsibility in developing the site specific operating chemistry requirements.

290 The description provided in the response to RO-AP1000-57.A2 (Ref. 165) shows that the pH$_T$ in AP1000 is likely to follow an "*elevated chemistry*" pH programme, whereby the lithium is held as close to the [redacted] mg kg^{-1} limit as possible for most of the cycle, until the boron concentration decreases to such a level that the lithium and boron can be coordinated to maintain a constant pH$_T$. This results in a pH$_T$ that varies throughout the cycle, gradually increasing as the burn-up increases before reaching the plateau as the coordination stage begins. Such chemistry is shown below, and is common in many US PWRs. This type of chemistry regime has been shown to reduce radiation levels in plants, compared to coordination at constant, lower pH$_T$. The RO-AP1000-57.A2 response (Ref. 165) indicates that the pH$_T$ will start at around 7.0 and rise to around 7.3 towards the end of the cycle, but this is dependant upon many factors including the detailed core design which are not known at present.

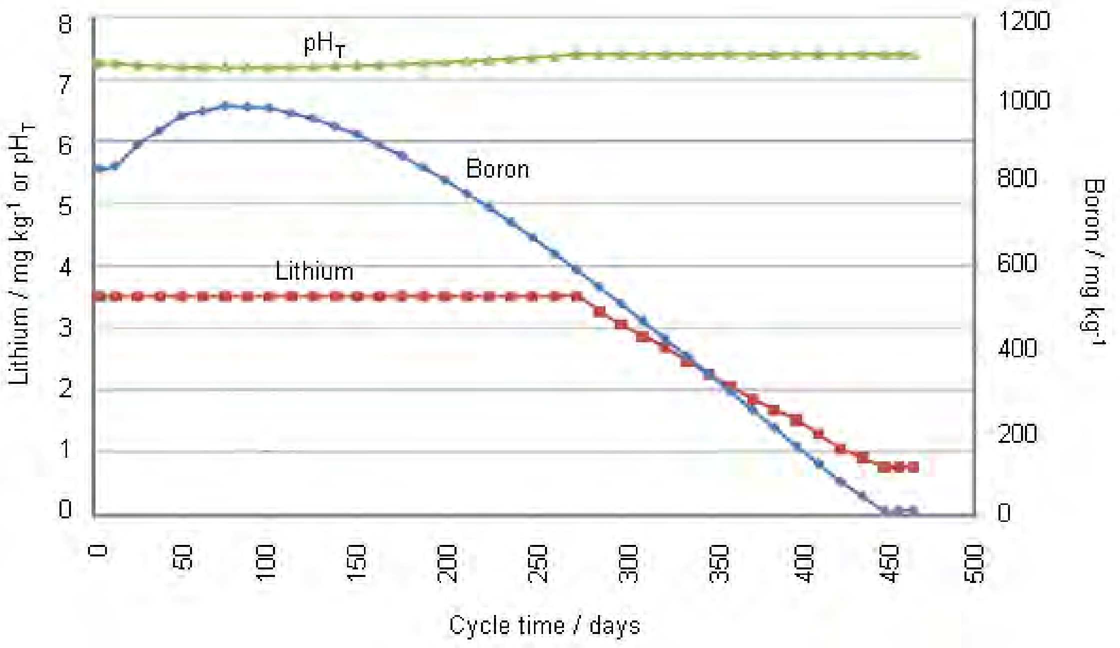

Figure 4: Typical AP1000 Boron-Lithium Coordination and pH$_T$ Profile

291 Based on these parameters Westinghouse claims that “*worst case*” contamination levels will be around 1 GBq m^2 in the SG (Ref. 135). At face value this can be considered as excellent performance especially given the higher duty of the generic core and a number of the design features of AP1000. In producing such an optimistic prediction there is a risk that this may not motivate a Licensee to implement the key controls needed to ensure crud production, out of core radiation and radwaste production will be ALARP.

292 As described in Section 4.1, Westinghouse does not specify a precise operating chemistry for AP1000. While these parameters make a reasonable start to defining a safe chemistry envelope for AP1000, in operating a PWR there a great number of other chemical and radiochemical parameters for which Westinghouse does not recommend values, but defers to the EPRI guidance. Until a licensee writes a site-specific chemistry policy for AP1000, and fully defines the operating chemistry programme it is not possible to conclude if the chemistry regime has reduced radioactivity SFAIRP. This is related to Assessment Finding **AF-AP1000-RC-01**.

293 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 activated corrosion products in the RCS increase, as the residence time within the core flux 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.

294 The production of fuel crud is a complex process involving many aspects of the design which are not related to the operating chemistry, such as the amount of boiling and core thermal hydraulic performance. At a high level AP1000 could be considered prone to fuel crud formation as the reactor has a small core and a large area of SG tubing, although there are a number of current operating PWRs with comparable ratios of SG tubing area to active fuel surface area. As the core boiling rate in AP1000 is likely to be towards the high end of current operating plants, some amount of crud will inevitably build up on the fuel.

295 Prior to Step 3, the only estimates for the levels of radiation in the nuclear island were based on source terms defined in Refs 31 and 135. These were based on methods which took no account of the additional crud that could be produced due the high ratio of tubing to core area and operational chemistry such as the pH_T of the coolant. Two of my TSC advised independently (Refs 162 and 164) that AP1000 may be more prone to the production of crud than some other current PWRs.

296 In order to understand the consequence of this further I undertook three strands of assessment, namely:

- At my request, Westinghouse provided estimates for the crud produced in AP1000 (Ref. 169). These calculations were based upon using the BOA (Boron Offset Anomaly) code. Westinghouse calculations with BOA have been performed with BOA v2.0 (with version 1.0 functions) for the generic AP1000 first core design.
- In TQ-AP1000-910 (Ref. 8) I also requested Westinghouse 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 similar boiling duty to AP1000, but had different SGs at the time. The purpose of this request was to “*benchmark*” the Westinghouse calculations against known plant data.

- Finally, I also commissioned independent expert analysis (Ref. 163) for the likely quantities of crud expected, using the same base data (from TQ-AP1000-565 (Ref. 8) as the Westinghouse 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 Westinghouse calculations and provided estimates for radioactivity transport around the AP1000 RCS.

297 As with all such modelling there are many assumptions and approximations associated with the calculations. Westinghouse predicts [redacted] to [redacted] kg crud in the core of AP1000 and [redacted] to [redacted] kg crud at Callaway at the end of the cycles studied. Predictions of [redacted] kg for AP1000 are lower than expected for a standard 4-loop PWR with a low boiling duty. The difference is possibly due to the way the mass of iron was calculated, but suggests that Westinghouse is under-predicting the mass of crud, which is optimistic for radioactivity.

298 In summary a comparison of the entire dataset provided by the Westinghouse and TSC calculations indicates that, in general:

- Compared to TSC estimates and other 4-loop plants Westinghouse appears to predict a lower mass of crud for AP1000.
- Westinghouse appears to predict thinner crud for Callaway, compared to the measured data.

299 The values produced by any such modelling should be treated with caution as the real benefits are in understanding the trends and the parameters that may drive radioactivity towards or away from ALARP. Similarly the TSC calculations (Ref. 163) are not intended to replace experience or experiment but provide a framework for verifying and prioritising predictions of activity production in AP1000. The TSC calculations predict the total crud produced throughout a cycle, which is greater than the crud remaining in the core at the end, and surface activities of a number of nuclides at different points in the circuit.

300 A more detailed comparison between the two reveals that:

- Both the TSC and Westinghouse calculations agree there will be crud deposits around [redacted] μm on some fuel in the core during cycle 1.
- The TSC model predicts looser deposits on other reactor surfaces than the Westinghouse model.
- Westinghouse appears to be combining a surprisingly low rates for iron and nickel corrosion with credit for the use of zinc in their calculations. These assumptions, together with the assumed carry-over between cycles, will need further justification.
- Westinghouse has not adequately justified the quantity of iron on the fuel surfaces.
- Levels of radioactivity in AP1000 are likely to be higher than a non-boiling PWR of the same power, but the difference due to boiling will be within normal variations and the surface activities claimed in the Westinghouse evaluation of the corrosion product source term (Ref. 135).

301 Through other parts of my assessment Westinghouse provided additional data on fuel crud in AP1000:

- Westinghouse provided additional detailed justification for crud and radiocobalt levels at the end of November 2010 in Reference 116, as part of the response to RO-AP1000-84.A2 (Ref. 7). Westinghouse figures for “*worst-case*” out-of-core contamination agreed more closely with the prediction for "*expected level*" generated by my TSC in Reference 163.

- In RO-AP1000-84.A2 (Ref. 7), ND requested evidence that crud could be controlled in the AP1000 auxiliary systems. Westinghouse provided References 116 and 200 in response, providing data that help to characterize the crud, but not to quantify it.
- In response to RO-AP1000-55.A5 (Ref. 7) Westinghouse provided an estimate of fuel crud levels in the spent Fuel Pool (Ref. 117), however this latter also appears to be based upon the original Westinghouse estimates for the generic first core (Ref. 169 and Section 4.3).
- Modern methods of reactor management including the use of zinc are improving understanding of the control of radioactivity and Westinghouse have provided an update on the latest available iron and nickel release data during shutdowns in their response to TQ-AP1000-1171 (Ref. 8).

302 Overall, Westinghouse has provided much information on fuel crud in AP1000. However much of this is tempered by the fact that Westinghouse does not specify the operating chemistry for AP1000 and therefore had to make a number of assumptions for this. For example, the minimum pH_T for coolant recommended for AP1000 is [redacted]. As described earlier, Westinghouse recommend this is increased as high as possible within the control band but this may not result in pH_T above 7 at the beginning of cycle due to the lithium limit. I believe that a pH_T of 7 may not be enough to prevent higher ORE in AP1000, without other means. Responding to TQ-AP1000-714 (Ref. 8), Westinghouse said that the pH_T could be controlled to be always greater than 7 at beginning of a cycle within the [redacted] mg kg^{-1} lithium limit. Specifying a control on boiling is another means of limiting crud also recognised in Ref. 217. Westinghouse believes such control measures would be a matter for the Licensee, as these could have economic impacts. Examination of recent data supplied by Westinghouse (Ref. 169) suggests that boiling may in fact be greatest and the pH_T lowest at the middle of a fuel cycle.

303 While Westinghouse has demonstrated that the design of AP1000 could allow operation to achieve levels of radioactivity which are tolerable, these have not been demonstrated to be ALARP. On the basis of the evidence I have seen I believe that AP1000 may be more prone to fuel crud production and higher levels of radiation than comparable plants if adequate and strict controls are not implemented by the Licensee. Much of the evidence supplied by Westinghouse appears to use assumptions which are optimistic for fuel crud production. As such, I believe it would be possible to fabricate and operate AP1000 to generate and accumulate much more crud and radiocobalt than the Westinghouse predictions suggest. Therefore I require the future Licensee to run sensitivity calculations to identify the key factors that cause crud with the first UK AP1000 core and help to identify the key parameters that define tolerable operating bands, or identify generic controls for crud. Since Westinghouse does not specify the operating chemistry, it will be the task of the Licensee to develop a suitable operating regime that controls crud. I consider this to be an Assessment Finding, **AF-AP1000-RC-11**.

304 In leaving the licensee to define a precise chemistry regime, Westinghouse has not justified that levels of crud and radioactivity produced from corrosion products will be controlled ALARP. This is related to Assessment Finding **AF-AP1000-RC-01**.

305 Having considered the production of radiocobalt and other radionuclides from crud and other mechanisms, I also assessed what happens to it, when it leaves the core of the reactor. The controls needed to maximise the capture of corrosion products by the CVS during a shutdown are discussed in Section 4.2.11 and TQ-AP1000-807 (Ref. 8). In RO-

AP1000-84 (Ref. 7), I have asked Westinghouse to identify how activity build-up in the nuclear island (i.e. parts of the reactor outside the core) would be controlled. Like the CVS, the Normal Residual Heat Removal System (RNS) in AP1000 is a multi-function system and I raised TQ-AP1000-1157 (Ref. 8) to ask Westinghouse how unintentional spread of radioactivity via the RNS would be avoided. In their reply, Westinghouse demonstrated that RNS can be flushed and connected to purification systems in all operations with the possible exception of mid-cycle shutdowns.

4.2.3.3.2 Tritium

306 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.

307 The amount of ^{10}B in the coolant is determined by other safety considerations and cannot be altered, other than by enrichment. The reference design for AP1000 uses natural boron, which contains around 19 to 21% of the useful ^{10}B isotope. Enriched boron use often requires extensive additional equipment to recycle the expensive boron. The amount of lithium in the coolant is determined by the total amount of boron and the need to control corrosion. The primary advantage of enriched boron in that it requires less lithium to compensate for the pH change. The use of "*grey rods*" and fixed poisons in AP1000 reduces the quantity of boric acid needed. This has consequential effects on reducing the tritium produced during a cycle.

308 Westinghouse directs operators to 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.

309 Tritium is also generated by ternary fission of the nuclear fuel. A small percentage diffuses through the claddings of the fuel, poisons and neutron sources into the coolant. The ZIRLO® used in AP1000 reduces the tritium escape from the fuel cladding and Westinghouse has provided a bounding estimate of 2% of the tritium produced by fission to escape to the coolant. Work to more accurately quantify the release of tritium from burnable poisons and secondary sources is ongoing, however Westinghouse claim the current estimate remains bounding (TQ-AP1000-455, Ref. 8). I am content with this approach.

310 Secondary neutron sources are included within the core to provide a measureable background neutron flux for the core detectors. The AP1000 design proposes the use of Sb-Be sources (TQ-AP1000-455 (Ref. 8) superseded by RO-AP1000-84.A1 (Ref. 138)). Beryllium in the source generates significant quantities of tritium via the two step reaction $^{9}Be\ (n,\alpha)\ ^{6}Li\ (n,\alpha)\ ^{3}H$. 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 alone) and they potentially account for a significant fraction of the tritium generated. This is related to **AF-AP1000-RC-09**.

311 High levels of tritium mid-cycle would become a problem if it was necessary to lift the reactor head under such circumstances. Since this is not a normal operation, I am satisfied that a Licensee would be able to take appropriate measures in this unlikely event, such as discharging coolant to the WLS before opening the RCS. The licensee will

keep levels of tritium in the coolant and pools under review as part of their normal business.

4.2.3.3.3 Carbon-14

312 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 at solid waste facilities, to which strict ^{14}C limits apply. ^{14}C is mainly produced from neutron activation of the water, which is unavoidable, or from dissolved nitrogen present in the coolant. As described in Section 4.2.2.3.3, there are a number of design features of AP1000 which may mean that the levels of dissolved nitrogen in the coolant may be higher than other PWRs.

313 Chapters 11 and 12 of the EDCD (Ref. 22) contain no discussion of ^{14}C production. The Environmental Report (Ref. 92) provides estimated ^{14}C releases from an AP1000 and these have been assessed by the Environment Agency. Westinghouse has provided estimates of the ^{14}C production in response to a request from the Chinese National Nuclear Safety Administration. The total annual production of ^{14}C from neutron irradiation of ^{17}O and ^{14}N is 552 and 110 GBq per year respectively. The production from ^{14}N irradiation assumes a nitrogen concentration in the primary coolant of 15 mg kg^{-1}, which appears bounding even given the differences highlighted in Section 4.2.2.3.3.

314 Under primary coolant conditions the majority of the ^{14}C will be in the gas phase, mainly as methane. The proportion of the ^{14}C in the solid and liquid wastes has been estimated from US data at below 5% of the gaseous discharge, Ref. 179. Data collected from the Ringhals plant, Ref. 216, and elsewhere, Ref. 215, 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 ^{14}C as carbonate species. Appreciable quantities of carbon have also been found in crud from time to time, which must have been created under reducing conditions. The use of the ion-exchange resins as filters in AP1000 makes it more likely that some ^{14}C will end up on the resins, in whichever conditions. The estimates of 5 and 10 % above, multiplied by 662 GBq per year result in a transfer of 33 to 66 GBq per year ^{14}C in solid radwaste. Based on Ref. 216, Westinghouse quotes 53 GBq per year in Ref. 179. I have shared these results with both the Environment Agency and the Radwaste and Decommissioning inspectors.

315 I have discussed with Westinghouse a number of factors that may influence carbon distribution including the addition of acetate to the coolant with zinc, and the amount of adventitious carbon from air and other sources, TQ-AP1000-978 and 980 (Ref. 8), and it is clear that there remains some uncertainty in exact levels of ^{14}C that could be accumulated in radwaste on the site. Whilst an uncertainty of this magnitude is not surprising at this stage, limits for ^{14}C accumulation on some sites can be tight. Since ^{14}C is not easy to measure, it would be expected for the Licensee to plan for some testing of carbon distribution in AP1000, once the plant had been operational for one or more cycles, see Section 4.2.6.1.3.

4.2.3.4 Summary

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

- Westinghouse has provided information on how the material and chemistry choices in AP1000 are predicted to influence the plant radiation fields.

- In broad terms Westinghouse plans related to materials are well developed and comprehensive and are consistent with modern practices in this regard. Similarly, Westinghouse plans for foreign material control and control of materials delivered seem comprehensive. Westinghouse has provided wide-ranging descriptions for the fabrication procedures to be used in AP1000 and I am content that these will be adequate for the control of cobalt production. I have raised a number of Assessment Findings where gaps in the case are evident:
  - i) Westinghouse have not fully defined the extent of Stellite^{TM} use in AP1000 allowing some choices to be made in valves and other locations by the Licensee. While reasonable arguments have been presented for retaining this material the Licensee will need to justify these choices when made, including the use of Stellite^{TM} more generally if alternative materials are available.
  - ii) The requirements for secondary neutron sources should be kept under review. Secondary sources and control rods should be maintained in high working order and not be allowed to wear out.
- As Westinghouse do not specify the precise operating chemistry to be used in AP1000 it is not possible to confirm if an ALARP position has been reached in this regard. While I am content that operation within the bands defined by Westinghouse will be safe, small variations in precise levels may alter radiation levels by much larger factors. I have raised a number of Assessment Findings which require the Licensee to fully justify the intended chemistry in this regard.
- Many reactors operate safely a small amount of fuel crud but advice from a number of our TSCs is that AP1000 may be more prone to crud build-up due to its large SGs and small core in combination with a core duty towards the high end of current operating plants. Further work will be needed by the Licensee to demonstrate that out-of-core radiation has been appropriately controlled, with the results generated by Westinghouse for GDA appearing to underestimate the fuel crud levels likely in AP1000. Westinghouse claims that "*worst case*" contamination levels around 1GBq m^2 in the steam generator. Whilst modelling does not replace experience or experiments, efforts by Westinghouse to model radioactivity are providing valuable insights that should help to direct efforts by the Licensee to reduce uncertainty in the design and fabrication of equipment to ensure levels of radioactivity and discharges should be tolerable, given strict and robust controls.
- Westinghouse use CORA and BOA to predict core crud and surface contamination on out-of-core surfaces in AP1000. Whilst representing "*state of art*" when these calculations were performed, a newer version of the BOA software offers superior capabilities. The new version of BOA, or other appropriate method, should be used to conduct sensitivity analyses to identify which parameters affect crud production the most in AP1000, such they can be targeted for control. Potentially over-optimistic predictions may obscure the actions necessary for a licensee to achieve ALARP. Realistic predictions for core crud and radiocobalt should provide licensees with the motivation to implement the key controls needed to minimise crud production.

317 While Westinghouse have made a reasonable case to support GDA, further work will be required in this area as Licensing of UK AP1000 progresses and I have identified a number of Assessment Findings to support this.

4.2.3.5 Assessment Findings

318 Based upon the assessment of radioactivity in AP1000 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-AP1000-RC-06*** *– 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 controls 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-AP1000-RC-07*** *– The Licensee shall review which valves could be subject to Stellite*^{TM} *replacement, especially those which are "optional" according to procurement specifications. The review shall include environmental conditions of the valve in service and likely wear rates with evidence supporting the final selection made. 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-AP1000-RC-08*** *– The Licensee shall review and consider alternative materials to Stellite*^{TM} *for applications within AP1000, 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-AP1000-RC-09*** *– 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-AP1000-RC-10*** *– The licensee shall define a surveillance programme for control rods, flywheels 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-AP1000-RC-11*** *– The Licensee shall conduct sensitivity analysis for fuel crud formation in AP1000. This should be used to demonstrate that levels of crud can be controlled and reduced So Far As Is Reasonably Practicable (SFAIRP) in AP1000 and should be based upon the detailed operating chemistry and core design for the UK AP1000 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 AF-AP1000-RC-01; Target milestone – Initial criticality.

4.2.3.6 GDA Issues

319 Based upon the assessment of radioactivity in AP1000 described in Section 4.2.3 above, I have identified no GDA Issues which require resolution before nuclear island safety-related construction of a reactor could be considered, however this topic is related to the cross-cutting GDA Issue on operating limits and conditions **GI-AP1000-CC-01**, described in Section 4.1.3.3.

4.2.4 Assessment – Material Integrity and Corrosion Control

320 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.

321 Some 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 stainless steel pipework and 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.

322 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 results from 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 sensitized 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 minimize the effects from local heating.

323 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 due to 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. For AP1000, Westinghouse have engineered the majority of Inconel 600 out of the design and instead specified Inconel 690. 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. These measures minimise the number of potential threats caused by localised corrosion in AP1000.

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

325 External corrosion, as can occur from when boric acid is allowed to leak and concentrate by evaporation on external primary circuit surfaces (See Ref. 139), such as occurred at Davis Besse in the USA (Ref. 140), 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 4.6.

4.2.4.1 Material Selection for Corrosion Prevention

326 The principal materials of construction of the AP1000 are identified in Section 5.2.3 of the EDCD (Ref. 22) and the response to TQ-AP1000-710 (Ref. 8). 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:

- The low-alloy steels, from which the reactor vessel and certain other components are made, do corrode in water and will be clad in Grade 304, 304L, 304LN, and 304H stainless steels.
- Other structural components inside the reactor core will also be made from Grade 304, 304L, 304LN, and 304H 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. There have been historic problems associated with valve stems running at high temperatures. Westinghouse requires valve manufacturers to provide a material selection report for the stem material in their valves. Use of alloy 17-4 PH has been restricted in AP1000.

327 I procured TSC support in reviewing the selection of materials for AP1000, the scope of their review covered compatibility of the metals chosen with the general guidance provided by Westinghouse on primary coolant chemistry (Ref. 164). Additional details on material choices and controls highlighted in their extensive review include:

- Materials selection requires a balance between structural integrity, cost and minimizing radioactivity.
- All wetted materials inside the reactor vessel are 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 304 or 316 with low-carbon variants used for specific parts.

- Use of sensitized austenitic stainless steel is prohibited anywhere inside the reactor vessel.
- The outer surfaces of the control rods which are in contact with the coolant will be made of three types of alloy; stainless steels, Inconel alloys and a small amount of cobalt-based alloy.
- The reactor vessel head penetrations will be made from Inconel 690.
- Any heat-treatments will be tightly controlled to avoid sensitization.
- High levels of cleanliness will be maintained to minimise any risk of localised corrosion such as IGA or SCC.

328 The full selection of materials was not complete for AP1000 when my TSC conducted their review and therefore much of it was based on the information in the European DCD (Ref. 22). Westinghouse has revised specifications of materials for a few components since then and the Licensee or suppliers may make further changes. As such, the final specifications are not yet confirmed for all of the reactor circuit materials. These conclusions are based on those that are and the stated approach that Westinghouse takes to materials selection. Any further material changes will need to be justified by the Licensee going forward.

329 Overall, the materials proposed are accepted nuclear grade materials used by the industry, with many years of operating experience. Much of the AP1000 design can be considered “*routine*” in this respect, with the principal material choices being consistent with many current plants, operating experience and current knowledge from experimental work. Combined with adequate surface treatments, material preparation techniques and operating chemistry the AP1000 material choices appear reasonable from the perspective of general corrosion affecting integrity, noting the assessment earlier in this report on radioactivity which is also relevant (Section 4.2.3).

330 In order to assess the potential for SCC in AP1000 I commissioned TSC support to review recent experience from other water reactors and look for systematic features of other designs common to AP1000 that might be vulnerable to PWSCC (Ref. 196). Prior to this I commissioned a general review of experience of PWSCC in other reactors (Ref. 193). The main conclusions of the review of SCC of Inconel 690, stainless steels and claddings (Ref. 193) were:

- 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. Such a phenomenon, known as Low-Temperature Crack Propagation (LTCP), has not been seen in service and is thought unlikely to be a problem in operating reactors under normal operations. See Section 4.2.11 on start-Up and shutdown chemistry.
- In stainless-steel, a few instances of cracking have occurred in regions of stagnant coolant, such as canopy seals or dead-leg pipework, or in regions of low coolant flow, such as found near the control rods or in the pressuriser. In these areas impurities can accumulate. This is especially true for crevices. Residual stresses remaining from fabrication, called cold work, can also increase cracking susceptibility. Instances of

cracking have occurred as a result of such non-uniform cold work remaining from fabrication.

- Alloy X750 springs have also been subject to cracking (Ref. 212).
- 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.

331 I raised TQ-AP1000-490 (Ref. 8) which asked Westinghouse to consider if any areas of AP1000 were considered prone to SCC. This can be considered the principal response from Westinghouse relating the SCC in AP1000. The response was a thorough and comprehensive review of the materials and chemistry in AP1000. It identifies the main material types (nickel based alloys, stainless steels and low carbon alloy steels) in the primary circuit, tabulating locations where they are used and provides arguments in terms of the manufacturing, component design and environment as to why the susceptibility to SCC has been decreased in AP1000. The overall conclusion from this response was that "*AP1000 employs many methods of reducing Stress Corrosion Cracking in the primary side of the reactor. These methods include proper material selection, optimised thermal mechanical processing and heat treatment, using 'Lessons Learned' from previous PWR experience, and finally utilisation of robust geometrical design to further reduce stress which can contribute to SCC. Through these modifications the Westinghouse AP1000 successfully reduces the susceptibility of Stress Corrosion Cracking in the PWR.*" I was content with the response to TQ-AP1000-490 and would generally agree with the conclusion that AP1000 has incorporated many features which should lead to a reduction in PWSCC compared to previous reactor designs.

332 There have been instances of Intergranular stress cracking in some stainless steels in reactors in the past. These have been attributed by US NRC and Westinghouse to a phenomenon known as sensitisation, often associated with steels that contain relatively high level of carbon. For AP1000, Westinghouse has specified that no sensitised steels should be used in a stressed condition where they may be exposed to chloride or oxygen, effectively removing this concern.

333 Westinghouse has designed the control-rod penetrations to protrude further to improve access for inspection. Canopy seal welds have been eliminated, along with some instrumentation ports, thereby removing locations where problems have been experienced in the past.

334 There have been problems in older reactors with control-rod drive pins made from alloy X750. Westinghouse has replaced alloy X750 wherever possible with alloy 718 and in some applications by strain-hardened 316SS. Alloy X750 is still used for the springs inside the control rod drives. For these components, Westinghouse set limits for strain-hardening of the material and performing a specific heat-treatment (Ref. 212). Elsewhere, springs will generally be made from alloy 718. Alloy 718 is less susceptible to SCC than alloy X750. There have been no known cases of SCC in alloy 718 in the past 46 years of operation.

335 In terms of material selection for corrosion control, I am content with the case presented by Westinghouse for AP1000. While some detailed choices remain to be made, those that have appear reasonable given OEF and other constraints. Westinghouse have demonstrated strong controls over the material selection process for those that have not yet been chosen.

336 As for the radioactivity assessment, the controls applied to the SG tube Inconel 690 are important from an integrity perspective both because this is a large surface area and it is relatively thin to allow efficient heat transfer. Similarly, I selected this as a particular area for sampling during GDA and my assessment of the specifications and controls for Inconel 690 are assessed below, with Westinghouse pointing out that there have been no instances of SCC in Inconel 690 in over 20 years of operating experience.

4.2.4.1.1 Surface Conditioning and Finishes

337 In addition to alloy substitution, SCC risks 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. I queried the primary circuit material finishes to be applied in AP1000 in TQ-AP1000-1235 (Ref. 8). The response is a comprehensive overview of the main techniques to be applied in AP1000 and contains many supporting references to Westinghouse documentation that details the requirements for individual components or materials, including the specification for Inconel 690 SG tubing in AP1000 (Ref. 142).

338 Extensive fabrication controls applied in AP1000 include:

- Westinghouse has 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. 142). ND commissioned a TSC review of SG tubing manufacturing routes (Ref. 141). Westinghouse procedures are consistent with that review.
- The external surfaces of the pressuriser heaters will be shot peened or burnished to requirements specified by Westinghouse, who will request the fabricators procedure and qualification test reports for approval (TQ-AP1000-1235 (Ref. 8)). This area is assessed as part of the Structural Integrity assessment of AP1000 (Ref. 137).
- Welds in stainless steels will be subject to an ASTM intergranular corrosion test.
- Welds between stainless steel and Inconel 690 weld material equivalents will be subject to additional controls for sulphur content (TQ-AP1000-1235 (Ref. 8)).
- The external surfaces of the Passive Residual Heat Removal (PRHR) heat exchanger tubes will be shot peened because they will be in contact with oxygenated IRWST water (Ref. 155). The PRHR is assessed further in Section 4.2.8.1.

339 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 particularly important, as the barrier between the coolant and the base metal must be complete. I asked Westinghouse for details of their procedure for cladding, which they provided. The Westinghouse procedure (Ref. 195) is assessed in the ND Structural Integrity report (Ref. 137) and I am content that the procedures for fabricating and testing the cladding in AP1000 will be adequate from a Reactor Chemistry perspective.

340 Austenitic stainless steels and nickel-based alloys will be handled, protected, stored and cleaned to minimize pick-up of contaminants that could lead to IGA or SCC (TQ-AP1000-1235 (Ref. 8), Ref. 194 and chapter 13 of Ref. 25). The controls extend to tools and consumables such as tapes.

341 I also commissioned TSC support to examine surface conditioning and finishing in AP1000, both from a radiation and integrity perspective (Ref. 143). This review concluded that the choice of finishes in AP1000 would be resilient to cracking caused by the coolant. Particularly with the long service life expected, my TSC recommended that surface improvement techniques should be investigated at a later stage by the Licensee.

342 Overall, as for material selection, Westinghouse have presented well reasoned arguments for the selection of surface treatment and conditioning options to be applied in AP1000. These should minimise the corrosion concerns for the reactor design, including benefits in associated areas such as radiation protection and contamination. I was content with the arguments presented for the SG tubes.

4.2.4.2 Chemistry for Materials Integrity

343 Westinghouse consider the chemistry that limits cracking of Inconel 600 will also be beneficial to modern alloys such as Inconel 690, which has never been known to crack in service. The suggested chemistry regime is compatible with this, albeit this is implicit in the EPRI guidelines which cater for plants with both alloys (Ref. 15). Even with the introduction of Inconel 690 for SG tubing and other components, I agree with Westinghouse 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 AP1000. Chapter 4 of the Westinghouse AP1000 *"chemistry manual"* (Ref. 25) confirms the important role chemistry plans in assuring the integrity of AP1000 and states "*As detailed in Reference 1* [EPRI guidelines, Ref. 15] *primary water chemistry control for these Primary System pressure boundary and internal components is required in order to avert unacceptable risk of corrosion to these materials*". 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 principal factor determining reactor lifetimes of many decades.

344 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.

345 Good control of primary coolant chemistry is needed to avoid corrosion of the primary circuit materials. Westinghouse states that a constant target pH_T in the range [redacted] [redacted] is expected. This will be achieved by the controlled addition of enriched lithium hydroxide at a [redacted] mg kg^{-1} upper limit. During normal operations the controls on chemistry described in Sections 4.2.3.1 and 4.2.10 should offer sufficient protection to the primary circuit materials to remove the possibility of integrity damage by general corrosion.

346 As would be expected for an optimised chemistry, provided the additives and impurities are maintained within the defined operating bands, the primary chemistry parameters generally have little effect on localised corrosion. The concentrations of additive species such as boron and lithium have little effect on SCC of Inconel 690 type alloys (Ref. 236). 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 (Ref. 193). This is one of the reasons why there is a tight limit on lithium in place for AP1000. Of the remaining primary chemistry parameters those that can have the greatest influence on localised corrosion phenomena are the hydrogen and impurity levels, depending upon the precise alloy and corrosion mechanism.

347 Nickel-base alloy materials, such as Inconel 600, and to a lesser degree Inconel 690, 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 an important chemistry influence is provided by the hydrogen concentration which influences the electrochemical potential. In AP1000 Westinghouse expect hydrogen gas to be added to the coolant at levels consistent with the EPRI guidelines, which are currently between 25 and 50 cc kg^{-1} H_2 (Ref. 233). 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 Sections 4.2.2.2.3 and 4.2.7 in more detail. In terms of material integrity the levels specified for AP1000 appear reasonable and are consistent with OEF from operating plant with Inconel 690 which has not experienced any PWSCC in over 20 years of operation. Research on the effect of hydrogen on long-term cracking of Inconel 690 would be beneficial.

348 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 the water chemistry environment. 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. The levels of these species present within the primary coolant are monitored and minimised. 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, Westinghouse proposes adoption of the EPRI (Ref. 15) maximum oxygen and chloride concentrations, which are [redacted] and [redacted] $\mu g\ kg^{-1}$ respectively. These values (or similar) have been used successfully in PWRs for many decades.

349 Westinghouse 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, but do expect potential benefits from its application.

350 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 AP1000 are generally adequate. These are discussed further in the assessments of the CVS (Section 4.2.2) and overview (Section 4.2.10).

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

352 The chemistry controls proposed by Westinghouse for AP1000 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.

4.2.4.3 External Corrosion

353 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 Ref. 139 for many examples). As this aspect is not a fundamental Reactor Chemistry design issue and is more appropriately assessed during Site Licensing, this 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; there is no reason why such a strategy could not be implemented in AP1000.

354 I have noted instances where external corrosion has been considered by Westinghouse. Westinghouse specifications include details for the protection of external surfaces, not in normal contact with the coolant. These include treatment of some external parts with a manganese phosphate coating. For example; the reactor head closure studs, nuts and washers will be coated and are never expected to be in contact with borated water during refuelling. The studs, nuts and washers will be removed completely and stored dry. The selection of thread lubricants will be specified by Westinghouse (see Ref. 164).

355 I am content that arrangements for inspecting for external boric acid corrosion can be suitably addressed at a later stage of Licensing for a UK AP1000.

4.2.4.4 Summary

356 When my assessment of the materials of the AP1000 was conducted, not all the materials had been fully specified. 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 Westinghouse for AP1000 are generally high-grade and offer good resistance to corrosion, and Westinghouse clearly has good procedures in place to prevent the use of inappropriate materials or materials in an inappropriate condition.
- The AP1000 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) Locations susceptible to SCC have been designed out, by eliminating susceptible geometry and controlling residual stresses and cold work.
    iii) Alloy X750 fuel springs have been replaced by Alloy 718.
    iv) Avoiding sensitization and adoption of low carbon stainless steel alloys, where possible.
- PWSCC of stainless steels is rare in modern PWRs. I have not assessed the specific design rationale for the selection of austenitic stainless steels in AP1000. The stainless steels that I have assessed are high – grade low carbon types that I would expect.
- The lithium and boron levels in the coolant should not adversely affect crack growth rates in the materials chosen and are consistent with current EPRI primary water chemistry guidelines. Hydrogen levels, assessed in Section 4.2.7, are appropriate in this regard, but the system to control hydrogen at the correct level is the subject of the GDA Issue **GI-AP1000-RC-03**, see Section 4.2.2.6.
- 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. Westinghouse has put robust procedures in place to provide potential operators with the information they need to control corrosion in the field.

- My assessment has concentrated on corrosion caused by primary coolant from the inside to the outside. Corrosion from the secondary side inwards is considered in Section 4.4.3 of this report. I expect the licensee to develop procedures for detecting substantial corrosion of the reactor vessel externals and components as part of their normal business.

357 When taken as a collective answer, the TQ responses under this area add significantly to the AP1000 safety case for primary circuit integrity. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.2.4.5 Assessment Findings

358 Based upon the assessment of primary circuit integrity in AP1000 described in Section 4.2.4 above, I have identified no Assessment Findings from this section of my report however there is a related Assessment Finding on hydrogen in Section 4.2.7.

4.2.4.6 GDA Issues

359 Based upon the assessment of primary circuit integrity in AP1000 described in Section 4.2.4 above, I have identified no Reactor Chemistry GDA Issues in this area. However, this area is related to the cross-cutting GDA Issue on Limits and Conditions **GI-AP1000-CC-01**, described in Section 4.1.3.3.

4.2.5 Assessment – Fuel Integrity

360 In AP1000, 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. The AP1000 core is described in the PCSR (Ref. 1, Section 6.3) which states that the core is produced from 157 fuel assemblies with each assembly configured as a 17 x 17 square array of fuel rods. The number of fuel rods in each fuel assembly is 264 with 24 guide tubes and one instrumentation tube. The fuel rods are clad in ZIRLO®, a Westinghouse development from the previous Zircaloy-4 cladding alloy, which contains 1% Sn, 1% Nb and 0.1% Fe as additional alloying elements to reduce corrosion and oxidation. Westinghouse introduced ZIRLO® cladding in 1991 and claims the new alloy 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.

361 The lifetime of the fuel is limited mainly by two factors, the oxidation 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. 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. 1) does not discuss corrosion of the fuel, which is as significant departure from my expectations. The consolidated GDA PCSR (Ref. 105), with the inclusion of a chemistry chapter, should address this shortfall and I will confirm this as part of the cross-cutting GDA Issue **GI-AP1000-CC-02**. 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.

362 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 tubes, 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 4.2.3.3 of this report, the chemistry of crud itself and the calculations undertaken, by both Westinghouse and by TSCs for ND, are assessed below.

363 Modern fuel rarely leaks and Westinghouse support the US industry target to have no fuel leaks. The PCSR for AP1000 assumes 0.25% fuel cladding defects at any one time, which is very pessimistic (Ref. 171). Given good coolant control, the main causes of leaks would be mechanical wear due to debris. 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 any reactor will typically specify the maximum burn-up of the fuel and maximum tolerable leakage as important parameters. The lifetime of the fuel (burn-up) is partly determined by the extent of corrosion by the water, and the build up of internal pressure inside the rod. The PCSR for AP1000 contains a limit for radioactivity in the coolant, rather than a target number of failed rods. It is nevertheless good practice to monitor for fuel leaks so that damaged fuel can be removed and segregated at the earliest opportunity.

364 Even rare fuel leaks cannot be ignored so that Reactor Chemistry relating to fuel considers:

- The chemical additions and exclusion of impurities that minimise cladding corrosion in general and ZIRLO® 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.

365 The effects of chemistry on the fuel were an important part of the request under RO-AP1000-55.A1 (Ref. 7). I also raised several important TQs on this topic, including TQ-AP1000-565, 714 and 910 (Ref. 8). Westinghouse also provided their analysis of fuel crud production in AP1000 (Ref. 169) in TQ-AP1000-671 (Ref. 8). The response to these, amongst other Westinghouse documents, is described below.

366 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. 144).

4.2.5.1 Effects of Coolant Chemistry on Fuel Cladding

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

368 Since it is likely that burnable poisons (TQ-AP1000-072 (Ref. 8)) will be used in AP1000, the boron concentration and boiling will peak in the middle of the cycle. Westinghouse is quoting initial boron levels around 1000 mg kg^{-1} and peak boron levels up to around 1300 mg kg^{-1}. The lithium limit of [redacted] mg kg^{-1} and the boron levels give room to assure a reasonably high pH_T.

369 On its own, lithium is known to be harmful to Zircaloy cladding by increasing the corrosion rates. Lithium is added to the coolant to reduce the acidity of the boric acid but combining lithium with boric acid makes it less harmful to Zircaloy. Lithium has the greatest effect when the zirconium oxide layer is already > 60 – 70 µm. The primary reason for the Westinghouse limit of [redacted] mg kg^{-1} on the primary coolant lithium level is to protect the fuel cladding. Historically lower levels, of 2.2 mg kg^{-1}, were used but recent operating experience has shown that much higher levels, up to 6 mg kg^{-1}, can be successfully used without causing significant increases in cladding corrosion (Ref. 145). Additionally, since the oxide layers tend to be thinner on ZIRLO® than Zircaloy, the lithium limits specified by Westinghouse, in Ref. 26, will be adequate.

370 The addition of Nb to ZIRLO® resulted in fuel cladding corrosion falling by 60% in the presence of hydrogen. However, without extra hydrogen dissolved in the coolant, the corrosion of ZIRLO® would be worse than the Zircaloy-4 it replaced (Ref. 224). Excessively high levels of hydrogen can lead to hydride embrittlement, so it is normal practice to specify lower and upper concentrations for hydrogen of 25 – 50 cc kg^{-1}, which I consider to be acceptable for fuel protection. Due to problems with older reactors which contain Inconel 600 (unlike AP1000) EPRI is considering changing the maximum hydrogen limit, potentially to allow higher than 50 cc kg^{-1} (Ref. 233). On current knowledge there appears to be no justification for doing so in AP1000.

371 Impurities can increase the corrosion rate of fuel cladding. High fluoride levels have been shown to be particularly detrimental to Zircaloys. The effect of chlorides and iodides is smaller than fluoride (i.e. equivalent damaging concentrations are higher) although fission-product iodide can accumulate on the inside surface of the cladding. The threshold level for fluoride effecting cladding is around 10 mg kg^{-1}, above which the corrosion rate increases sharply, but the ion-exchange resins in the CVS will not remove fluorides efficiently, so fluoride ingress must be prevented by effective purification of the feedwater. Fluoride is measured in the primary coolant and controlled to levels below [redacted] µg $kg^{-1,}$ according to the EPRI guidelines (Ref. 15). Other impurities such as sodium hydroxide, chlorides, sulphates and chromates can have a moderate effect, but much less than lithium and fluoride. Such effects are well understood and the "*routine*" controls suggested by Westinghouse are reasonable.

372 Westinghouse has specified zinc addition to guarantee their fuel in AP1000 and in their supplemental guidelines (Ref. 26). Section 4.2.6 of this report covers the effects of zinc, which would be added to control fuel crud formation.

373 It is clear that Westinghouse has taken account of the effects of additives and impurities on the fuel in their specifications for AP1000, but the chemistry of fuel clad corrosion was not discussed in the original PCSR (Ref. 1). The corrosion effects outlined are slow and with planning, problems due to corrosion should be avoidable. I raised RO-AP1000-55.A1 (Ref. 7) asking Westinghouse to generate a topic report on chemistry and action A9 requesting a PCSR chapter. The draft PCSR chapter (Ref. 23), described in Section 3.2,

contains much more information on the effects of chemistry on fuel integrity, which is also given as a "*safety goal*" for primary coolant chemistry. This is much improved on the Step 4 PCSR (Ref. 1).

374 The effects of coolant chemistry on the fuel cladding are an important part of Assessment Finding **AF-AP1000-RC-01**.

4.2.5.2 Fuel Crud

375 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 a major factor in causing deposits (fuel crud) to accumulate.

376 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 4.2.3.3, in addition to generating waste and an ORE hazard. As more fuel crud deposits this can result either in damage to the fuel cladding, via Crud Induced Localised Corrosion (CILC), or in extreme cases as a distorted power profile, via 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 CIPS has been observed in more than one PWR. 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, the power at Callaway had to be reduced for several cycles until the cause of the problem could be rectified (Ref. 218). 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.

377 No PWR in the world operates with zero fuel crud. In fact, a thin layer of low-density crud is perfectly tolerable as coolant can boil inside the crud and helps to keep the cladding surface cool. Thick dense crud build-up can have several effects (Ref. 168) harmful to fuel and the core including:

- Crud of low porosity, such as created by silicates, is much less effective at removing heat from the fuel.
- Hotter fuel surfaces corrode more quickly.
- The presence of crud can measurably decrease the flow of coolant, slightly increasing cladding temperatures.
- Lithium can concentrate inside the crud.
- Thicker crud absorbs boron to potentially cause CIPS.

378 Several of these effects were also assessed as part of the GDA for fuel (Ref. 144). The total boiling area and thickness of the crud are the key determining factors for CIPS and CILC. CIPS is caused by a large mass (in the kg range) of soluble boron from the coolant becoming absorbed into the fuel crud, so a large boiling area is needed. Therefore the limiting value of crud thickness (in addition to the normal oxide layer) will be higher than suggested above, and the chemistry of the coolant could minimise accumulation of crud in the core, rather than prevent it. The rate of boiling in AP1000 is similar to Callaway but Westinghouse believes the Licensee can control the build-up of fuel crud by using advanced modelling techniques to assess the impact of different operational regimes and adopting the following strategy:

- Operate at a minimum pH_T of 7 (TQ-AP1000-714 (Ref. 8) and Ref. 217).
- Use of Inconel 690 rather than 600 for SG tubing, which generates fewer dissolved solids all other factors being equal.
- Adding zinc and placing additional controls on the chemistry to minimise the risk of precipitation of zinc compounds on the fuel.
- Excluding silica from the core by such practices as avoiding use of glass-fibre filters.

379 Westinghouse argues that even though the boiling rates in Callaway and AP1000 would be similar, substituting Inconel 690 for Inconel 600 and adding zinc has the effect of reducing crud build-up on the fuel to acceptable levels. By acceptable in this context, Westinghouse means that crud thicknesses will be low and the risk of either CILC or CIPS will be low. This neglects the effects of fuel crud on the radioactivity in the coolant, as discussed in Section 4.2.3.3.1.

380 To support these arguments Westinghouse has provided their own predictions of crud build-up on fuel in AP1000, using the "*generic*" core design (Ref. 169). As described in Section 4.2.3.3, I have compared these results with equivalent calculations by my TSC using the same base data but slightly different models (Ref. 163). Because modelling PWR chemistry in this way is still quite novel, I also asked Westinghouse to compare results for AP1000 with their own calculations for Callaway, in TQ-AP1000-910 (Ref. 8). The Westinghouse Callaway calculations were "*unverified*". However, I do not believe that numerical results of this type of modelling should be taken too literally, but the trends and orders of magnitude are credible. Such comparisons do however provide valuable insights into understanding the factors important to controlling crud formation and its effects.

381 The Westinghouse calculations (for AP1000 cycle 1 to 3 and Callaway cycles 6 to 9), as given in the response to TQ-AP1000-910 (Ref. 8), indicate that:

- The amount of boiling in the core will be similar in Callaway and AP1000 and boiling in AP1000 will be highest in cycle 2. The reasons why cycle 2 should have a higher boiling duty were unclear.
- The total mass of crud in the core of AP1000 will be [redacted] kg at the end of cycle 1 and [redacted] kg at the end of cycles 2 and 3.
- The comparable figures for Callaway cycles 6, 7, 8 and 9 are [redacted], [redacted], [redacted] and [redacted] kg respectively.
- The maximum crud thickness in AP1000 would be [redacted] μm during cycle 3.
- The maximum crud thickness for Callaway is predicted to be [redacted] μm for cycle 6.
- The measured thickness of crud at Callaway was 125 μm at the end of cycle 9, compared to a predicted [redacted] μm by Westinghouse (averaged over ¼ assembly or 66 fuel rods).

382 The TSC calculations for AP1000 and a "*standard*" 4 loop PWR are described below. The calculations used the Westinghouse supplied boiling rates and plant data, as used by Westinghouse for their AP1000 model (TQ-AP1000-565 (Ref. 8)).

- At the end of cycle 1 there will be 17 kg of crud in the AP1000 core, of which 11.6 kg was nickel. This is much more than was calculated by Westinghouse ([redacted] kg).

- For the "*standard*" 4 loop PWR without boiling, there will be around 5 kg of nickel in the core at the end of cycle 1.
- Crud thicknesses predicted were similar to the predictions by Westinghouse

383 As with all such comparisons there needs to be due recognition of the difficulty in comparing estimates too precisely. In addition the models used were similar but not identical between Westinghouse and my TSC. However, the general trend appears to indicate that Westinghouse is predicting much lower masses of fuel crud than my TSC, although the thicknesses appear similar. There may be a number of reasons for these differences, including:

- Westinghouse appears to use a corrosion rate for Inconel 690 which is very low. My TSC uses the average from a number of data sources.
- Similarly, it is not clear what corrosion rate Westinghouse has used for stainless steel, which affects the mass of iron in the core. Westinghouse did not indicate in TQ-AP1000-910 (Ref. 8) or elsewhere how they calculated levels of dissolved iron. In the absence of a corrosion rate for the stainless steel pipework, Westinghouse normally 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 the total mass of crud produced. The iron produced by corrosion of stainless steels is more of a factor for CIPS and CILC than it is for radiation.
- The TSC calculations model crud outside the core in much greater detail than the Westinghouse model used for AP1000. The version of BOA used by Westinghouse includes the feedback effect of crud causing more boiling and this should lead to an over-estimate of crud build-up in the boiling regions. However, the modelling of chemistry in this version is simplified and provides no estimates for crud or radiocobalt outside the core. Westinghouse uses their CORA code for this. Westinghouse think that the amount of crud residing outside a core is comparable to that inside the core in a PWR. The model maps thicknesses of crud over the fuel and Westinghouse uses a figure of 40 μm as the threshold for CILC.
- There may be differences in how both calculations have accounted for the effects of temperature and zinc. Westinghouse takes credit for the effects of zinc by reducing the corrosion rates by 25%.

384 Primary circuit pH_T can affect the risks from fuel crud formation at the beginning of the fuel cycle. The normal EPRI guidelines recommend a minimum pH of [redacted] and I consider this may be too low for AP1000. I am still to be convinced that this minimum pH_T is high enough to control crud and Westinghouse have not justified that this will reduce fuel crud levels SFAIRP. Similarly, overestimating crud in the boiling region would be pessimistic for CIPS and CILC (provided the iron calculation is correct) but it may be optimistic in terms of radioactivity build-up elsewhere in the plant. Other assumptions in the Westinghouse calculation, such as the extent of carry-over from one cycle to the next, also need clarifying and confirming. This is related to Assessment Findings **AF-AP1000-RC-01** and **AF-AP1000-RC-11**.

385 From their calculations, Westinghouse concludes that there should be low risk of CIPS or CILC in AP1000 (Ref. 169). This is based on the 40 μm threshold applied by Westinghouse, below which CILC does not occur. This threshold appears to be based purely on plant OEF. The Licensee will need to clarify how the threshold figures for both CIPS and CILC are justified, and the measurement method to which it applies. I consider this to be an Assessment Finding, **AF-AP1000-RC-12**.

386 Westinghouse also claims the use of low levels of zinc reduces fuel crud. This is the first time zinc will have been applied specifically to control crud build-up on fuel in a PWR. The magnitude of the effect of zinc on corrosion rates under operating conditions is a key input to assessments of crud build-up. Section 4.2.6 of this report covers the evidence that zinc helps to prevent the build-up of radiocobalt on reactor surfaces. There was little evidence provided for zinc reducing production of dissolved solids by corrosion in the EPRI zinc addition guidelines (Ref. 217) which only briefly mentions relevant laboratory tests. When I requested evidence from Westinghouse, I was provided with Refs 219 to 221, summarising laboratory tests and plant operating experience of Westinghouse and others. The bulk of the laboratory corrosion rates were measured at 20 μg kg^{-1} zinc and concentrated on Inconel 600. There is data for stainless steels and Inconel 690 but less of it, and practically none at the level of zinc proposed for AP1000. I am satisfied that these reports explain the effect of zinc, but quantification of its effectiveness at low concentrations is weak.

387 Adding zinc to an existing reactor tends to increase the release of nickel and cobalt for a few cycles before it falls. This is why Westinghouse proposes to add zinc during commissioning, to fully condition the surfaces before using nuclear fuel. Furthermore, the improvement possible with zinc may not be large if the initial corrosion rate is small. The Japanese reactor Tomari-3 was the first PWR in the world to apply zinc during commissioning (Ref. 219) and results from its first fuel inspection are due later in 2011 and may provide useful evidence to support the AP1000 case. The addition of zinc during Hot Functional Testing (in commissioning) is discussed further in Section 4.2.12.

388 The AP1000 is a relatively high duty core, but Westinghouse has never experienced severe CIPS in a reactor with Inconel 690 SG tubing. Providing that due care is taken during commissioning, and subject to further sensitivity analyses by the Licensee in **AF-AP1000-RC-11**, I am content that the levels of crud on fuel could be controlled in an AP1000 to prevent fuel damage (CILC) and despite some differences between the Westinghouse and TSC calculations, it does not appear that AP1000 is at significant risk of developing CIPS. It is nevertheless important that the limits and conditions that keep the chemistry benign for fuel integrity are defined, and I have identified a finding for the licensee to define these and importantly, to define actions and timescales for chemistry that is out of specification. I consider this to be an Assessment Finding, **AF-AP1000-RC-13**. This is also related to the cross-cutting GDA Issue on Limits and Conditions **GI-AP1000-CC-01**.

4.2.5.3 Summary

389 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of fuel are:

- Modern ZIRLO® fuel cladding proposed by Westinghouse for the AP1000 allows greater margins regarding end of life oxide thickness than the Zircaloy-4 cladding used in the past.
- The fundamental chemistry should have negligible effect on the fuel cladding of AP1000 directly and has been successfully used in many PWRs for a number of decades with very few fuel failures.
- Despite this, it would still be possible to operate a PWR using a chemistry that would increase the risk of fuel failures, even with modern cladding alloys. This is the reason that rigorous chemistry limits should be defined along with actions if the limits are exceeded. Chapter 4 of the EDCD discusses the effects of oxide and crud growth on

heat output from the fuel, but these effects are small. Extensive boiling of the coolant tends to create thicker crud deposits on the fuel that increase the corrosion rate and absorb boron from the coolant. The basis for the various limits relating to fuel integrity control should be documented by Westinghouse. This is related to the cross-cutting GDA Issue on limits and conditions, **GI-AP1000-CC-01**.

- Westinghouse presented their analysis for fuel crud deposition in the generic core of AP1000 over cycles 1 to 3. Because it has a relatively high-duty core and a large SG surface area, AP1000 may be prone to develop fuel crud unless strict controls are put in place by the Licensee. My own analysis of the AP1000 indicated that even more fuel crud is possible, with the Westinghouse calculation appearing optimistic.
- Westinghouse is helping to develop advanced computer models to understand and control fuel crud. Assumptions in the Westinghouse calculations, such as the extent of carry-over from one cycle to the next, need clarifying and these calculations should be repeated with more analyses of sensitivity to factors such as pH_T, boiling and dissolved corrosion products when the plant specific operating chemistry and core design is known. This is addressed by Assessment Finding **AF-AP1000-RC-11** in the radioactivity section of this report, but is equally applicable to fuel protection.
- Westinghouse stipulates the addition of zinc in AP1000 to reduce corroded metal release to mitigate the impact of boiling. This is a novel approach. I have requested more evidence quantifying the use of low levels of zinc in this particular way, under the zinc section of this assessment (Section 4.2.6).
- Providing that due care is taken during commissioning, I am content that general levels of crud on fuel could be controlled in an AP1000, but Westinghouse have not demonstrated that crud really would be controlled, and it is not at this stage clear what margins the proposed operating parameters allow. 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 should not be left in the reactor for more than one cycle and is normally segregated in the pool.

390 On the basis of the evidence presented by Westinghouse during GDA, I consider that a reasonable case has been provided to support GDA, although I believe that the Licensee will need to build upon this case during later stages of Licensing for AP1000.

4.2.5.4 Assessment Findings

391 Based upon the assessment of fuel in AP1000 described in Section 4.2.5 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-AP1000-RC-12** – *The Licensee shall review how the thresholds for power-shift due to crud (CIPS) or crud induced localised corrosion (CILC) are justified, and the methods of measurement to which they apply. The Westinghouse threshold appears to be based purely on plant Operational Experience Feedback (OEF). This Assessment Finding should be completed before nuclear operations, as this is when fuel crud is formed; Target milestone – Initial criticality.*

AF-AP1000-RC-13 – *The licensee shall review and justify the controls that are in place throughout the fabrication, installation and commissioning of metal surfaces that will be in contact with primary coolant to ensure that releases will be ALARP. This may involve a review of fabrication and site controls that influence corrosion release. This Assessment Finding should be completed before relevant metal surfaces are delivered to site; Target milestone – Mechanical. Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

4.2.5.5 GDA Issues

392 Based upon the assessment of fuel integrity in AP1000 described in Section 4.2.5 above, I have identified no GDA Issues specific to fuel integrity which require resolution before nuclear island safety-related construction of a reactor could be considered, however this topic is related to the cross-cutting GDA Issue on Limits and Conditions **GI-AP1000-CC-01**, described in Section 4.1.3.3.

4.2.6 Assessment – Zinc Addition

393 The power of the AP1000 is similar to that of some of the plants that have experienced high levels of fuel crud, which has led to problems with fuel and radiocobalt production. Westinghouse proposes two main measures that will ensure similar problems in AP1000 do not arise; the use of Inconel 690 for the SG tubing and the addition of zinc. Zinc is recommended as a means of controlling out-of-core radiation by EPRI and is used in many reactors overseas, but its use to control fuel crud is novel. Westinghouse has made the use of zinc a condition of their guarantee for fuel in AP1000, as stated in the Westinghouse supplement to the EPRI guidelines (Ref. 26). Zinc addition is a process which is gaining more widespread acceptance amongst PWR operators worldwide (especially within the US) and is common in reactors which have existing issues with dissolved solids, crud and high ex-core radiation fields, or with material integrity concerns (Ref. 15). In contrast, Westinghouse claims the AP1000 will not suffer from these problems, but that zinc will still be essential.

394 At the start of GDA, Westinghouse had provided no evidence either to support zinc addition or prove it was harmless. At the end of Step 3, I raised RO-AP1000-56 (Ref. 7) and several TQs to obtain the required evidence. I also raised TQ-AP1000-978, 1171 and 671 the latter to obtain References (Refs 169, 197, 199 and 220 to 222). This section concerns the detailed operation of zinc and evidence for its usefulness; my assessments of radioactivity in AP1000 and the integrity of fuel appear in previous sections of this report, where zinc also has effects.

395 It is notable that there are many discrepancies in the PCSR and supporting documents assessed during Step 4 regarding the application of zinc in AP1000. These include differences in the concentration (up to 40 μg kg^{-1}), depletion (natural or depleted) and claims made regarding zinc (radiation protection, corrosion rate reduction, fuel crud mitigation and SCC prevention). These differences need to be rectified in the safety case, so that a single consistent safety case is presented. I consider this to be an Assessment Finding, **AF-AP1000-RC-14**.

396 I have used the response to RO-AP1000-56 (Ref. 146), which specifically asked for evidence supporting the use of zinc in AP1000, as the basis for my assessment. This response states that:

- Zinc will be added as zinc acetate at [redacted] μg kg^{-1} zinc.

- Natural or depleted zinc will be used, with depleted recommended by Westinghouse.
- Zinc is primarily claimed to reduce corrosion rates and mitigate fuel crud, but benefits are also expected in plant radiation levels and SCC mitigation.

397 Achieving such a low level requires careful control over the addition, and I assessed how this was achieved in AP1000 as part of the assessments of the CVS (Section 4.2.2) and sampling systems (Section 4.2.9) reported elsewhere in this report.

4.2.6.1 Potential Zinc Detriments

398 The overall benefits of zinc are cited in many sources, both by Westinghouse and more widely in the nuclear industry, namely reducing radiation fields and protecting materials. However, any potential drawbacks to zinc addition are much less well known and publicised. There are several potential negative effects of zinc addition. I have assessed several of these elsewhere in this report:

- Zinc is preferentially absorbed onto the ion-exchange resins in the mixed / cation bed of the CVS, forcing lithium out. Westinghouse calculations in the response to RO-AP1000-55.A3 (Ref. 32) show that Zn addition does adversely affect CVS resin performance but the effect is small at the Zn concentration specified for AP1000. The impact of adding more zinc may not be trivial if it impacts on the capacity of the resins, see Section 4.2.2.3.1.
- I am content with the Westinghouse assessment in Ref. 197 that concluded there were no negative effects on auxiliary system components, effects on special alloys or thermowell response times. There are no main pump seals in AP1000 for zinc addition to affect.

399 My assessment of those that remain is given in the following sub-sections.

4.2.6.1.1 Zinc Precipitation

400 Solid zinc borate has been found in crud and zinc can react with lithium hydroxide to form solid zinc oxides. Therefore, zinc should not be added in such quantities as to increase crud formation, particularly if boron gets incorporated with zinc deposited on the fuel. Responding to TQ-AP1000-978 (Ref. 8), Westinghouse said up to 5 kg zinc would be added to AP1000 in each cycle in order to maintain [redacted] μg kg^{-1} in solution, but this is very much subject to uncertainty as absorption rates depend on the previous plant history. Much of this would be absorbed on metal surfaces in the reactor and some would be lost to the CVS resins.

401 Some zinc chemistry was included in the TSC calculations of crud growth in AP1000 (Ref. 163) and the results indicate there was no evidence of appreciable zinc borate precipitation on the fuel where crud was less than 20 μm thick. The area of thicker crud was small. Another TSC also independently reviewed the chemistry and materials in AP1000 (Ref. 164) and advised that zinc addition up to 15 μg kg^{-1} would have no detrimental effects in terms of CIPS or CILC. Since zinc would not be added at the same point as lithium hydroxide or boric acid, and the design change to the hydrogen/zinc dosing system in the CVS both separates and moves the zinc injection point, I was content that zinc hydroxide or zinc borate would not precipitate in AP1000 under the conditions expected.

402 The formation of small amounts of crud on nuclear fuel is 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. It is the potential of developing thick and tenacious crud with zinc addition that is the greatest concern for PWRs. Such deposits can impede heat transfer between the cladding and coolant and cause cladding failures, as well as enhance the crud environment for developing CIPS and higher levels of radiocobalt. Species like silica can form a denser crud, with zinc silicate being particularly insoluble, and for this reason, silica levels should be controlled in higher duty cores with zinc addition. To prevent the formation of denser fuel crud and limit interactions with dissolved metals a "*limit*" or suitable controls on soluble nickel and iron should also be set before zinc can be added (Ref. 168). Westinghouse specifies a silica limit of ≤[redacted] mg kg^{-1} prior to criticality in their supplemental AP1000 guidelines (Ref. 26) and no limits for nickel or iron. No justification is given for these limits, or lack thereof, which are standard practice in many high core duty PWRs which inject zinc. Westinghouse guidelines for their fuel customers (Ref. 217) do specify additional controls for nickel (<[redacted] μg kg^{-1}) and iron (<[redacted] μg kg^{-1}), but only if anomalous behaviour is observed. In effect Westinghouse have described these values as 'action levels' for the Licensee but have not formally defined what the action(s) should be. I see no reason why such controls are inappropriate for AP1000 and require the Licensee to justify limits on silica, iron and nickel in their plant specific chemistry plan. I consider this to be an Assessment Finding, **AF-AP1000-RC-15**.

4.2.6.1.2 Effects on Fuel crud

403 A thin, dark deposit on the surface of the fuel rods is often observed when the fuel is removed from PWRs. The concern is whether zinc makes fuel crud more dense and adherent.

404 Westinghouse claims that with zinc crud is thinner, more widely distributed, less activated, more easily released in shutdown, depleted in iron and has a low incorporation of zinc. In addition, Westinghouse reports that fuel crud formed with zinc falls off the fuel more easily, once in the fuel pond.

405 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-appearing 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. It has been speculated to be carbon, from the reduction of acetate, the organic component of the zinc additive that is used. The thickness of these deposits has been measured and was found to be very thin (Ref. 199). Examination of the crud scraped from fuel from the eleventh cycle at Diablo Canyon revealed that 5 -15 % was solid carbon, Westinghouse report (Ref. 199).

406 The zinc levels suggested for AP1000 are within current plant operating experience and therefore should not pose additional concerns regarding fuel crud, noting that this is subject to an Assessment Finding, **AF-AP1000-RC-11**, requiring further work in this area.

4.2.6.1.3 Effects of Acetate

407 Westinghouse suggests zinc will be added to AP1000 from a dilute solution of zinc acetate. The acetate counter ion contains natural ^{12}C and there is the possibility that this may alter the distribution of ^{14}C in the RCS and plant. The low neutron capture of ^{12}C

means that generation of additional ^{14}C is negligible. The acetate counter ion is also likely to be destroyed in the neutron flux of the core, leading to the production of mainly methane but also other species such as soluble carbonates. The lack of VCT in the AP1000 CVS may also impact on what happens to the acetate or its degradation products.

408 I asked Westinghouse whether alternatives to the acetate had been considered, such as zinc borate or zinc formate. The borate would add nothing to the primary coolant that is not already present, other than the zinc itself. In the response to RO-AP1000-56 (Ref. 146) Westinghouse confirmed that they did try zinc borate some years ago, but the borate is rather insoluble and the resultant line blockages made controlling zinc levels less precise, in their experience. The addition of zinc formate would add half the carbon added from zinc acetate, but this is not a sufficient reduction that natural carbon could be ignored and the formate form was found to be less readily available.

409 I raised TQ-AP1000-516 (Ref. 8) on the effect on ^{14}C distribution of dosing zinc acetate and further data were also provided by Westinghouse in responding to TQ-AP1000-930 (Ref. 8). Westinghouse expects 1 to 4 kg of natural ^{12}C will be added in acetate form during each cycle. This is an order of magnitude higher than other sources of natural carbon and several orders of magnitude greater than the mass of ^{14}C produced in the reactor. Thus the dominant source of carbon is the acetate and the fate of this carbon may become important in determining what happens to the ^{14}C.

410 At non-zinc plants, 90% of the ^{14}C is gaseous, with only 0.5% remaining in liquid waste. Westinghouse does not expect this proportion to change with the addition of zinc acetate, quoting experience at the Halden test reactor, when formate was added to the coolant and was fully decomposed by radiation in the core (Ref. 179).

411 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 exhausted during the cycle. Since the resins continued to function in these plants, Westinghouse assumes that little of the acetate results in bicarbonate (Ref. 199).

412 Overall, there appears to be a shortage of conclusive evidence for the fate of the acetate dosed with the zinc. The design features of AP1000 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 US 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 appears to relate to the influence of this species on the ^{14}C fate in AP1000. I have shared this information with both the Environment Agency and Radwaste inspectors during Step 4.

4.2.6.1.4 Generation of ^{65}Zn

413 Natural zinc contains 49% ^{64}Zn. In a reactor, this 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 in some wastes. Adding zinc to some reactors has caused an increased accumulation of some radioactive materials on site, so it is necessary to demonstrate an overall benefit from zinc addition. BWR reactors that use natural zinc accumulate more ^{65}Zn activity in radwaste than ^{60}Co. Consequently, many operators use zinc that has been depleted in ^{64}Zn (< 1%), which generates less radwaste. Westinghouse recommends use of depleted zinc in AP1000, and have based many of their assessment for AP1000 on the use of depleted zinc (for example, Ref. 170), but allow customers of AP1000 to use either. I conclude that a licensee would have to justify using natural zinc, since depleted

zinc clearly generates less radwaste and contamination. I consider this to be an Assessment Finding, **AF-AP1000-RC-16**.

4.2.6.2 Evidence for Zinc Benefits

414 Westinghouse summarised their evidence to support zinc addition in the response to RO-AP1000-56 (Ref. 146), which contained many supporting references. Westinghouse bases its evidence for reducing corrosion on direct laboratory evidence and plant data. The main laboratory results from Reference 197 were based on autoclave corrosion tests with Inconel 690, 600, 750, Stellites^{TM} and other alloys. Westinghouse also provided data from early inactive loop experiments, Ref. 222. These showed:

- Substantial reductions in the rate of corrosion measured by weighing, typically by a factor of around 3 for relevant metals.
- Surface examinations showed thinner oxide layers with zinc than without zinc, suggesting that zinc was helping to stabilise a non-corroding surface layer.
- Many BWR plant data exist; the main PWR plant data quoted were from Farley 2 and Callaway (Ref. 197).
- Spectroscopic examinations of SG tubes from Farley 2 showed zinc concentrating under the oxide layer closest to the metal surface.
- Radiocobalt release is slower in the presence of zinc.
- Fuel inspections from Callaway showed decreased crud thicknesses on fuel after SG replacement and zinc addition.

415 Westinghouse cited five PWRs with Inconel 600 SGs that had operated for many cycles without zinc and then started to add zinc. In this case, nickel releases during shutdown increased for 2 or 3 cycles then seemed to drop. The explanation for this was that, as zinc gets absorbed into an existing corroded layer, it displaces some of the cobalt and nickel already there. After 3 cycles of addition to a mature plant with Inconel 600, nickel releases did fall below previous levels.

416 Westinghouse also provided data from five PWRs which upgraded their SGs to Inconel 690, two of which used zinc. In the plants without zinc, shutdown nickel releases increased after the upgrade before they decreased. In the zinc plants, nickel releases appeared to decrease immediately and continued to decrease further to 8% of their pre-replacement values after 3 cycles. The zinc concentration was 30 and 15 $\mu g\ kg^{-1}$ before and after the SG replacement in each case (Ref. 220). Westinghouse also claims the support of Ref. 141, which is a TSC report produced for the ND Structural Integrity assessment of AP1000.

417 An important difference between AP1000 and the supporting evidence quoted by Westinghouse is the concentration of zinc added. Overall, on the basis of the evidence presented by Westinghouse I conclude there is good evidence that adding > 20 $\mu g\ kg^{-1}$ zinc is beneficial in the long term in PWRs which have trouble with radiation fields or problems with cracking in Inconel 600. Laboratory tests have shown that levels of zinc above 20 $\mu g\ kg^{-1}$ does indeed reduce the corrosion rates of several alloys (including Stellites^{TM}) when tested individually (Ref. 217). In reviewing aspects of AP1000, my TSCs noted that evidence from trials at Vandellós II for reducing fuel crud deposition with zinc was less convincing (Refs 164 and 168), although this was for an existing plant with Inconel 600 SG tubing. Since the mechanism by which zinc might reduce nickel and iron

release is still not fully understood, it seems difficult to guarantee the concentration of zinc needed in order to achieve the desired affect.

418 A further subtlety in the use of zinc is that it is accepted that the actual concentration is not as good an indicator of performance benefits as the cumulative addition (i.e. $\mu g\ kg^{-1}$ multiplied by the number of months; ppb-month). This may mean that the expected benefits for AP1000 may not be realised as early in operation as expected. Westinghouse proposes the use of zinc during HFT to counter some effects of this, see Section 4.2.12. This is another reason to suggest the Westinghouse fuel crud estimates may be optimistic, which assume an immediate 25% reduction in corrosion rates, and support the Assessment Finding related to conducting further studies in this area, **AF-AP1000-RC-11**.

419 I consider that further evidence is required in this area. The Licensee should demonstrate that corrosion rates can achieve the expected benefits claimed by Westinghouse given the reactor zinc injection profile. This will demonstrate that a low zinc concentration is acceptable and present a comparison of corrosion rates with ppb-months of zinc delivery with some assessment of the reduction achievable for a reactor with new ready-passivated surfaces. I consider this to be an Assessment Finding, **AF-AP1000-RC-17**.

420 I am content that evidence for the benefit of depleted zinc addition exists and that it would probably help in AP1000. However, I find that the extent by which corrosion is reduced by [redacted] $\mu g\ kg^{-1}$ zinc and hence the amount of zinc needed, are still unclear.

4.2.6.3 Controlling Zinc Addition

421 The zinc addition system in AP1000 is described in Section 4.2.2.2.4.

422 After adding zinc for the first time (which would be during commissioning in AP1000), at such low levels it would take some time for zinc to absorb into surfaces and for concentrations in the coolant to become steady. Zinc is so easily absorbed onto metal surfaces and the CVS resins, that sampling and measuring its presence at $\mu g\ kg^{-1}$ levels is difficult. Section 4.2.9 of this report covers the difficulty of measuring and controlling the presence of zinc.

423 Westinghouse recommends [redacted] $\mu g\ kg^{-1}$ zinc for AP1000 and has advised that the key measurements for zinc are:

- The zinc concentration multiplied by the number of months of zinc addition (conveniently quoted in ppb-months), or
- The total number of kilograms added (about 10kg for effective passivation of a typical PWR).

424 These specifications are different because the number of kg needed does not correspond directly to ppb-months due to factors such as the CVS clean-up rate and the surface area to be treated.

425 In TQ-AP1000-978 (Ref. 8) I asked Westinghouse to quantify the amount of zinc needed to saturate metal surfaces in AP1000. Based on their experience with plants with similar new SGs, around 5 kg of zinc must be added over the course of the first cycle to maintain the target concentration, assuming a certain rate of removal by CVS. This is around half the amount quoted by Westinghouse as needed for a typical large PWR in Ref. 197. Westinghouse said they experience zinc uptake rates between 20% and 90% on average during one cycle, with up to 95% in the first few months. Uptake can very between similar

plants and from one cycle to the next. These large variations in the amounts of zinc added imply a similar variation in the corresponding amount of corrosion.

426 Because of the use of different measures, 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. The mass of zinc added and the concentrations of corrosion products could be better control measures of zinc effectiveness in my view, since the ppb-month is plant-specific and is not directly measuring the effects of zinc.

427 Sudden bursts of particulate or "*crud bursts*" have been observed occasionally in plants that operate without zinc addition and in a small number of plants operating with zinc. It does not appear that zinc is a contributing factor to the frequency or scale of such events. As zinc mostly impacts the inner oxide layers, which should not be affected by such events, I am content that even if such events were to occur in AP1000 they should not significantly affect the zinc addition programme, although the Licensee should plan for such events including any requirements to replace lost zinc to regain protection.

4.2.6.4 Summary

428 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 [redacted] μg kg^{-1} depleted zinc will not adversely affect AP1000 safety provided specifications for pH_T 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 AP1000. The application of zinc specifically to limit fuel crud is novel and evidence that the zinc level proposed by Westinghouse will be sufficient is not comprehensive.
- 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.
- Overall there are net benefits from the controlled addition of zinc to a PWR. The licensee should review the latest evidence for its effectiveness before deciding on a regime for the addition of zinc.

429 When taken as a collective answer, the TQ and RO responses under this area add significantly to the AP1000 safety case for zinc addition. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA, but note some areas where further work will be required by a future UK AP1000 Licensee.

4.2.6.5 Assessment Findings

430 Based upon the assessment of zinc addition in AP1000 described in Section 4.2.6 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-AP1000-RC-14 – *The Licensee shall ensure that the safety case related to zinc addition in AP1000 is consistent regarding concentrations, limits, zinc form and claims. This Assessment Finding should be completed before zinc is first used in the reactor systems; Target milestone – Hot Ops*.

AF-AP1000-RC-15 – *The licensee shall justify limits for silica, iron and nickel in the primary circuit of AP1000 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*.

AF-AP1000-RC-16 – *The Licensee shall ensure that the form of zinc used and the amounts added will result in a net reduction of radioactivity across the plant and in wastes. This Assessment Finding should be completed before zinc is applied to the reactor with nuclear fuel present; Target milestone – Initial criticality*.

AF-AP1000-RC-17 – *The Licensee shall review the latest evidence for the effectiveness of low levels of zinc at controlling corrosion in Inconel 690 and stainless steels before deciding on a regime for its addition. The review should consider both the Inconel 690 and stainless steel components. This Assessment Finding should be completed before hydrogen is first applied to the reactor; Target milestone – Hot Ops*.

4.2.6.6 GDA Issues

431 Based upon the assessment of zinc addition in AP1000 described in Section 4.2.6 above, I have identified no Reactor Chemistry GDA Issues in this area. However, this area is related to the cross-cutting GDA Issue on Limits and Conditions, **GI-AP1000-CC-01**, described in Section 4.1.3.3.

4.2.7 Assessment – Hydrogen Dosing

432 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 AP1000 was supported by TSC contracts, whose reports are in Refs 186, 198 and 201, including a specific review of the AP1000 hydrogen controls and dosing systems.

433 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 diffusion and radiolysis. The RCS hydrogen concentration recommended by Westinghouse for AP1000 is between 25 and 50 cc kg^{-1} with values down to [redacted] cc kg^{-1} at start-up. Westinghouse has in the past recommended a tighter range (30 to 40 cc kg^{-1}) in some of the documentation for AP1000, but this advice has since been withdrawn, TQ-AP1000-711 (Ref. 8) and Ref. 26. As discussed later in Section 4.2.7.2, there have been recent international industry discussions of increasing hydrogen levels towards 60 cc kg^{-1} (Ref. 233). Ultimately, the selection of an appropriate regime will be the responsibility of the Licensee. Whilst some of the published literature suggests that minor adjustments of hydrogen (as little as 5 cc kg^{-1}) have an effect; I do not believe this to be the case when operating in a range similar to that suggested for AP1000. 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 cc kg^{-1}. Plant and theoretical data do not justify closer control than this.

434 The capability of the AP1000 systems to support the target level of hydrogen is presented in Section 4.2.2.2.3. This concluded that there was insufficient evidence that the new

modification to the injection system is capable of supporting the target level and I have therefore raised this as a GDA Issue, **GI-AP1000-RC-03**, which must be resolved; see Section 4.2.2.6.

435 In addition to adding hydrogen to the coolant, it is also necessary to be able to remove it if required, to avoid flammable gas mixtures developing during a shutdown, or if too much is created or injected by some fault. TQ-AP1000-086 and 491 (Ref. 8) cover some hazards from excess hydrogen. Section 4.2.2.3.3 of this report assesses systems for physical degasification in AP1000. The addition of peroxide for chemical degasification is assessed in Section 4.2.11 of this report.

436 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 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.

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

4.2.7.1 Effects on Radiolysis

438 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 promotes high-temperature corrosion and can also potentially create flammable mixtures, these alone 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 cc 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 change once hydrogen gets much below 10 cc kg^{-1}, so for this and other reasons, the minimum practical hydrogen concentration is taken to be 10 cc kg^{-1}. The AP1000 minimum level is comfortably above this level so can be considered adequate.

4.2.7.2 Effects on Corrosion

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

440 Hydrogen is also beneficial in controlling SCC in nickel alloys, although less significantly than the stainless steels. There is data, often quoted, that shows high levels of hydrogen (> 50 cc kg^{-1}) suppressing crack growth rate and lower levels (< 10 cc kg^{-1}) suppressing

crack initiation rates. This data 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 Inconel in AP1000, such as X750, for which hydrogen addition would still be beneficial. 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. In TQ-AP1000-490 (Ref. 8), Westinghouse summarised operational experience of cracking from existing reactors and the actions taken to prevent it. Amongst the actions Westinghouse claimed to protect stainless and Inconel alloys, was the maintenance of dissolved hydrogen.

441 EPRI has been considering recommending higher hydrogen concentrations (up to 60 cc kg^{-1}) on existing plant to reduce the risks of PWSCC of Inconel 600 (Ref. 233). It is not clear what the upper hydrogen limit in the design of AP1000 (probably with or without the DCP change given by Ref. 192) would be, as this will ultimately be determined by the balance between the addition and removal mechanisms described earlier, although in principal operation at the upper levels appear feasible but this would require a more detailed evaluation by the Licensee. This evaluation would need to consider the impact on other systems such as the Gaseous Radwaste System (WGS).

442 There remains controversy amongst experts as to the exact mechanisms whereby hydrogen controls crack initiation and crack growth in Inconel 600. 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 AP1000. Therefore many experts now recommend a change either to higher or to lower concentrations of hydrogen, than those used historically.

443 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) and start-up and shutdown chemistry (4.2.11). In summary, I do not expect LTCP to affect an operating PWR like AP1000, particularly in normal operations but this should be considered as part of shutdown chemistry planning.

444 Overall, Westinghouse's suggested hydrogen levels appear reasonable for corrosion protection. There is insufficient evidence to support a change in levels, either to higher or lower levels in AP1000.

4.2.7.3 Effects on Radiation

445 Westinghouse believes that a hydrogen level between 25 – 50 cc kg^{-1} is needed to limit general corrosion and nickel release from Inconel 690 for the control of ORE; TQ-AP1000-530 (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, $Ni + 2H^+ \rightarrow Ni^{2+} + H_2$.

446 It is still not clear which will be the dominating factor for AP1000 but the very limited data in the literature would suggest that lower hydrogen concentrations (25 – 40 cc kg^{-1}) result in decreased ^{58}Co, which would be beneficial.

447 Higher values (50 – 80 cc kg^{-1}) may create more fuel crud and might cause hydriding of the fuel. ZIRLO® fuel cladding suffers 60% less corrosion under primary circuit conditions in the presence of hydrogen. However, without hydrogen in the coolant, the corrosion of ZIRLO® would be worse than the Zircaloy-4 it supersedes. For cladding, the presence of hydrogen is thus beneficial up to the concentration at which zirconium alloy hydriding

occurs. Westinghouse have not presented data to me that operation with hydrogen greater than 50 cc kg^{-1} will not cause hydriding of the ZIRLO® fuel cladding (Ref. 198). EPRI is conducting a series of tests on this, but since hydriding occurs mainly by the corrosion reaction this is not anticipated to be a problem. Very low hydrogen levels (< 10 cc kg^{-1}) may allow oxygen to build up within crud. On the basis of current knowledge therefore, the optimum hydrogen level for fuel appears to be in the range 10 – 50 cc kg^{-1}.

4.2.7.4 Other Effects

448 Hydrogen should not be deliberately added in such large quantities that it causes other hazards elsewhere in the reactor. I raised TQ-AP1000-086 covering the possibility of gases causing pump run-out and TQ-AP1000-491 and 1239 (Ref. 8) covering the potential build-up of hydrogen in ancillary vessels and pipework. In general, vessels and lines in AP1000 are small and easily purged and I was content with the Westinghouse response to these TQs from a chemistry perspective.

449 An appropriate concentration of hydrogen for AP1000 will lie somewhere in the band proposed by Westinghouse, which is based on the EPRI guidelines. Some concentrations of hydrogen within this band will generate more crud than others, or have other undesirable effects. The Licensee will need to define the control band, giving consideration to the optimum levels of hydrogen for a new reactor with Inconel 690, which could be more precise. Most reactors with Inconel 690 steam generators operate at lower hydrogen concentrations in the smaller range of about 30 to 40 cc kg^{-1} hydrogen. The ability of AP1000 to provide and control a level of hydrogen is a GDA Issue that I have raised in another section of this report. At the present time, I do not consider there is sufficient evidence to justify a change from the current levels of hydrogen outside accepted regimes, especially for AP1000. I consider this to be an Assessment Finding, **AF-AP1000-RC-18**.

4.2.7.5 Summary

450 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of hydrogen chemistry in AP1000 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.
- I consider Westinghouse proposals for the optimum level of hydrogen in AP1000 to be satisfactory, although it permits a wide range of operation.
- 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, especially for AP1000.
- There is still work to be done to identify which will be the dominating factor for AP1000, solubility of nickel metal or nickel ferrite, determining the influence of hydrogen on crud.

451 When taken as a collective answer, the TQ responses under this area add significantly to the AP1000 safety case for hydrogen. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA, subject to satisfactory closure of the GDA Issue (**GI-AP1000-RC-03**) identified in Section 4.2.2.2.

4.2.7.6 Assessment Findings

452 Based upon the assessment of hydrogen chemistry in AP1000 described in Section 4.2.7 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, the Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-18*** *– The Licensee shall decide on the optimum band for hydrogen concentration in AP1000, once Westinghouse has demonstrated that the design of the dosing system fulfils its required function (in GDA Issue* ***GI-AP1000-RC-03****). The specification should include justification for the limits chosen and the actions to be taken when limits are exceeded. This Assessment Finding should be completed before hydrogen is first applied to the reactor; Target milestone – Hot Ops.*

4.2.7.7 GDA Issues

453 Based upon the assessment of hydrogen chemistry in AP1000 described in Section 4.2.7 above, I have identified no Reactor Chemistry GDA Issues in this area. However, this area is relevant to the GDA Issue on hydrogen dosing in the CVS, **GI-AP1000-RC-03**, raised earlier in my report (Section 4.2.2.6).

4.2.8 Assessment – Control of Safety System Chemistry

454 Westinghouse has included a number of dedicated safety systems to provide functions in an emergency and a number of these are relevant to the Reactor Chemistry assessment as they supply borated coolant, contain chemically treated water or can interface with the plant during normal operations particularly during shutdowns. The following section describes my assessment of these systems from a Reactor Chemistry perspective.

4.2.8.1 Passive Core Cooling System

455 AP1000 has a Passive Core Cooling System (PXS). This is described in the PCSR (Ref, 1, Section 6.4.5) and the SSD (Ref. 155). This comprises the Core Make-up Tanks (CMT), Automatic Depressurisation System (ADS), Accumulators, In-containment Refuelling Water Storage Tank (IRWST) and Passive Residual Heat Removal (PRHR) heat exchanger. The pH adjustment system for Loss of Coolant Accidents (LOCA) is assessed in Section 4.6. The primary function of the PXS is to bring the plant to safe shutdown conditions using only Class 1 equipment by providing the means for boration, injection, and core cooling. They can be used in a number of modes following LOCA and other non-LOCA accident events. The safety functions of these systems during fault conditions are assessed elsewhere (Ref. 67).

456 The PXS, when providing passive safety injection is shown schematically below (Ref. 1):

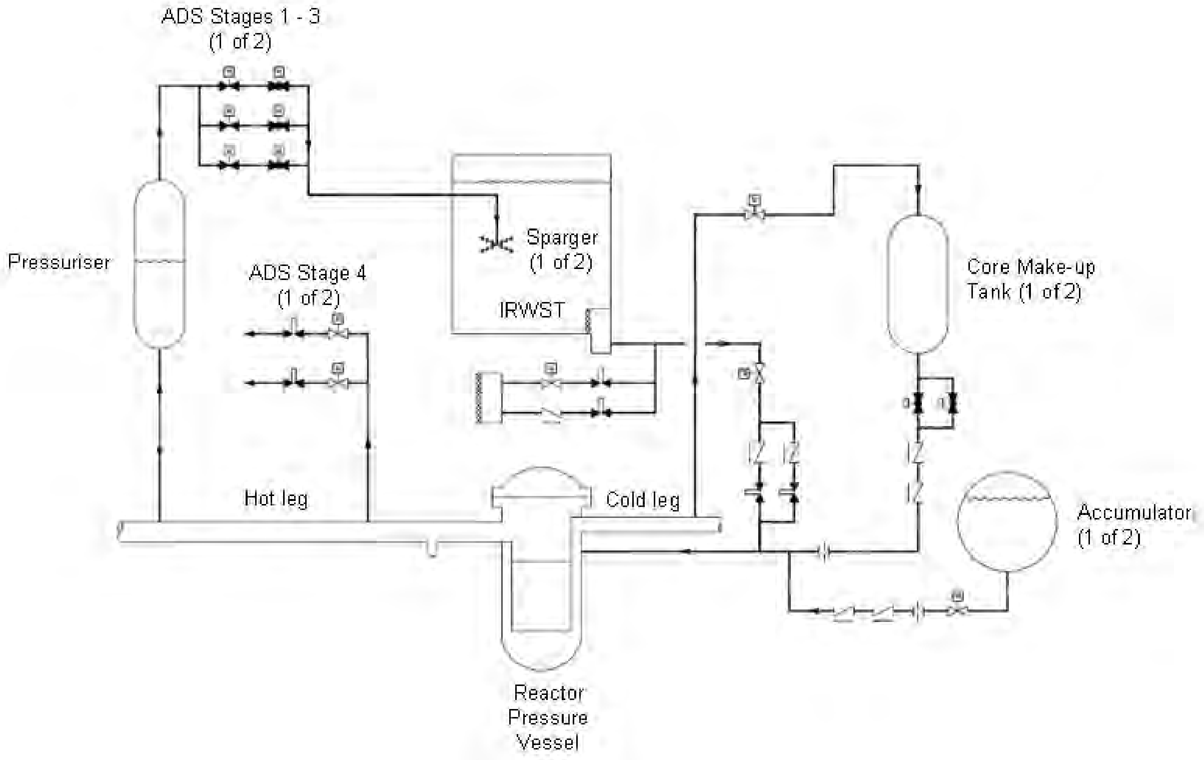

Figure 5:AP1000 Passive Core Cooling System providing Safety Injection

457 Similarly, the PXS schematic when providing decay heat removal capability is shown schematically in the following figure (Ref. 1).

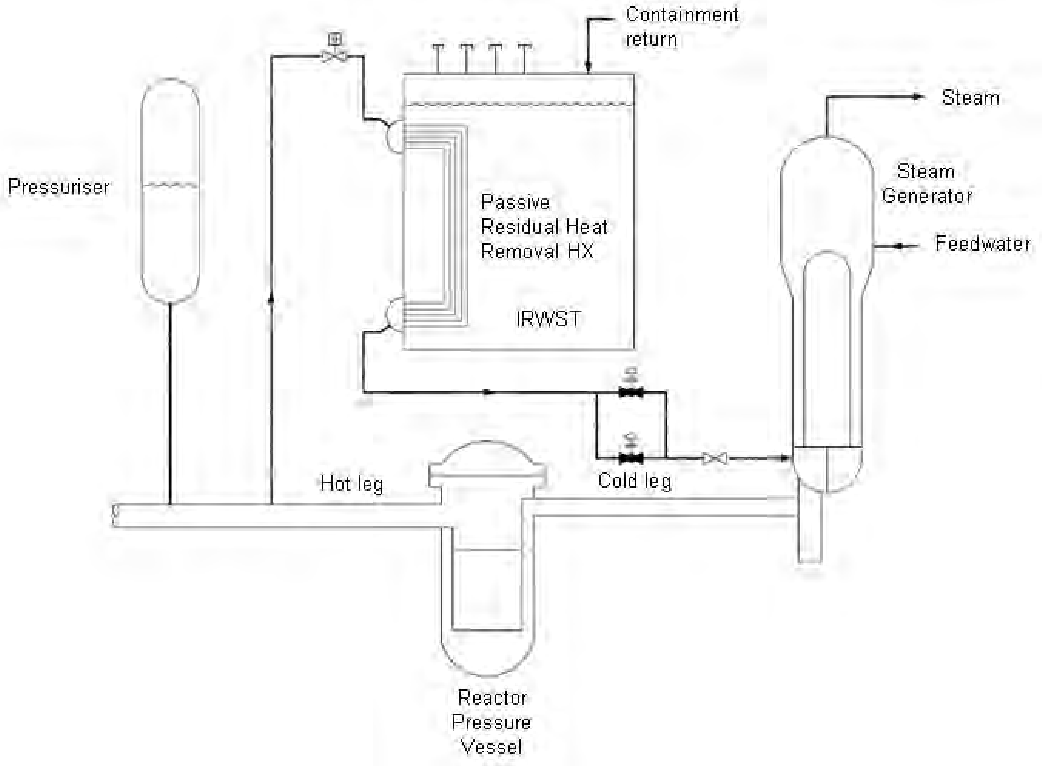

Figure 6: AP1000 Passive Core Cooling System providing Decay Heat Removal

4.2.8.1.1 Core Makeup Tanks

458 The two Core Make-up Tanks (CMT) provide emergency borated coolant to the reactor at pressure. Once their level falls to a certain point, AP1000 is designed to depressurise automatically (via the ADS) and the rest of the PXS provides longer-term cooling. The CMTs are vertical, cylindrical tanks connected to the RCS through a discharge injection line and an inlet pressure balance line. During normal operation, the CMTs are completely filled with cold borated water at around 3500 mg kg^{-1} and are maintained at RCS pressure by the balance line connected to a cold leg. The boration capability of these tanks is specified to provide adequate core shutdown margin following a steam line break. They have two operating modes; water recirculation and steam-compensated injection, which are described in the PCSR (Ref. 1). The tanks are carbon steel with an internal stainless steel cladding.

459 Connections are provided for remotely adjusting the concentration of the borated water in each CMT during normal plant operation. Make-up water for the CMTs is provided by the CVS. Samples from the CMTs are taken periodically to check boron concentration using the primary sampling system. I am content these arrangements appear adequate to control the CMT water chemistry. The Licensee will need to develop the procedures required to ensure the chemistry of the safety systems is controlled, including detection and remediation of off-specification parameters. I consider this to be an Assessment Finding, **AF-AP1000-RC-19**.

460 Westinghouse calculations show that, in recirculation mode, the gas bubble in the CMT would not be transferred to the PRHR as a result of the solubility of gases in coolant.

4.2.8.1.2 Accumulators

461 The two accumulators are spherical tanks made of carbon steel and clad on the internal surfaces with stainless steel. The accumulators are filled with cold borated water, at around 2700 mg kg^{-1}, and pressurised with nitrogen gas. Unlike the CMTs which inject into the coolant pipework, the accumulators are connected directly to the RPV. When the RCS pressure falls below the accumulator pressure, two check valves open and borated water is forced out. The accumulators are designed to deliver a high flow of borated water to the RPV in the event of a large LOCA.

462 Connections are provided for remotely adjusting the level and boron concentration of the coolant in each accumulator during normal plant operation. Accumulator water level may be adjusted either by draining or pumping borated water from the CVS to the accumulator. Samples from the accumulators will be taken periodically to check the boron concentration. The nitrogen pressure can be adjusted during normal plant operation, although the accumulators are normally isolated from the nitrogen supply. The system also includes the capability to remotely vent gas from the accumulator, if required. I am content these arrangements appear adequate to control the Accumulator water chemistry. Assessment Finding **AF-AP1000-RC-19** applies here as well.

4.2.8.1.3 IRWST and PRHR Heat Exchanger

463 The IRWST is a large tank located inside the containment used to flood the refuelling cavity during normal refuelling operations. The use of the IRWST for refuelling operations is described in Section 4.3. In an accident it would provide:

- a heat sink for the PRHR;
- a large, elevated supply of borated water for gravity injection to the RCS, and;
- flooding the lower portion of containment to a depth sufficient for long-term core cooling via gravity driven containment recirculation.

464 The IRWST is connected to the CVS for provision of borated water, at around 2700 mg kg^{-1}. Connections to the IRWST provide for transfer to and from the RCS / refuelling cavity via the RNS, purification and sampling via the SFS, and remote adjustment of the boron concentration via the CVS. The supplementary guidelines produced by Westinghouse include additional specifications, over and above those provided by EPRI, specifying limits of < [redacted] $\mu g\ kg^{-1}$ for halides and sulphates and additional limits for species that can form harder types of fuel crud such as silica. The IRWST is also vented, so the coolant is aerated, but it is not open to the containment so evaporation and loss of coolant to the containment is minimised (TQ-A1000-809 (Ref. 8)).

465 The PRHR is designed to remove core decay heat if a loss of cooling capability via the SGs and feedwater systems occurs. The PRHR consists of a Heat Exchanger (HX) which is submerged in the IRWST water, which provides the heat sink. The PRHR HX consists of a bank of 689 "*C-tubes*", connected at the top (inlet) and bottom (outlet) to a tubesheet and channel head mounted on the IRWST wall, using the same type of connections as the SGs. The tubes are fabricated from Inconel 690 and the channel heads are carbon steel with an internal stainless steel cladding. During normal operations the PRHR HX is filled with primary coolant, with the inlet open and the outlet closed, and is in thermal equilibrium with the IRWST water.

466 In discussions, Westinghouse engineers were clearly aware of the need to fabricate the PRHR cooling pipes to withstand the oxidising IRWST environment and propose to shot peen the tubes to mitigate the potential risks of SCC (Ref. 155). This is a standard technique.

4.2.8.1.4 Automatic Depressurisation System

467 The Automatic Depressurisation System (ADS) is a series of automatic valves which operate in a prescribed sequence to depressurise the RCS of AP1000 when required. The ADS uses "*squib*" valves. Actuation is via a pyrotechnic process, which is triggered by an electronic control signal, and is a once only sequence, unless the valve is refurbished. Use of such valves is a novel concept, and one that has not been utilised in previous PWR designs in such a role. The assessment of these devices was lead by the Mechanical Engineering inspector and is reported elsewhere (Ref. 136).

468 The first 3 stages of the ADS discharge from the pressuriser into the IRWST, via two spargers submerged in the IRWST water. This is to increase the mass transfer between the discharged coolant and the IRWST water, minimising releases to the containment atmosphere and providing more effective steam condensation. The spargers are of a four arm cruciform pattern, fabricated in stainless steel. This material choice is reasonable for long term submersion in the IRWST water. The final stage of the ADS discharges directly into the containment.

4.2.8.1.5 Permanent Gases

469 A general concern with any system which relies on passive flows is the accumulation of permanent gases in 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. Section 4.2.2.3.3 discusses the systems in AP1000 which degasify the primary coolant during normal operations. Radiolysis can also produce flammable mixtures of hydrogen and oxygen. A siphon break would hinder the PRHR HX and gases could stall the RNS pumps.

470 Responses to my questions were contained in the Westinghouse responses to RO-AP1000-55.A3 (Ref. 32) and TQ-AP1000-086, 491, 1229 and 1239 (Ref. 8). Detailing of the piping layout, some of which was finalised in 2008, resulted in features such as:

- Normal Residual Heat Removal System (RNS) - continuous sloping and a special bleed for the suction lines to the RNS pumps.
- Monitor for potential gas intrusion at the high points for the passive residual heat removal heat exchanger and core makeup tank inlets, respectively. These include manual vent valves, along with continuous void sensing instrumentation and alarms for the high-point pipe stubs. The continuous monitoring and alarm requirements are captured in an appropriate "*Technical Specification*".

471 On completion of these design changes in 2008, Westinghouse undertook a technical evaluation of potential gas intrusion and accumulation mitigation strategies according to the procedures introduced by US NRC and NEI (Nuclear Energy Institute) the same year. These are documented in Section 6.3.6.3 of the EDCD (Ref. 22). The detailed analysis of such faults is assessed elsewhere (Ref. 67). I am content with these arrangements from a Reactor Chemistry perspective, subject to the satisfactory resolution of Assessment Finding **AF-AP1000-RC-03**, as described in Section 4.1.2.

4.2.8.2 Passive Containment Cooling System

472 The AP1000 incorporates a Passive Containment Cooling System (PCS) as described in the PCSR (Ref. 1, Section 6.4.3) and SSD (Ref. 147). The PCS is an engineered safety system which serves as the means of removing heat for events resulting in a significant increase in containment pressure and temperature. The PCS makes use of the steel containment shell as a heat transfer surface; air is drawn from the environment via an "*always open*" airflow path over the containment vessel and is returned to the environment after removing heat from the containment shell. The containment shell is wetted by gravity draining of a water storage tank that is incorporated into the Shield Building structure above the containment, and is known as the Passive Containment Cooling Water Storage Tank (PCCWST). This is a stainless steel lined concrete vessel. A water distribution system and zinc paint coating is provided to ensure adequate flow distribution and surface wetting.

473 The PCCWST is filled from the demineralised water supply. To control corrosion and microbiological growth the tank is dosed with hydrogen peroxide at [redacted] mg kg^{-1}. This is checked by manual sampling on a weekly basis and the PCCWST has a small volume chemical addition tank for adding further doses. I examined the water specification for the PCCWST and was content with its specification for biocide and impurity control as

provided by Westinghouse in the AP1000 "*chemistry manual*" (Ref. 25, Section 16). Assessment Finding **AF-AP1000-RC-19** also applies to the PCCWST.

474 The influence of this system on the chemistry occurring inside the containment during an accident is assessed in Section 4.6.4, and more generally in terms of containment performance elsewhere (Ref. 80). The use of the PCCWST to supply make-up water to the Spent Fuel Pool (SFP) in an accident is assessed elsewhere in this report, Section 4.3.2.4.

4.2.8.3 Normal Residual Heat Removal System

475 AP1000 has a Normal Residual Heat Removal System (RNS) whose primary function is to remove heat from the reactor during shutdowns, in addition to providing a number of other functions, including:

- Refuelling heat removal – following reactor cool down, cooling of the refuelling cavity.
- Refuelling drain down – from the IRWST to the refuelling cavity and vice versa.
- Shutdown purification – provision of flow through the CVS.
- IRWST cooling – during operation of the PRHR HX or during normal operations.
- SFP cooling – the RNS can supplement or replace the Spent Fuel Pool Cooling System (SFS) if required.
- Post-accident cooling – using the normal RCS cooling arrangement.
- Low pressure RCS make-up – from the IRWST, cask loading pit or external sources.

476 The RNS is described in the PCSR (Ref. 1, Section 6.5.3.) and the associated SSD (Ref. 148). The RNS includes two mechanical trains of equipment, each consisting of one pump and one heat exchanger, cooled by the Component Cooling Water System (CCS), located in the auxiliary building. The two trains of equipment share a common suction line from the RCS and separate discharge lines which return the flow to the RCS via the two PXS DVI lines. The RNS is also interconnected with the IRWST, SFP and CVS. The RNS is shown below (Ref. 22):

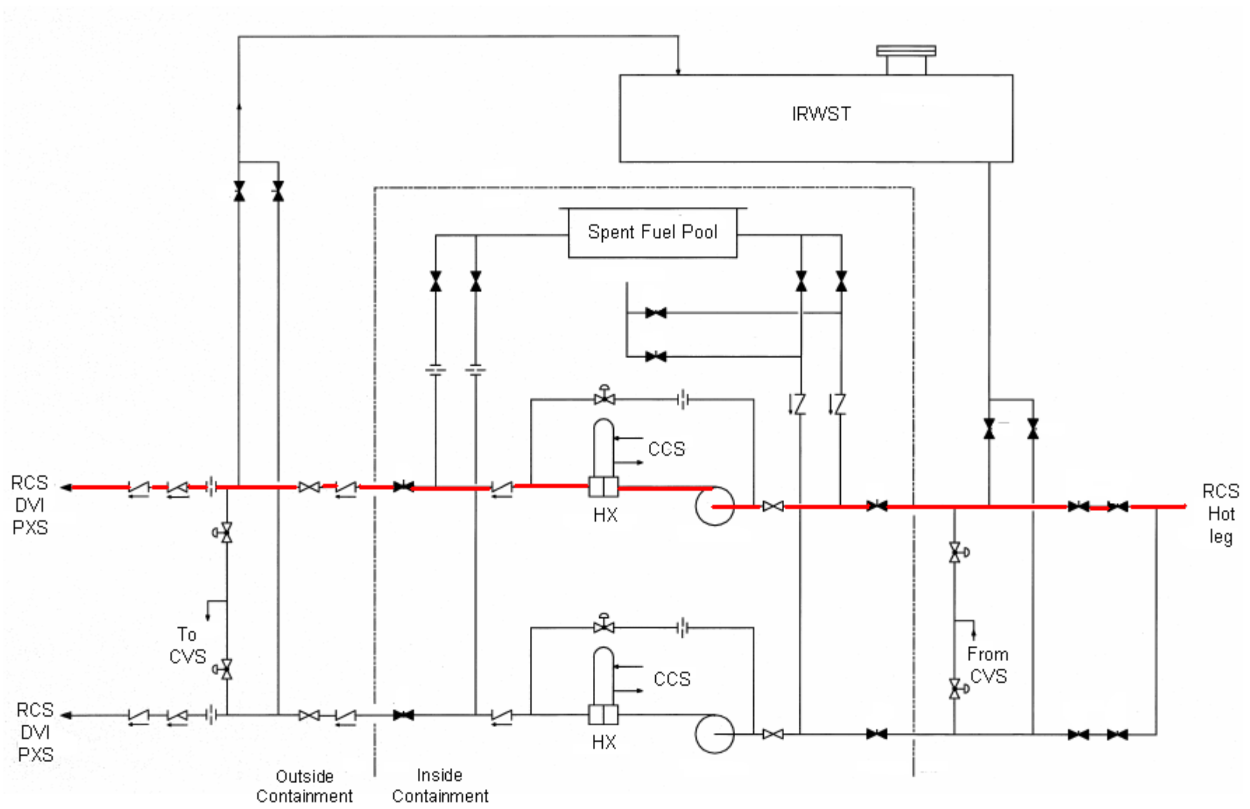

Figure 7: AP1000 Normal Residual Heat Removal System

477 Through its connections the RNS may potentially cause poor chemistry or contamination to be spread by mixing coolant from the RCS to the IRWST. Westinghouse outlined the sequence of operations required to isolate and flush the RNS on each outage to ensure its contents remain free of radiocobalt and lithium in TQ-AP1000-1157 (Ref. 8). The CVS, RNS and SFP are highly interconnected systems and good operator training and procedures are needed to ensure that inappropriate connections are not made.

478 Use of the RNS during start-up and shutdowns is assessed in Section 4.2.11 and its use as part of the SFP systems in Section 4.3.

4.2.8.4 Summary

479 Based upon the evidence presented during GDA, the main conclusions I draw for the Safety Systems assessment are:

- As with all PWRs, in AP1000 a number of safety circuits and systems need to be filled with borated water of the correct specification. In addition to the normal filling pipework, the safety systems all have sampling points and facilities for top-up.
- Westinghouse has recognised that permanent gas intrusion is a potential hazard and have provided for gas detection and bleed. These will need monitoring by the licensee, as in any LWR.
- Westinghouse has recognised the special metal finishing and water chemistry controls needed for each system, taking account of the design of AP1000.

- Procedures for dealing with deviations from specifications will have to be devised, as for any reactor. I have raised an Assessment Finding to cover this point.

480 When taken as a collective answer, the TQ and RO responses under this area add significantly to the AP1000 safety case for safety systems. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.2.8.5 Assessment Findings

481 Based upon the assessment of safety systems chemistry in AP1000 described in Section 4.2.8 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-AP1000-RC-19*** *– The licensee shall specify operating procedures for monitoring safety systems chemistry, detecting and removing out of specification fluids, and reviewing any unusual behaviour. This Assessment Finding should be completed before any safety stocks of coolant are needed and filled for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

4.2.8.6 GDA Issues

482 Based upon the assessment of safety systems chemistry in AP1000 described in Section 4.2.8 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.2.9 Assessment – Sampling Systems

483 As described in the previous sections, the primary chemistry of AP1000 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 delays, doses or unrepresentative sampling of important chemical parameters.

484 A number of the design features of AP1000 are relevant to the sampling system design and should be considered:

- High pressure in-containment CVS without a VCT – sampling provisions, speed of primary circuit chemistry changes possible and recycling of effluents.
- Direct injection of hydrogen – sampling frequency and capability.
- Addition of zinc – sampling capabilities.
- Core duty and likelihood of significant corrosion product generation.
- Avoidance of containment entry at power.

485 Assessment of the AP1000 primary sampling capabilities began during Step 3 and continued during Step 4. The overall assessment objective was to confirm if AP1000 has adequate sampling capabilities and capacity to support safe operation of the plant during all modes of operation. Overall, at the end of Step 3, I had a number of fundamental concerns over the proposed design of the AP1000 PSS and considered it to be of dated design, be compromised due to simplifications and appear not to have benefited from a significant specialist input during development. The main concerns regarding the PSS functionality and design, included:

- Capability of the system to deliver representative samples (i.e. the potential for sampling mixed or contaminated samples, grab sampling arrangements).
- Isokinetic sampling capability, especially for particulate sampling of the primary circuit.
- Potential for system failure or unavailability due to use of a single sample line.
- Possibility of misrouting of fluids across the sample manifold, especially driven by pressure differential.
- Suitability of sample cooling functions.
- Absence of effluent recycle provisions.

486 I requested evidence to resolve these concerns during Step 4, as well as information regarding the detailed operation of the system and hence its suitability to provide the chemistry functions.

487 My assessment of sampling systems has been informed by a TSC contract, which specifically reviewed the AP1000 design (Ref. 34), following a review of relevant good practice in sampling PWRs (Ref. 176). In addition the LCC4 annual report provides information on primary sampling considerations (Ref. 35).

4.2.9.1 Primary Sampling System Overview

488 The AP1000 features a Primary Sampling System (PSS) as described in the PCSR (Ref. 1, Section 6.5.16) and this is used to sample the RCS and primary auxiliary systems of the AP1000. The PSS was still undergoing detailed design during Step 4. The PSS includes the capability for sampling both liquid and gaseous samples and includes a provision for post accident sampling (as discussed more in Section 4.2.9.4). Westinghouse states that the PSS must be available for monitoring of the primary coolant during all of the plant operating conditions. The entire wetted surface of the PSS is fabricated from stainless steel.

489 The liquid sampling portion of the PSS collects and transports liquid samples from the RCS and associated auxiliary systems to a common location in a sampling room located in the auxiliary building. A total of 11 liquid sampling points are included in the system. The RCS sampling points are:

- RCS hot leg (before CVS demineraliser) loop 1.
- RCS hot leg (before CVS demineraliser) loop 2.
- Pressuriser liquid phase

490 The line connections to the RCS (hot legs and pressuriser) include flow restricting orifices in the line to ensure that the let-down flow is always within the make-up capacity of the CVS, even in the unlikely event of a line break.

491 In addition the PSS is used to sample those primary auxiliary components that must be sampled as part of the plant "*Technical Specifications*", namely the accumulator tanks (2 lines, 1 per accumulator) and the CMTs (4 lines, 2 per tank; 1 top, 1 bottom). The final PSS sample liquid line used during normal operation is from the CVS demineraliser outlet. Westinghouse preference is to use local grab samples whenever possible; however for these samples a containment entry would be required which is generally prohibited in normal operations.

492 During Step 4, partly in relation to concerns expressed by ND, Westinghouse proposed a design change to the PSS (Ref. 36). The original PSS design, at the start of Step 4, used an in-containment manifold to direct the sample through a single containment line which penetrates the containment and transfers the liquid to the sampling room. The accumulator, CMT and CVS sample lines combine to a common header, with the individual accumulator and CVS lines isolated by non-return valves. Connections exist to flush the header to waste, with input from the CVS demineralised water supply and drain to the Liquid Radwaste System (WLS), both isolated by non-return valves. The header is terminated at both ends by non-return valves that allow sample flow out of the header only. The RCS loop 1 sample connects to one end of the header after the non-return valve. Similarly the RCS loop 2 and pressuriser liquid samples connect to the header at the opposite end, after the non-return valve. All of the individual lines have solenoid operated globe valves which dictate which sample stream is flowing at any given time. Two lines, which combine to form the single containment penetration, are taken from the two ends of the common header (i.e. one from the RCS loop 1 sample end and one from the RCS loop 2 sample end), each of the two lines feature a delay coil to allow for ^{16}N decay in the RCS coolant samples and a further solenoid isolation valve.

493 The assessment that follows is based upon the original PSS design, as specified in the PCSR and EDCD, plus the modifications made by the design change. The Westinghouse justification for the design change is based on four principal considerations, namely:

- Facilitation of accurate sampling.
- Sample transit times.
- Sampling for non-soluble species.
- Purging requirements.

494 The design change altered the sampling manifold arrangement and added a second containment penetration. These changes effectively make the system one where the two RCS loop samples, which share a common line, are normally isolated from the manifold. The remaining samples are connected to the sample manifold which shares a single sample line. With regard to the manifold, the specific changes made can be summarised as:

- Moving the RCS loop 2 sample to the same end of the manifold as the RCS loop 1 sample and isolating them from the remainder by replacing the non-return valve with a solenoid valve.
- No longer combining the two lines which exit the manifold, thus creating two containment penetrations.
- Addition of manual isolation valves to each sample line.

495 After exiting from containment the two sample lines are cooled by separate heat exchangers cooled by the CCS. Two possible routes exist for the samples, either to the

'*radiochemistry laboratory*', directly above the sampling room, or to the Grab Sample Panel (GSP), inside the sampling room.

- A needle valve at the inlet to the laboratory is used to control the amount of flow into the laboratory and to depressurise the incoming flow with the flow returning from the laboratory directed to the WLS, via the GSP. The laboratory employs an exhaust-ventilated, hooded enclosure to minimise the radiation exposure to personnel.
- The GSP is a lead shielded sampling device which receives cooled, high pressure liquid samples and conditions them for sampling. The GSP includes an eductor device to allow sampling when system pressures are insufficient to provide the motive force for the samples. Waste from the sampling or line purges is sent to the WLS. Samples taken via the GSP must be transported to the radiochemistry laboratory for analysis.

496 The main features of the "*final*" AP1000 PSS design, including the design modifications, are shown below (Ref. 238):

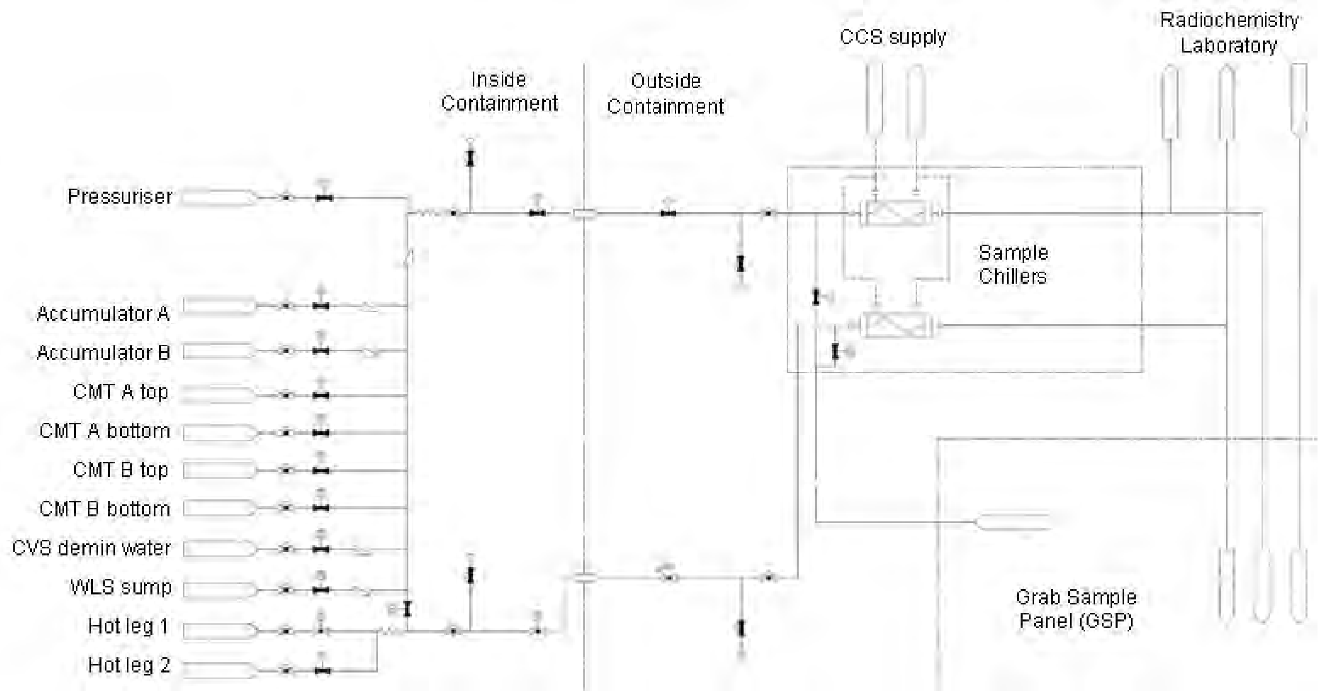

Figure 8: AP1000 Primary Sampling System

497 The system also provides on-line measurements for dissolved hydrogen, dissolved oxygen and primary coolant activity. Other parameters are measured as required by manual methods. A number of local grab sample points (33) are also available but are not connected to the PSS. The local grab sampling locations are given in the EDCD (Ref. 22, Table 9.3.3-2). The PSS does not include the grab samples, which are within the sampled systems, however they are included in the assessment that follows.

498 The PSS also has some functions during post accident sampling conditions in AP1000. Two separate lines take samples from the either the containment sump or RCS hot legs, for liquid samples, or from a further line used for sampling the containment atmosphere. Samples are drawn using eductors to drive the sample flow. The GSP features provisions

to dilute such samples. In a post accident situation, the containment isolation valves of the PSS are automatically closed on a containment isolation signal. These can be re-opened as necessary to sample the RCS for boron content, to measure the primary activity (via the RCS hot leg samples) and to determine the composition of the containment (sump and gas phase).

4.2.9.2 Primary Coolant Sampling

499 Neither the PCSR (Ref. 1) nor the EDCD (Ref. 22) provide any details on considerations given to the chemical sampling performance of the PSS, instead providing a mechanical description of the equipment. The SSD (Ref. 37) provides some limited information on these aspects. For these reasons, and the concerns highlighted during Step 3, I raised RO-AP1000-55.A8 (Ref. 7) which requested Westinghouse to provide further detailed evidence for the performance of the PSS in a number of detailed areas (Ref. 109). In addition I raised a number of detailed TQs on the PSS during Step 4; TQ-AP1000-533 and 535 to 541 (Ref. 8). The responses to these queries were provided before the design change (Ref. 36), hence do not accurately represent the final GDA design. The most relevant parts of the responses, including the design change, are discussed in the paragraphs that follow. The main lines of enquiry can be summarised as:

- Provisions to assure representative sampling.
- System design.
- Waste generation.

500 Each of these aspects is discussed in turn below, although they are very much interrelated.

4.2.9.2.1 Representative Sampling

501 The fundamental requirement for any sampling system is to ensure representative sampling of the source. For the primary coolant samples the main requirement is the ability to measure boron for reactivity control purposes. Other important requirements are the sampling of other additives to ensure proper chemistry control, impurities for material protection and activity for waste and ORE control. Some of the species will be present in the sample as soluble, particulate or even colloidal species at varying concentrations. Operational experience indicates that sampling frequencies increase greatly during transient periods such as start-up and shutdown or deviations from normal operations, for example during fuel leaks. I asked Westinghouse to supply the "*design requirements*" that were used to develop the AP1000 PSS design, including the intended frequency of sampling, in TQ-AP1000-537 (Ref. 8). This was referred to RO-AP1000-55.A8 (Ref. 109); however the response does not provide this information directly instead attempting to show compliance to the underpinning requirement documents cited by Westinghouse; namely the US Utility Requirements Document (URD) (Ref. 38), EPRI primary chemistry guidelines (Ref. 15), ASTM Standards (Principally Ref. 39), US NRC Regulatory Requirements and the PSS SSD. Most of these requirements are high level and do not specifically address the chemistry requirements. A number of notable items, such as "*Samples shall be representative of the sampled stream*", are noted as "*pending completion of design*". The AP1000 "*chemistry manual*" (Ref. 25) provides some information on sampling in AP1000 however Westinghouse state that the definition of sampling requirements is the responsibility of the Licensee; "*Refer to Reference 1* [EPRI Primary Chemistry Guidelines, Ref. 15] *for detailed specific guidelines and surveillance*

recommendations regarding the trending and sampling considerations for Primary System Parameters. Refer to Chapter 12 of the AP1000 Chemistry Manual [Ref. 25] *for specific attributes of radiochemistry considerations in assessing the AP1000 Primary System. Refer to the Westinghouse Supplemental Guidelines* [Ref. 26] *for specific trending and monitoring attributes to support the RCS zinc injection program*."

502 Those species which are present as soluble species in the primary coolant should generally pose no difficulties to the AP1000 PSS, provided it can be assured that the sample stream is adequately purged and isolated from other sources. Provided the PSS is available the ability to sample boron in the primary coolant should not be jeopardised. The design change greatly reduces the chances of PSS failure affecting the ability to monitor boron concentration, with two potential sample lines. It is notable that the RCS loop lines combine before a single delay coil. Failure here would remove both RCS loop connections, although the pressuriser liquid phase line would still be available. This would only be an issue during start-up when equilibrium between the pressuriser and RCS boron concentration must be assured.

503 Although zinc is a soluble species it can be problematic to sample accurately due to interactions with sample lines and the low concentrations ([redacted] μg kg^{-1}). This is recognised in much industry OEF and guidance, including by EPRI (Ref. 40). Zinc readily incorporates into sample line metal oxide films, especially at elevated temperatures. Zinc is a required parameter for both the primary chemistry control and Westinghouse fuel warranty. The large SG area (15% larger than comparable 4 loop plants) combined with core boiling could cause more crud in the AP1000 design and hence higher levels of activity, if not adequately controlled, (see Section 4.2.3). Therefore the accurate application of zinc is important. The "*Westinghouse Supplement to EPRI PWR Primary Water Chemistry Guidelines*" (Ref. 26), specifies a minimum sampling frequency of twice daily during the first 2 months, daily thereafter with an increased frequency during start-up. Sampling for zinc was the subject of TQ-AP1000-533 (Ref. 8). The response (as part of RO-AP1000-55.A8) stated that "*the possibility to ensure that an accurate sample that represents the true zinc concentration in the reactor coolant become less likely*", based on the original design of a single sampling line. The design change similarly discusses zinc sampling concluding that the original design was inadequate. The design change to two sample lines is proposed to resolve this, by allowing one line from the RCS hot leg to flow continuously (at reduced flow) to allow equilibration. Westinghouse has not yet provided evidence to support this and I am not convinced by this argument. In comparison, the more common solution used on current PWRs is to sample from the CVS influent flow, which is at lower temperature. AP1000 does not have a sample point in this location. I consider that the addition of a sample point in this location would be advantageous both for zinc sampling and for monitoring the performance of the CVS purification systems, which as discussed in Section 4.2.2, have several differences to other western PWRs.

504 Fuel Reliability Index (FRI) is a method used to understand the condition of fuel in the core based upon the ratio of radioiodines in the coolant. Westinghouse describes this method in the *"chemistry manual"* (Chapter 12, Ref. 25). It is not clear how successfully the PSS will be able to perform these measurements, however, as described for boron in para. 502, the fundamental requirements of measuring coolant activity levels should not be hindered in AP1000.

505 Irrespective of how much control is placed on plant operations some quantity of Corrosion Products (CP) will be generated in the RCS and transported in the coolant. Since AP1000 may be more prone to CP generation without sufficient controls and while some of this is

in the remit of the Licensee, I consider that sufficient sampling arrangements should be in place to counter this eventuality. Accurate sampling of CP allows the Licensee to monitor plant performance and provide early indications of actions required, especially during transient periods. Sampling of CP is another area where experience feedback indicates difficulties in sampling (for example, Refs 15 and 35). The original design of the AP1000 PSS was again recognised as being deficient for this purpose by Westinghouse, who proposed that the same design change would allow accurate RCS CP sampling. The fundamental requirements for CP sampling, based on OEF, are taken to be continuous and steady sample flow, over minimal sample line length with constant (low) temperature and no exposure to oxygen (Refs 176 and 35). I consider that the final GDA design for AP1000, while much improved, remains deficient due to the use of a high temperature RCS hot leg sample, with potentially changeable (and low) flow over long sample lines at elevated temperatures. It is notable that the design change document (Ref. 36) does not discuss CP sampling and the response to RO-AP1000-55.A8 (Ref. 109) states that "*Instrumentation to provide collection and/or analysis of primary circuit corrosion products is not provided as part of the AP1000 design*" suggesting that sampling capabilities have also not be considered. I queried the use of isokinetic sampling provisions, which could be important for particulate sampling. Westinghouse responded (Ref. 41) with a review of isokinetic sampling in general, the outcome of which was that they consider this to be unnecessary for AP1000. Even the best PWR sampling systems do not truly sample isokinetically, but do approximate this behaviour and it has been shown that those that do get much more representative results for CP measurements. While I agree with the justification provided for not sampling isokinetically for the most part, the response concentrates on discounting isokinetic sampling in general without justifying that AP1000 is adequate for sampling corrosion products. I consider that a more robust justification for corrosion product sampling in AP1000 is required. This is part of the justification requested in GDA Issue **GI-AP1000-RC-02**.

506 No details are provided on the cobalt content of the steel sample lines to limit ^{60}Co concentration disturbances in active samples. I consider that a restriction needs to be placed on the PSS line cobalt content both for representative sampling and ORE control. The UK AP1000 Licensee will need to define and justify an appropriate level of residual cobalt in the lines, which may vary dependant upon the location or environment of the line. I consider this to be an Assessment Finding, **AF-AP1000-RC-20**.

507 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. Reference 30, describes the pressuriser vent line modification for AP1000 (see Section 4.2.2.3.3) which indicates that such a sample point was removed from the PSS for AP600, and subsequently AP1000, based on a survey of operating plants (in 1997) which showed that "*these plants do not need to sample the vapor and are typically not doing so*." The addition of the vent line does remove some of the necessity for sampling this regard; however AP1000 does not have a VCT in the CVS and hence could be more prone to pressuriser accumulation of gases. This point was recognised in the EPRI review of AP1000 (Ref. 55) which stated that; "*The lack of a volume control tank in the AP1000 … could affect nitrogen concentrations in the reactor coolant … Helium concentrations may also need to be monitored since helium removal will likely be less than at plants with VCTs.*" A more specific justification for not having the capability to sample the pressuriser vapour space is required as part of GDA Issue **GI-AP1000-RC-02**.

508 Overall, while the RO-AP1000-55.A8 responses concentrate on justifying the design choices for the AP1000 PSS they do not explain why it will perform adequately. Based on

the evidence I have been provided with during Step 4, I consider that representative sampling may not be possible for a number of important parameters in AP1000 with the current PSS design. I consider this to be part of GDA Issue **GI-AP1000-RC-02**. I judge that this Issue is resolvable, but may require further modifications to the AP1000 design.

4.2.9.2.2 System Design

509 The fundamental logic behind the AP1000 PSS design, namely avoidance of containment entry for sampling is an entirely justifiable basis. However, combining this with the intent of plant simplification has resulted in restrictions on the number of sampling lines exiting containment and hence the use of an in-containment manifold. Westinghouse themselves acknowledge that “*there are no known occurrences of sharing a single sample line between multiple samples in nuclear power plants*”. The design change to increase this to two lines is a welcome addition; nonetheless the design still uses the manifold, with changes to the isolations between sample streams.

510 The response to RO-AP1000-55.A8 (Ref. 7) provides details of the consideration given to the possibility of misrouting of fluids across the sample manifold, especially driven by pressure differential, and the potential for sampling mixed or contaminated samples. The design change incorporates manual isolating valves to interrupt leaking solenoid valves and specifies different solenoid valves to support longer periods of sampling. Westinghouse also indicates that the Licensee will need to specify procedures to allow only certain combinations of valves to open at a given time. Based on the final design I am content that the potential for misrouting of samples across the manifold could be adequately controlled, provided robust controls are put in place by the Licensee, although demonstration that the system is sufficiently robust against this type of fault is part of the justification required under **GI-AP1000-RC-02.** Due to the in-containment location the manual valves can be considered as remedial action in case of an identified failure. It is not clear whether these could be used with the reactor at power. I consider this to be an Assessment Finding, **AF-AP1000-RC-21**.

511 For the PXS components, the CMTs and accumulators, I can appreciate the logic and justification for combining these to one sample line as the main requirement here will be to ensure the soluble boron concentration is within limits, which should be relatively straightforward. I remain unconvinced over the justification for combining other sample streams into this manifold. With the original design of one sample penetration, the chance of a failure causing the inability to sample was higher than other PWRs, thus I requested Westinghouse to consider other sampling provisions to cater for this eventuality. A review (in the response to RO-AP1000-55.A8) concluded that there are no other provisions in the design to enable sampling of RCS fluids due to the high pressures and temperatures. The addition of the second containment penetration line makes the possibility of this situation even more unlikely and the modified manifold allows the samples (with the exception of the pressuriser liquid) to be directed to either line, if necessary. While I am content that this means the plant can be controlled in this degraded condition, I consider that this may need operational controls to prohibit extended periods of operation in this state. This is part of Assessment Finding **AF-AP1000-RC-21**.

512 I queried the lack of boron metering in the AP1000 PSS. Boron control and dilution events are discussed in Section 4.2.2.2.1. The response (Ref. 42) provided a general critique of boron meters (which Westinghouse assumed to be neutron attenuation devices only) and concluded they are unreliable and inappropriate for the AP1000. Another reason for this choice is the lack of permanent sample flow in AP1000. Westinghouse claim this has been addressed with the design change, hence should now

be feasible for AP1000. I consider that given the importance of soluble boron a means of continuously monitoring this parameter would be appropriate and can be demonstrated to be reasonable given OEF.

513 As described in Section 4.2.2, AP1000 doses hydrogen to the primary circuit at high pressure in the CVS. No other commercial PWR adds hydrogen in this manner. Hydrogen is a "*Technical Specification*" parameter. Westinghouse specifies increased monitoring frequencies for this parameter in AP1000 during normal operations and during start-up and shutdowns. A design change (Ref. 43) included an on-line hydrogen meter for use during start-up and shutdown periods. The ability to monitor hydrogen using the meter is dependant on steady flow conditions, see Section 4.2.9.2.1.

514 It is not clear from the safety case which samples are expected to be taken using the GSP and which using the radiation laboratory supply. The GSP appears to be based upon PASS facilities which have been installed at a number of existing PWRs. OEF with such systems is poor, with many never commissioned, decommissioned, modified or replaced. Insufficient details have been provided on the operation of this part of the PSS. It is not clear how samples will be degassed adequately when required, with gaseous activity in the coolant accounting for most of the activity. ORE protection is important for the GSP design and I have not seen evidence of spillage protection and ventilation provisions. Similar provisions in the radiation laboratory are equally important.

515 The location of the heat exchangers is important to accurate sampling for thermally sensitive species. Westinghouse states that the coolers in AP1000 will be located behind the GSP, behind the concrete shield wall. Many European PWRs have sample coolers located as close as possible to the sample source, including inside containment. The PSS coolers are many tens of meters from the sample source.

516 Similarly, the PSS is designed to transport samples at full RCS pressure to the GSP or radiochemistry laboratory. This appears to be an unnecessary hazard which could be removed by pressure reduction to much lower values while still maintaining sample flow and gases in solution.

517 Overall, despite the improvement made to the original PSS design several aspects of the system design merit further attention including the use of an in-containment manifold for all samples, the GSP / radiochemistry laboratory sampling provisions and the location and use of sample conditioning equipment. Based on the evidence I have been provided with during Step 4, I consider that the PSS design does not meet relevant good practice and has been inadequately substantiated. I consider this to part of GDA Issue **GI-AP1000-RC-02**. I judge that this Issue is resolvable, but may require further modifications to the AP1000 design.

4.2.9.2.3 Waste Generation

518 The main functional change brought about by the design change to the PSS is that the RCS loop sample (either loop 1 or 2 hot leg) will operate "*semi-continuously*". This claim has not been substantiated. The original PSS design could not operate in this manner due to restrictions on the waste generation. The design change claims to have addressed this by reducing 1" line diameter section lengths and, as described in Section 4.2.9.2.1, reducing the flowrate such that the sample flow is within the WLS allowance for the PSS (of 0.763 m^3 per day). In order to achieve this the flowrate has been reduced to around 20% of its original design value (or 50% of its original intended operational flowrate), leaving only around 25% of the maximum PSS input to the WLS for any other sampling needs. The sample flow per line in AP1000 is an order of magnitude lower than many

other PWRs. The impact of these changed conditions on sample representatively needs to be considered in addition to relating the effluent generation to the operational needs of the plant.

519 With the intermittent sampling line there is a requirement to flush and purge the sample lines. Westinghouse claim that a minimum of three line volume, but indicate that up to ten may be required in some instances. The additional waste generated by these sources will also be waste for disposal.

520 The design of AP1000, without a low-pressure VCT to accept recyclable primary coolant, means that any fluid taken as part of the sampling system must be disposed as waste. Westinghouse claims that it is not ALARP to recycle the PSS effluent in AP1000 but I have not yet been presented with evidence to support this. The impact of this extra let-down from the RCS needs to be considered, for example in relation to CVS requirements.

521 This is a significant aspect of the PSS design which has not yet been completed. I consider this to be part of GDA Issue **GI-AP1000-RC-02**. I judge that this Issue is resolvable, but further work is required to the case to demonstrate acceptability.

4.2.9.3 Primary Auxiliary System Sampling

522 As described in para. 497, AP1000 includes a number of local “*grab sample*” locations for sampling of other primary auxiliary systems. The principal samples, all of which are potentially active, include;

- RNS heat exchanger
- SFS (upstream and downstream of purification)
- IRWST
- BDS (Steam Generator Blowdown System) inlet (which is described as part of the Secondary Sampling System (SSS), see Section 4.4.4, although it is notable that a number of existing PWRs incorporate the capability to sample using the primary sampling systems due to the potential for activity caused by tube leaks or Steam Generator Tube Rupture (SGTR))

523 Apart from the BDS inlet (which is part of the SSS) none of these samples are part of the PSS and must be sampled locally. None of the documentation supplied as part of GDA provide much information on these provisions, which raises a number of queries, including:

- Westinghouse have not provided details of the PSS operations during shutdowns hence it is assumed that the hot leg samples remain available during ¾ loop. operations; some plants are required to change to RNS sampling under these conditions.
- It is not apparent how the IRWST can be sampled with the reactor at power, which will be required before a refuelling shutdown to ensure the correct boron concentration and purity.
- No details are provided in the safety case on facilities to sample these locations, such as sampling enclosures, degassing facilities and ventilation provisions.
- No provisions exist for CP sampling of the SFP.

524 As described in Section 4.2.9.2.1, the omission of a CVS inlet sample is an important design choice in AP1000. This requires a more substantial justification.

525 While much of the assessment during Step 4 has concentrated on the PSS as the major system which provides sampling of the primary chemistry, it is clear that a number of other provisions exist outside of this system. As part of the wider justification for the PSS these need to be considered. I consider this to be part of GDA Issue **GI-AP1000-RC-02**. I judge that this Issue is resolvable.

4.2.9.4 Post Accident Sampling

526 The PSS also has functions during post accident sampling conditions in AP1000. In a post accident situation, the containment isolation valves of the PSS 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. This will use the normal RCS hot leg samples. Sampling of the containment sump and atmosphere is also possible, although a separate containment hydrogen control system (VLS) is used to measure hydrogen post-accident. Samples are taken using the GSP, which includes provisions for diluting high activity samples ‘on-line’. In the event of an accident, highly contaminated samples can be routed back into the containment sump. The eductor is used to sample when insufficient driving pressure is available at the sample source.

527 TQ-AP1000-539 (Ref. 8) provides information on post-accident sampling using the PSS. The GSP can operate to provide four types of post accident sample; undiluted liquid, 1000 fold diluted liquid, diluted liquid sample off-gas and diluted containment atmosphere. High activity samples are taken using shielded casks using septum and needle assemblies. This type of arrangement is common to current system designs for post accident situations.

528 Purely as a post accident sampling system the PSS design appears appropriate, allowing the requisite samples to be taken and providing adequate operator protection. However as indicted in previous sections the use of this type of system for routine sampling has not been adequately justified and does not appear consistent with relevant good practice.

4.2.9.5 Summary

529 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of the AP1000 primary sampling systems are:

- Westinghouse made a number of changes to the AP1000 primary sampling systems during Step 4 which have improved the system substantially from that assessed during Step 3, specifically related to system failure, reliability and sample contamination. Due to the timing of these changes and the on-going system development internal to Westinghouse, the safety case and evidence for their suitability is not yet complete and a number of concerns remain.
- The safety case does not demonstrate that the system design is sufficient to support safe operation of the plant during all modes of operation as it does not link the design with the operating requirements. This is particularly important during periods of increased sampling activity, such as during start-up and shutdown. A number of samples which have historically been included as part of PWR primary sampling system designs are not included in the AP1000 PSS design. The use of a GSP for post accident sampling appears reasonable, but its use for normal operations is uncertain especially given the design change to flowing samples. I consider this to be

an omission from the safety case, particularly relevant to the AP1000 design due to the design differences from other PWR sampling systems.

- In line with the overall AP1000 design philosophy, the AP1000 PSS is a very simplified design. The design is based around an in-containment manifold where all samples are routed through one of two main sampling lines which pass through the containment penetrations, with one claimed to operate continuously and the other on a grab sample basis. I do not believe this arrangement is representative of relevant good practice for RCS samples. The in-containment location does not permit ready access to repair defects or perform maintenance with the reactor at power. The assumption that flushing will provide representative samples, even if the system operates as designed, has not been justified.
- On a functional level, based on the evidence I have been presented with to date I believe that the system, as currently designed, will not provide reliable and representative samples for a number of important AP1000 parameters, potentially affecting zinc, corrosion products, hydrogen or for monitoring fuel reliability. Due to the design of AP1000 these are all important parameters for which accurate measurements will be required. The justification for not including isokinetic-type sampling for corrosion products has not been adequately made, especially with the potential for elevated corrosion product levels in AP1000.
- The current design does not include the use of a boron meter (or similar technology). I consider that given the importance of soluble boron a means of continuously monitoring this parameter would be appropriate and can be demonstrated to be reasonable given OEF.
- Questions remain over the capacity of AP1000 to support a true fully flowing sample as evidence has not been provided to demonstrate that the waste generation is acceptable.

530 Overall, despite some improvement made during Step 4 there remains a number of unresolved concerns over the adequacy of the AP1000 primary sampling systems and their ability to support safe operation of the plant. These will need to be resolved under GDA Issue **GI-AP1000-RC-02** before I can be content with the Westinghouse safety case in this area.

4.2.9.6 Assessment Findings

531 Based upon the assessment of the primary sampling systems in AP1000 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-AP1000-RC-20** – *The Licensee shall define and justify restrictive specifications for cobalt in the primary sampling system lines. This Assessment Finding should be completed before procurement of the sampling system lines; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*
>
> **AF-AP1000-RC-21** – *The Licensee shall review the need for manual operation of isolating valves on the primary sampling system manifold, including consideration of operator radiation exposure and operability with the plant at power. Consideration should be given to operating rules to limit the time spent with the sampling system in*

a degraded functional state. This Assessment Finding should be completed before active operations commence; Target milestone – Initial criticality.

4.2.9.7 GDA Issues

532 Based upon the assessment of the primary sampling systems in AP1000 described in Section 4.2.9 above, I have identified the following GDA Issue which requires resolution:

> ***GI-AP1000-RC-02** – Primary Sampling Systems - Demonstrate that the sampling arrangements for the primary circuit and connected auxiliary systems of AP1000 are adequate to support safe operation of the plant.*

4.2.10 Assessment – Holistic Approach to Normal Operating Chemistry

533 In the preceding sections of this report I have assessed the impact many of the normal operating chemistry parameters have on fuel integrity, structural integrity, ORE and radwaste in AP1000 including how much is added, how it is added, how it is controlled and 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 from often divergent requirements. 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 addition of ^{7}LiOH / H_3BO_3 to a desired pH_T based upon reactivity considerations.
- Maintenance of reducing conditions throughout the circuit by hydrogen dosing.
- Minimisation of impurity ingress.

534 Plus, many reactors are now adding zinc.

535 Although these appear relatively simple, small changes to any of these parameters at power can have a pronounced effect on the chemical behaviour 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 Westinghouse 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.

536 During my assessment I encouraged Westinghouse to identify the chemical parameters that needed controls for safety. Although Westinghouse recommends EPRI guidance to define much of the regime needed for operation, they have also produced a *“chemistry manual”* and a supplemental guideline document to advise a future licensee how to commission the plant and develop their own site-specific chemistry programme.

537 Chemistry identifies a number of parameters, radiochemical specifications and other controls necessary to maintain radioactivity ALARP and assure the long-term safety of the reactor. Design-basis accident analysis identifies few of these directly but many are necessary to meet environmental and radiological limits. Westinghouse (and EPRI) sees these as matters for the Licensee to develop a local chemistry strategy. As described in Section 4.1.3, ND has raised a cross-cutting Issue on the development of Limits and Conditions for AP1000 to include chemistry, which needs to be satisfactorily resolved

before an adequate Reactor Chemistry safety case can be made for AP1000 (**GI-AP1000-CC-01**).

538 As described in Section 4.1, as a vendor Westinghouse does not specify precise values for the normal operating chemistry in AP1000, leaving such decisions to the Licensee. The AP1000 primary circuit chemistry is defined in the EDCD (Ref. 22, Section 5.2.2) and the RCS coolant specifications are given in 5.2 Table 1. Westinghouse produced an AP1000 "*chemistry manual*" (Ref. 25) which further defined their expectations for the operating chemistry. This recommended the adoption of the EPRI Guidelines (Ref. 15). Westinghouse also mandates additional constraints to the EPRI Guidelines in their supplemental guidance (Ref. 26), which appear at a similar level to the EPRI Action Level 2 values. By comparing these values it is possible to interpret a set of "*agglomerated*" values for the AP1000 normal operating chemistry, as follows, following the hierarchy ascribed to the various documents by Westinghouse (Westinghouse supplemental – EPRI – EDCD):

Parameter	**EDCD Value (Ref. 22)**	**EPRI Guideline Value (Ref. 15) – Action level 2**	**Westinghouse Supplemental Guideline Value (Ref. 26)**	**"*Agglomerated*" AP1000 Value**
Control Parameter				
pH$_T$	Determined by the concentration of boric acid and alkali present.	Plant specific	[redacted]	[redacted]
Lithium, mg kg^{-1}	Lithium is coordinated with boron per fuel warranty contract.	Plant specific	[redacted]	[redacted]
Chloride, μg kg^{-1}	≤ 150	≤ [redacted]	-	≤ [redacted]
Fluoride, μg kg^{-1}	≤ 150	≤ [redacted]	-	≤ [redacted]
Sulphate, μg kg^{-1}	-	≤ [redacted]	-	≤ [redacted]
Silica, μg kg^{-1}	≤ 1000	Plant specific	≤ [redacted]	≤ [redacted]
Hydrogen, cc kg^{-1}	25 to 50	25 to 50	-	25 to 50
Oxygen, μg kg^{-1}	≤ 100	≤ [redacted]	-	≤ [redacted]
Zinc, μg kg^{-1}	≤ 40	Plant specific	[redacted]	[redacted]
Diagnostic Parameter				
Suspended Solids, μg kg^{-1}	≤ 200	Plant specific	≤ [redacted]	≤ [redacted]
Aluminium, μg kg^{-1}	≤ 50	Plant specific	≤ [redacted]	≤ [redacted]
Calcium + Magnesium, μg kg^{-1}	≤ 50	Plant specific	≤ [redacted]	≤ [redacted]
Magnesium, μg kg^{-1}	≤ 25	Plant specific	≤ [redacted]	≤ [redacted]

Parameter	EDCD Value (Ref. 22)	EPRI Guideline Value (Ref. 15) – Action level 2	Westinghouse Supplemental Guideline Value (Ref. 26)	"*Agglomerated*" AP1000 Value
Nickel, $\mu g\ kg^{-1}$	-	Plant specific	[redacted]	[redacted]

Table 9: AP1000 Primary Circuit Chemistry Controls

539 For the most part, these parameters are consistent with many operating plants worldwide, however I note the following:

- Westinghouse describes chemistry for the primary circuit for AP1000 with a constant pH_T [redacted] with a [redacted] mg kg^{-1} lithium upper limit. I consider a lower limit of [redacted] would not be appropriate, leading to higher levels of fuel crud and radioactivity. I have made the sensitivity studies to understand the magnitude of effects the subject of Assessment Findings **AF-AP1000-RC-11** and **AF-AP1000-RC-13**, but I have no doubt that AP1000 can achieve an acceptable pH_T regime within this overall band.
- The supplemental guidelines also cover the SFP, BAST, IRWST and different operating modes of the primary circuit. They do not include a specification for nickel, which may be an important predictor for crud and radiocobalt levels.
- I note the broad tolerance given to hydrogen levels in AP1000. While these appear reasonable a site specific optimisation would no doubt result in tightening of the allowed variation.

540 Overall, through the documents produced by Westinghouse a holistic approach to chemistry seems to have been used. The "*agglomerated*" values this produces appear reasonable for the normal operating chemistry to be applied to AP1000, although the tolerances on some parameters remain broad and the Licensee will need to refine these as part of the plant specific chemistry procedures, including how these will affect the performance of the plant. This is an important part of **AF-AP1000-RC-01**. There is still a need to develop procedures for managing chemistry that is not within specification. The EPRI guidance on this is not always relevant to AP1000, for example where access to the CVS at power is difficult. I consider this to be an Assessment Finding, **AF-AP1000-RC-22**.

4.2.10.1 Summary

541 This part of my assessment is essentially a review considering the consistency of the overall chemistry specifications, whether they are appropriate to the AP1000 design and if the design can support the specifications. No specific ROs or TQs were raised. Overall, my assessment for the primary circuit chemistry is:

- Westinghouse has provided guidance for licensees to develop a site-specific chemistry plan which, with the PCSR, should indicate the rationale for some of the parameters chosen. The broad parameters suggested by Westinghouse appear to be an appropriate starting point for developing a plant specific operating chemistry by the Licensee.

- Westinghouse supplemental guidelines suggest a minimum pH_T of [redacted] but sensitivity studies are needed to demonstrate why a higher value might not be better. This is part of the findings on fuel crud identified in Sections 4.2.3 and 4.2.5 of this report. Similarly a number of other parameters will need to be justified by the Licensee.
- Westinghouse has begun to identify top-tier technical specifications but a number of lower-tier chemical and radiochemical specifications and controls are undefined as yet. Actions for dealing with off-specification chemistry should also be identified.

542 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA but I have a number of findings relating to the definition of limits, margins for variability and corrective actions.

4.2.10.2 Assessment Findings

543 Based upon the assessment of the holistic approach to primary circuit chemistry in AP1000 described in Section 4.2.10 above, I have identified the following Assessment Finding which needs to be addressed, as normal regulatory business, by a future Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-22*** *– 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.*

4.2.10.3 GDA Issues

544 Based upon the assessment of the holistic approach to primary circuit chemistry in AP1000 described in Section 4.2.10 above, I have identified no Reactor Chemistry GDA Issues in this area. However this topic is related to the cross-cutting GDA Issue relating to Limits and Conditions **GI-AP1000-CC-01**, see Section 4.1.3.3.

4.2.11 Assessment – Start-up and Shutdown Chemistry

4.2.11.1 Overview

545 At the end of each fuel cycle all PWRs shutdown for refuelling and maintenance and, when this is completed, are 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.

546 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 and lithiation. 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 later in this report.

547 During start-up and shutdown transients a number of significant chemistry changes take place 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 control.

548 The assessment of this area during Step 3 was rather preliminary, mainly due to a lack of information provided by Westinghouse. The assessment during Step 4, in a similar manner to HFT, has focussing on the principles and processes rather than fully developed and detailed procedures which are not yet available and part of the Licensee responsibility.

549 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 AP1000 primary sampling system is given in Section 4.2.9, including consideration of the system during such transients.

4.2.11.2 AP1000 Approach to Start-up and Shutdowns

550 During Step 4 a TSC contract was let to review the AP1000 start-up and shutdown arrangements (Ref. 33) including an initial review of current ‘relevant good practice’ in start-up and shutdown chemistry (Ref. 107), mainly that presented in chemistry standards such as EPRI (Refs 15 and 16) or VGB guidelines (Ref. 17). The main conclusions of this initial review are in agreement with the approach adopted by Westinghouse for AP1000 and indeed recognise the importance of plant specific optimisations. The review of AP1000 (Ref. 33) highlighted a number of aspects of the design that warranted closer review, and I have considered these as part of my assessment:

- The procedures for the operation of the purification systems (see para. 566).
- Limits and conditions associated with head-lift and shutdown criteria (see Section 4.2.11.4).
- The impact of high hydrazine additions for oxygen scavenging (see para. 568).
- The addition, control and monitoring of hydrogen levels (see Sections 4.2.2.2.3, 4.2.9.2.2 and 4.2.11.3).

551 Numerous TQs (715, 804 to 807, 811, 1157, 1228, 1234, 1238 and 1242; Ref. 8) were raised with Westinghouse on this topic during Step 4. In addition, the responses to RO-AP1000-55.A1 (Ref. 127) and RO-AP1000-55.A9 (Ref. 128) both contained information of relevance to this part of the assessment. In contrast the response to RO-AP1000-

57.A2, which asked for a justification that primary coolant activities had been reduced SFAIRP based upon the chemistry, including during start-up and shutdown transients, provided very little information on these aspects, other than some generalised statements. The most relevant of these responses are discussed further below.

552 Westinghouse presented their approach to start-up and shutdown chemistry during a Step 4 technical meeting, in addition to providing an overview in response to TQ-AP1000-804 (Ref. 8). This query requested an overview of the primary circuit start-up and shutdown sequence and the response details Westinghouse's expectations and philosophy for controlling AP1000 start-up and shutdowns. Westinghouse identify the principal chemistry steps, from "*AP1000 refuelling and maintenance outage schedule*" (Ref. 29) during a shutdown as:

- The liquid and gas radwaste systems (WLS and WGS) are prepared to accept waste generated from degassing operations prior to shutdown. The purification flow is routed to the WLS via the CVS letdown where the coolant is stripped of gases and returned to the make-up system. This is carried out prior to shutdown to reduce activity and hydrogen to levels appropriate for personnel access. Active hydrogen addition is maintained during the early stages of shutdown, when boration is occurring (to maintain ≥ 15 cc kg^{-1} hydrogen).
- Lithium removal is started 24 hours prior to shutdown by placing the CVS cation demineraliser in service. The pH_T is monitored and maintained at or above 6.9 while at power.
- The Boric Acid Storage Tank (BAST) and IRWST are sampled and analysed for quality prior to shutdown. Boration is carried out by adding a measured volume of boric acid solution via the CVS make-up system and verified by chemical analysis of reactor coolant. The reactor make-up control is set to the boron concentration required for shutdown and the make-up during depressurisation and cool-down is automatic. This produces acid-reducing conditions to aid solubilisation of crud. Lithium removal is completed following plant shutdown.
- The Pressuriser is vented to reduce the gaseous hydrogen inventory, fission gases and non-condensible gases. Hydrogen degassing can then be completed either by using the degasifier in the WLS and/or chemically by addition of hydrogen peroxide.
- Hydrogen peroxide is added to produce acid-oxidising conditions which aids solubilisation of corrosion products (particularly nickel metal) and activated corrosion products (notably ^{58}Co). The RCS oxygen concentration is maintained at greater than 2 mg kg^{-1} to ensure that an oxidising environment is maintained.
- Clean-up of the primary coolant continues using the CVS demineralisers to minimise refuelling cavity dose rates and support clarity of cavity water.

553 The start-up procedure uses similar steps in reverse order. Make-up comes from the CVS fed from the demineralised water supply and BAST. Westinghouse recommends a vacuum refill procedure is used to remove residual oxygen, with chemical dosing of hydrazine to complete deoxygenation. Hydrogen addition is commenced prior to criticality, with a concentration of > 15 cc kg^{-1} required, as is lithium dosing which is optimised to avoid wastage during dilution to criticality. Zinc dosing is initiated once RCS chemistry criteria for nickel and silica are met.

554 These are standard steps used during PWR shutdown and start-up and, as Westinghouse indicate; the methodology suggested does indeed appear consistent with international practice (EPRI (Ref. 15)). A number of the design features of AP1000

compared to progenitor PWRs could influence the operations during shutdown periods and these are discussed further below, along with some of the most important chemistry steps during shutdowns and start-ups.

4.2.11.3 Control of Gases

555 Control of gases, both radioactive and flammable, is an important safety consideration during shutdown periods. TQ-AP1000-805 (Ref. 8) further queried how this was controlled for AP1000, noting that the AP1000 design does not include a VCT and injects hydrogen directly. Both the Liquid Radwaste System (WLS) and Gaseous Radwaste System (WGS) are important systems during shutdowns, with the WLS degasser used to remove hydrogen and gaseous fission products from the coolant with the waste directed towards the WGS for processing before discharge. Both systems are assessed further in Section 4.5.1. When the WLS degasifier is to reduce the RCS hydrogen concentration, one of the dedicated effluent hold-up tanks must be completely drained before the processing begins both to ensure sufficient capacity is available, but more importantly to ensure that contamination or dilution of the RCS, particularly for boron, does not occur. This is controlled by administrative procedures which require the operator to ensure the tank is empty before proceeding. Similarly, the degasifier must be isolated before hydrogen peroxide addition to the primary coolant during shutdowns. Addition of peroxide creates oxidising conditions, potentially transferring oxygen to the hydrogen rich WGS stream. This is again controlled administratively, although interlocks stop this gas transferring to the WGS when a high oxygen concentration is detected. By controlling the reactor operations the operator can prevent and remove hydrogen pockets from areas such as the pressuriser headspace or Reactor Coolant Drain Tank (RCDT).

556 TQ-AP1000-806 (Ref. 8) confirms that the WLS degasifier will not be used during start-ups in order to control the flammability hazard described above, with a combination of mechanical (vacuum) and chemical (hydrazine) venting used instead. Westinghouse oxygen control practice ($O_2 \leq$ [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 AP1000. During any re-start procedure a quantity of non-condensable gases accumulate in the pressuriser vapour space and the SG tubes will remain gas locked; these bubbles must be removed. AP1000 may be more susceptible to non-condensable gas accumulation due to the deoxygenation process applied to the demineralised water (see Section 4.4.2.1.8). A design change (Ref. 30) allows AP1000 to vent the pressuriser to the RCDT. Most PWRs remove oxygen from the SG tubes by ‘jogging’ the RCPs periodically to dislodge any trapped gas; AP1000 will also follow this convention, however due to the use of canned pumps it is required that a vacuum is drawn on the pump stator cavities while at mid-loop.

557 Low Temperature Crack Propagation (LTCP) is a degradation mechanism for high nickel alloys exposed to hydrogenated primary coolant at low temperatures which has recently been observed in laboratory tests. No operating PWR has experienced LTCP. Westinghouse has not presented information on LTCP in the AP1000 safety case. Despite the very low risk of LTCP in an operating PWR with Inconel 690 SG tubing, as understanding in this area is still developing the Licensee will need to review the most up to date knowledge during development of start-up and shutdown procedures for a UK AP1000 to ensure the arrangements for hydrogen control are adequate.

4.2.11.4 Control of Radioactivity

558 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. 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. TQ-AP1000-807 (Ref. 8) requested information on the likely head lift criteria to be applied in AP1000. As for all limits and conditions, Westinghouse have decided not to specify any for AP1000, except for "*endorsing*" the recommendations made in the EPRI primary chemistry guidelines (Ref. 15) in this respect. This is linked to the GDA Issue on limits and conditions **GI-AP1000-CC-01**; see Section 4.1.3.3. The EPRI guidelines (Table 3.4) specify the following:

- ^{131}I < [redacted] MBq t^{-1}, ^{133}Xe < [redacted] MBq t^{-1} prior to opening or venting the RCS.
- ^{131}I < [redacted] MBq t^{-1}, total γ-emitters (^{58}Co, ^{60}Co, ^{134}Cs, ^{137}Cs and ^{54}Mn) < [redacted] MBq t^{-1} prior to flooding the refuelling cavity; assuming a ten fold dilution in concentration caused by mixing with clean refuelling water.

559 While these may be reasonable limits no attempt is made to reconcile these with the AP1000 safety case and the assumptions therein. This confirms the requirements for the controls and the values for these limits should be reviewed at a later stage of licensing, when available. I consider this to be an Assessment Finding, **AF-AP1000-RC-23**.

560 During a shutdown once flow is switched from the RCPs to the RNS, flow is no longer maintained through the SG tubes. This is common to many PWRs and AP1000 is no different. Thus, it is important that activity levels are controlled before this change over in order to ensure that coolant trapped in the SG tubes is of sufficiently low activity to minimise operator doses during any subsequent SG maintenance. This often involves selecting which RCP is the last in operation and specifying 'limits' on primary activity before the change from RCP to RNS flow. TQ-AP1000-1238 (Ref. 8) queried the Westinghouse expectations in this area. While the response did not specifically address this point I can see no design reason why such controls are not possible in AP1000. The response to TQ-AP1000-1242 (Ref. 8) suggested that the variable speed drives on AP1000 may give greater flexibility in this area. This aspect should be reviewed once detailed shutdown procedures are produced by the Licensee. I consider this to be an Assessment Finding, **AF-AP1000-RC-24**.

561 It was notable that no tritium value was included in the listing of chemistry controls during shutdown. RO-AP1000-84.A1 (Ref. 7) was raised to understand the management of tritium in AP1000. 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. In response to this RO, Westinghouse provided a report which estimated the expected AP1000 RCS tritium concentration through a fuel cycle. This report argued that specific limits or conditions were the responsibility of the Licensee but also aimed to demonstrate that no limits or conditions were required for AP1000. Westinghouse 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 AP1000 discharge predictions. The response demonstrates that high levels of tritium will be present during the cycle, peaking at the mid point at over 120,000 MBq t^{-1} and gradually reducing as the coolant is progressively more and more diluted to remove boron. This is

‘standard’ PWR practice for those plants which do not recycle boron, as in AP1000. This also has implications for the SFP and IRWST activities as whatever tritium is left in the RCS at head lift is distributed between these volumes during refuelling. This aspect is discussed further in Section 4.3. The Westinghouse response is built upon an assumption that all fuel cycles will proceed without interruption for the full 18 months. As such the impact of opening the RCS with mid-cycle tritium concentrations is not discussed, although the boration that would occur would dilute the concentration before head-lift. Fundamentally, there are several possible ways to control this hazard and it is not necessarily a requirement to limit the RCS tritium directly. This could be achieved indirectly, for example by limiting the SFP and/or IRWST concentrations.

562 The ‘*AP1000 Radiation Analysis Design Manual*’ (Ref. 31) indicates that Westinghouse propose ‘limits’ on the RCS tritium activity of 129,500 MBq t^{-1} and 92,500 MBq t^{-1} in the refuelling cavity. Data is presented on a “*design basis*” and “*best estimate*” analysis of tritium in the RCS both without and with one or two RCS volumes discharged per cycle. For the no loss or discharge case the results are clearly unrealistic and result in very high RCS tritium concentrations. One RCS volume results in a final RCS concentration of around 129,500 MBq t^{-1} with two volumes reducing this to around 92,500 MBq t^{-1}. These are significantly higher than the value given in the response to RO-AP1000-84 of around 8 MBq t^{-1}, but it is not clear if the former consider dilution caused by end of cycle boration. In any case, there is clearly a significantly higher discharge rate assumed in the RO-AP1000-84 response.

563 Overall, while I consider that an adequate case could be made to demonstrate that tritium control in AP1000 is possible, the assessment has reinforced the need for tritium controls during a shutdown and discharge of tritiated waste during the cycle. It is unclear from the case presented how the analysis relates to other assumptions in the AP1000 safety case, such as ORE or discharge limits. As discussed earlier, Westinghouse proposes no specific controls for tritium during a shutdown. I consider that a control is needed for tritium and a Licensee for AP1000 will need to justify the approach taken for controlling this nuclide during shutdowns. This is part of Assessment Finding **AF-AP1000-RC-23**. This is also linked to the cross-cutting GDA Issue on limits and conditions **GI-AP1000-CC-01**.

564 Westinghouse has recognised the contribution secondary neutron sources can potentially make to tritium build-up in PWRs. This aspect is discussed further in Section 4.2.3.3.2.

4.2.11.5 Control of Water Chemistry

565 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-AP1000-1157 (Ref. 8) provided information on how the RNS will be flushed to the IRWST in case of contamination with lithium, with the IRWST resulting in a large dilution (> 100). However, the IRWST dissolved oxygen content is not controlled and this will introduce oxygen to the RCS when connected. Westinghouse state that the RNS is connected at 177 °C, which means that the oxygen content should be low to protect the RCS materials. This may be above the “*limits*” suggested by Westinghouse (and EPRI) for material protection purposes. It is not clear from the safety case how this effect will be controlled. I consider this to be an Assessment Finding, **AF-AP1000-RC-25**.

566 An important consideration during start-up and shutdowns is the performance of the purification systems. Westinghouse described the intended operation of the CVS,

including during transient periods, in response to RO-AP1000-55.A3 (Ref. 7). The AP1000 CVS, and the response to RO-AP1000-55.A3, are discussed fully in Section 4.2.2, including capacities and modes of operation; however specific comments relevant to their use during start-up and shutdown are made here. In response to our queries Westinghouse described the expected operation of the CVS ion exchange demineralisers during shutdown and start-up periods. This was an important response in understanding the intended operation of the CVS 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 AP1000 is to operate the (two 100% redundant) mixed beds primarily as purification beds (Li^+/ BO_2^- form), although the second mixed bed may be used for limited deboration at end of cycle. The third vessel is used for lithium removal during the cycle, but is primarily held as a shutdown purification vessel containing hydrogen form cation resin. The addition of a third, large, shutdown bed in the design offers many potential advantages and options for shutdown activity management. In principle these arrangements are similar to many operating PWRs, however the novel location of the CVS inside containment in AP1000 may hinder the operational flexibility in practice. The options for resin change are either during outage or with the reactor at power. Westinghouse has estimated the doses for the latter case (Ref. 32) and it is clear that careful controls and planning would be required. The former option of change at outage means that the shutdown resin will not have decayed for a significant period before change. These factors may also influence how often the media is changed. As these are primarily dose control issues, I have passed on these observations to my Radiological Protection colleagues during Step 4. Overall an ALARP balance needs to be struck between what changes are made and when considering ORE, wastes and the effects on plant chemistry. These aspects will need to be demonstrated by the Licensee when detailed procedures are available. I consider this to be an Assessment Finding, **AF-AP1000-RC-26**.

567 During shutdowns the CVS flow is maintained by the RNS pumps once the RNS assumes cooling duties. The AP1000 purification flow rate is comparable to many plants in operation today at around 25 $t\ hr^{-1}$. Refer to Section 4.2.2 for assessment of the CVS systems.

568 The addition of hydrogen peroxide, a strong oxidising agent, has the potential to affect the ion exchange resins which operate during the oxidising phase of the shutdown. The effect of this was queried in TQ-AP1000-715 (Ref. 8). Westinghouse arguments and evidence in this area are reasonable and support the minimal effect this is expected to have in AP1000. The need is to maintain purification at these times when the burden is highest. Similarly the addition of hydrazine during start-up could affect the resins, mainly through the production and subsequent removal of ammonia. While I am content that AP1000 should not need to add excessive amounts the effects of this should be considered and factored into the plant operating procedures. This is related to Assessment Findings **AF-AP1000-RC-01** and **AF-AP1000-RC-27**.

569 A number of filters are installed in the AP1000 design for removal of particulate corrosion products, most notably the main CVS letdown filter. Westinghouse does not anticipate changing the filtration efficiency purposefully to account for start-up or shutdown variations.

570 In TQ-AP1000-1234 (Ref. 8) I asked Westinghouse to describe consideration given to particulate releases during shutdowns, and to lesser extent, start-ups. The response provides reasonable arguments to suggest that AP1000 should not be more prone to particulate release compared to existing plant, and may in fact be less susceptible due to

design differences such as lower cool down rates, variable speed RCPs and reflood provisions. This is only part of the story, but without specifying chemistry regimes Westinghouse are not able to justify the chemistry related arguments. As described in Section 4.2.3, Westinghouse were asked to provide evidence that radioactivity in AP1000 had been reduced SFAIRP based upon chemistry controls, including during start-up and shutdowns, in RO-AP1000-57.A2 (Ref. 7). While I am satisfied that a case could be made on this basis, due to Westinghouse not specifying precise chemistry during these periods this claim cannot be substantiated during GDA and will require justification from the Licensee. This would be required as part of Assessment Finding **AF-AP1000-RC-01.**

571 Similarly, Westinghouse has not directly provided any reassurance of the capability of AP1000 to accommodate deviations from ‘standard’ shutdown practices, for example with failed fuel. Although on the basis of the assessment I have done during GDA, I am satisfied that a suitable degree of flexibility and resilience could be demonstrated for AP1000. Fully developed start-up and shutdown procedures should recognise these possibilities and provide details on how to handle them in a safe and ALARP manner. I consider this to be an Assessment Finding, **AF-AP1000-RC-27**.

4.2.11.6 Summary

572 Westinghouse makes reasonable arguments to suggest that start-up and shutdown transients in AP1000 should be adequately controllable, although I note a number of areas where further consideration may be necessary. Post GDA fully developed start-up and shutdown procedures should be developed for the primary circuit of AP1000, building upon the basis presented for GDA. These should include due consideration of related topics such as limits and conditions, as appropriate. This is part of Assessment Finding **AF-AP1000-RC-01.**

573 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit start-up and shutdown assessment are:

- Within the bounds of the GDA assessment, notably without specifying detailed chemistry operating procedures, Westinghouse have presented a reasoned and justified approach for much of the start-up and shutdown chemistry in AP1000 that is consistent with relevant good practice and operational experience. I believe that AP1000 should be capable of well controlled chemistry during these transient periods, with resultant safety benefits.
- An important safety consideration during shutdown periods is the clean-up of the reactor coolant to a sufficient level to allow safe opening of the RCS. Westinghouse has not specified limits for these levels in the safety case, but endorses the guidance provided by EPRI. This is related to the GDA Issue on limits and conditions. A particular deficiency in this approach is the lack of any controls on tritium. While an adequate case could be made to demonstrate such controls are possible in AP1000, and the safety case undoubtedly contains some constraints on this nuclide, the safety case at present does not consider this. This will need to be addressed.
- A number of features in the AP1000 design impose limits or constraints on the operational flexibility available to the operator during shutdowns and start-ups and the impact of these needs to be clearly documented in the safety case.
- Post GDA, fully detailed chemistry procedures 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.

- No ALARP justification can be made for the shutdown and start-up chemistry based on the Westinghouse GDA submissions. This will need to be addressed moving forward.

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

4.2.11.7 Assessment Findings

575 Based upon the assessment of the primary circuit start-up and shutdown chemistry in AP1000 described in Section 4.2.11 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-AP1000-RC-23*** *– The Licensee shall specify values for radiochemistry parameters prior to head-lift during a shutdown, including evidence of their suitability and links to the safety case. This Assessment Finding should be completed before the plant is first operated with nuclear power, as this is when activity is first generated; Target milestone – Initial criticality.*
>
> ***AF-AP1000-RC-24*** *– The Licensee shall specify timings and criteria for stopping the main reactor coolant pumps, including swapping to residual heat removal flow control. The criteria should be linked to the claims for chemistry in the safety case. This Assessment Finding should be completed before the plant is first operated with nuclear power, as this is when activity is first generated; Target milestone – Initial criticality.*
>
> ***AF-AP1000-RC-25*** *– The Licensee shall ensure that oxygen levels are controlled in the residual heat removal system during shutdowns. Documented controls should include appropriate limits and conditions related to allowable concentrations and temperatures before connection to the reactor coolant system. This Assessment Finding should be completed before inactive commissioning activities commence; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-AP1000-RC-26*** *– The Licensee shall define arrangements that are specific to the design of AP1000, for the management of ion exchange resins and filters in the Chemical and Volume Control System (CVS). The effect of the timing of changes on operator radiation exposure, wastes and plant chemistry should be considered, as well as operational transients and un-planned operations. This Assessment Finding should be completed before nuclear operations, as this is when the ion exchange and filters will trap radioactive materials; Target milestone – Initial Criticality.*
>
> ***AF-AP1000-RC-27*** *– The Licensee shall specify chemistry requirements for start-up and shutdown following anticipated operational transients such as fuel failure. This Assessment Finding should be completed before fuel is first loaded into the reactor core; Target milestone – Initial Criticality*.

4.2.11.8 GDA Issues

576 Based upon the assessment of the primary circuit start-up and shutdown chemistry in AP1000 described in Section 4.2.11 above, I have identified no Reactor Chemistry GDA

Issues in this area. However, this area is relevant to the cross-cutting GDA Issue on Limits and Conditions, **GI-AP1000-CC-01**, described earlier in my report (Section 4.1.3.3).

4.2.12 Assessment – Hot Functional Testing

577 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). Many plants play close attention to this period in order to achieve low plant dose rates.

578 For GDA it is not reasonable to expect Westinghouse to have fully developed HFT methods and procedures, especially as these are areas where significant international experience is expected to influence the final choices (especially from AP1000 plant which may commission before any UK plant is licensed). Assessment of this area was not started during Step 3 but was progressed during Step 4.

579 RO-AP1000-57.A2 (Ref. 7) specifically asked for a justification for the expected AP1000 HFT procedure in relation to reduction in primary circuit radioactivity SFAIRP. The approach for AP1000 is targeted at producing a protective inner oxide layer, principally on the SG u-tubes, with as large an incorporation of zinc as possible. The approach suggested for AP1000 is defined in Chapter 9 of the AP1000 “*chemistry manual*” (Ref. 25); this is a specific chapter dealing with “*Pre-core Hot Functional Testing*”. The proposed procedure is based upon a three step process, which is similar to the steps taken during a normal operating cycle and plant shutdown, namely:

- Alkaline reducing – lithium hydroxide, zinc and hydrogen addition.
- Acid reducing – delithiation, addition of boric acid.
- Acid oxidising – forced oxygenation with hydrogen peroxide.

580 Westinghouse recommend a minimum of [redacted] days under alkaline reducing conditions, noting that any increase in duration will have additional benefits in producing a more stable oxide with higher levels of zinc incorporation. The chemistry changes required are accommodated by the normal RCS chemical control systems, such as the Chemical and Volume Control System (CVS) and Liquid Radwaste System (WLS), which are assessed elsewhere in this report (Sections 4.2.2 and 4.5.1 respectively), so are not repeated here. The chemistry requirements are generally akin to those expected during normal operations so the assessments undertaken there remain valid.

581 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 recognised steps in the Westinghouse 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.

582 In general the approach suggested by Westinghouse is consistent with the latest worldwide plant HFT techniques. The main differences to the Westinghouse procedure 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 reductions in Corrosion Product (CP) and dose rates are possible. As per the Step 4 assessment objectives, the precise definitions of these values were not considered during GDA. However, Westinghouse present well reasoned arguments for the expected values and I particularly welcome the addition of hydrogen (as opposed to a reliance on the residual and variable hydrogen generated by oxidation) and expect this to offer further benefits.

583 The main difference in the Westinghouse approach from previous HFT procedures is the addition of zinc. Westinghouse has specified a primary circuit chemistry for AP1000 which includes the addition of zinc for radiation field and fuel crud control. Primary circuit chemistry and zinc addition are discussed in Sections 4.2.2 and 4.2.6 respectively. In the context of HFT the addition of zinc is a recently suggested step but is not supported by significant plant experience, Westinghouse quote the example of the Japanese Tomari 3 plant which recently completed HFT with zinc. Full results are not yet available for review but initial suggestions are that significant improvements in plant dose and corrosion rates have been acheived. The application of zinc during HFT appears a reasonable proposal 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 concentrations than during normal operation or greatly increased duration to offer significant benefit. Westinghouse proposes operation at [redacted] $\mu g\ kg^{-1}$ zinc during HFT, compared to [redacted] $\mu g\ kg^{-1}$ during normal operations. This should have no noticeable effect on complementary procedures such as purification or sampling but it is recognised that zinc may not be detectable during HFT due to rapid absorption into oxide surfaces.

584 I have not reviewed the background technical basis for the proposed AP1000 HFT chemistry programme (Ref. 28), as this contains EPRI proprietary material and was only made available for ND review in February 2011. On the basis of the information presented elsewhere I am satisfied that Westinghouse has made appropriate use of industry wide experience and knowledge in developing the AP1000 procedure. This information should be included as part of the work required in addressing Assessment Finding **AF-AP1000-RC-28.**

585 A number of support systems will be required during HFT, such as the PSS and CVS. Capability and availability of these systems was not considered as part of the GDA HFT 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 AP1000. This information should be included as part of Assessment Finding **AF-AP1000-RC-28.**

586 Westinghouse recognises the importance of purification during HFT suggesting that the purification rate be maximised. The AP1000 approach will use the main CVS demineralisers operating at maximum throughput of 23 $m^3\ hr^{-1}$. The capability of the CVS system in AP1000 is assessed in Section 4.2.2 and was outside the scope for this HFT assessment area. Even so, recognition of the need to maximise purification is encouraging.

587 Westinghouse notes the requirement for testing of the Passive Core Cooling System (PXS) in the first three AP1000 plants. It is not apparent if such testing would be necessary for a UK AP1000 however the "*chemistry manual*" (Ref. 25) provides details of the chemistry considerations during this testing. The chemistry requirements for this testing should be fully documented and justified if such a test is necessary in the UK. I consider this to be an Assessment Finding, **AF-AP1000-RC-29**.

588 I believe the use of zinc during HFT is a positive step and support development and implementation of an AP1000 HFT process, based upon the fundamental principles outlined by Westinghouse for AP1000. I consider this to be an Assessment Finding, **AF-AP1000-RC-28**.

4.2.12.1 Summary

589 Based upon the evidence presented during GDA, the main conclusions I draw for the primary circuit HFT assessment are:

- Westinghouse have presented a proposed HFT approach for AP1000, based upon operational experience and including specifics for AP1000.
- 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.

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

4.2.12.2 Assessment Findings

591 Based upon the assessment of Hot Functional Testing described in Section 4.2.12 above, I have identified the following Assessment Findings which need to be addressed, as normal regulatory business, by a future Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-28** – 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 AP1000 units commissioned prior to any UK new build. The documentation should justify the controls during HFT of AP1000, 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-AP1000-RC-29** – The Licensee shall define the chemistry requirements associated with testing of the Passive Core Cooling System (PXS) during commissioning. This Assessment Finding should be completed before the PXS is first exercised and corrosive or flammable conditions may be created; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

4.2.12.3 GDA Issues

592 Based upon the assessment of Hot Functional Testing in AP1000 described in Section 4.2.12 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.3 Spent Fuel Pool

593 Operation of a PWR generates a quantity of used fuel during each operating cycle; although it should be noted that Westinghouse claim that AP1000 is an efficient reactor design and should be more efficient at fuel usage than comparable plants. 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. 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 degradation are very low, provided the pool chemistry and temperature is adequately controlled.

594 During Step 3, I started my assessment of the AP1000 SFP and associated systems, mainly concentrating on chemistry controls and how provisions have been made in the designs to accommodate these requirements. For Reactor Chemistry I consider the fuel pool systems to include the following 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, RNS, etc. (where not considered elsewhere in the assessment).

595 I examined a number of areas in much greater detail during Step 4. These areas were chemistry control, source terms in the SFP and the chemistry implications for loss of cooling faults.

4.3.1 Overview

596 Westinghouse presented an overview of the AP1000 fuel route and systems to ND in December 2009 and further information is given in the EDCD (Ref. 22, Section 9.1.2). Fuel is handled in two areas of the AP1000 plant; in the Containment Building and the Fuel Handling Area (FHA) of the Auxiliary Building. The two fuel handling areas are connected by a fuel transfer tube which penetrates the containment. The transfer tube is sealed in the reactor building side by a Quick Opening Transfer Tube Closure (QOTTC) and on the auxiliary building side by a manual gate valve. Fuel is moved on an underwater transfer car which passes through the transfer tube. The two main areas are:

- The auxiliary building contains three pools used during fuel handling; The spent fuel pool (SFP) is the largest and is dedicated to the storage of spent fuel whilst its residual 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 SFP is isolated from each of the 2 adjacent compartments by removable gates. Alongside the SFP is the fuel transfer canal which contains the transfer system that enables the fuel assemblies to be moved between the auxiliary and reactor buildings. The fuel transfer canal is normally filled with borated water. The Cask loading pit, on the side of the SFP opposite to the transfer canal, is used for loading fuel assemblies into the fuel cask for removal. The gate between the SFP and the cask loading pit is normally closed and opened only for cask loading operations. The cask loading pit is normally full of borated water.

- The reactor building contains the refuelling cavity, which is a two compartment pool, only filled during refuelling operations; the refuelling cavity is situated above the RPV and forms a single water volume with the RCS during refuelling. The part above the RPV can be isolated using a gate. The larger second part of the refuelling cavity is used as a set-down compartment for the core internals and other components during refuelling operations.

597 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 compartment 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.

598 The arrangements for transfer of spent fuel out of the AP1000 ponds following storage will be dependant upon the Licensee; as such this aspect was not assessed during GDA. However I note that AP1000 has facilities to support such operations, either as dry or wet exports, and is not fundamentally different to other PWRs in this regard.

599 The fuel pools in AP1000 are constructed of reinforced concrete and concrete filled structural modules. The portion of the structural modules in contact with the water in the pools is stainless steel and the reinforced concrete portions are lined with stainless steel plate.

4.3.2 Assessment – Chemical Control, Purification and Source Terms

4.3.2.1 Spent Fuel Pool Cooling and Purification System

600 In AP1000 the system for cooling and purifying the SFP water is a single system, the Spent Fuel Pool Cooling System (SFS). Details of the system are given in Section 6.5.23 of the PCSR (Ref. 1). Further details are provided in the System Specification Document (Ref. 65).

601 The SFS is responsible for cooling and purifying the SFP by extracting water from and returning it to the SFP. The SFS consists of two identical 100% trains consisting of a pump, a heat exchanger (cooled by CCS), an ion exchange demineraliser and a filter. The purification components (demineraliser and filter) branch from the main cooling line after the heat exchanger and as such can be isolated and by-passed, for example to facilitate resin or filter change, without impairing the cooling functions. During normal operations the second train is available to perform other functions required during refuelling such as:

- Purify and cool the refuelling cavity, fuel transfer canal or IRWST.
- Skim the reactor building or auxiliary building pools (two independent systems).
- Fill, empty or transfer water between the various pools.

602 This arrangement is summarised below (Ref. 1):

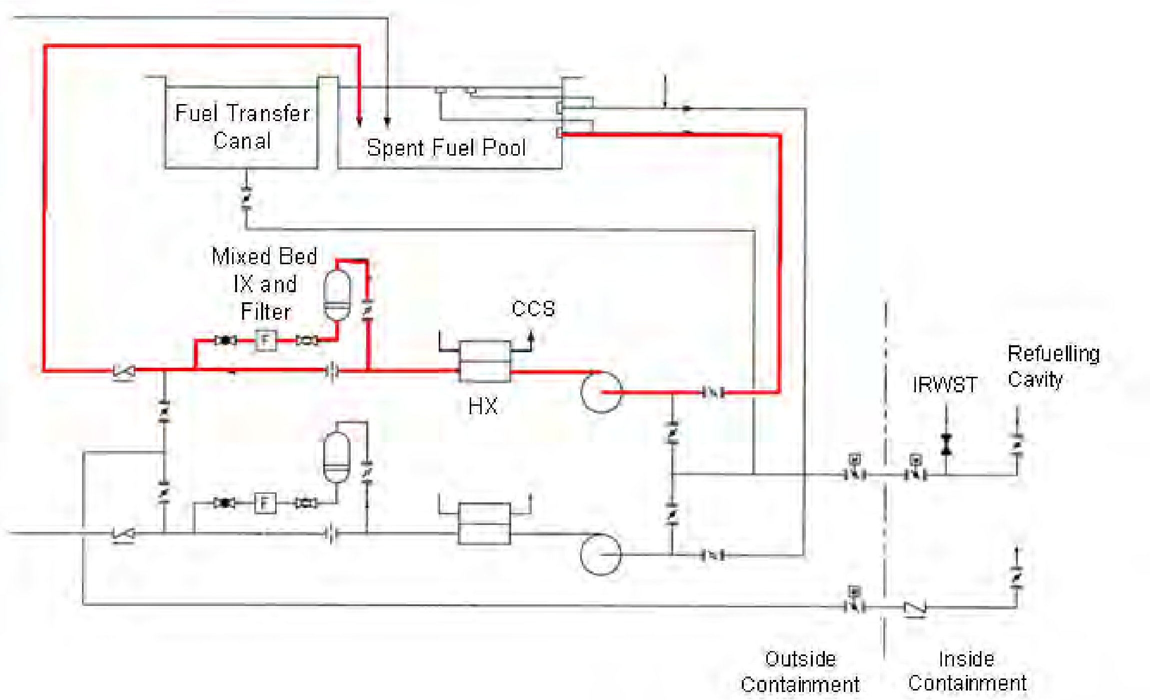

Figure 9:AP1000 Spent Fuel Cooling System

603 The operation of the two trains can be summarised as:

- During normal operations one train operates providing SFP cooling and purification, with the other in stand-by, undergoing maintenance or performing other functions, such as IRWST purification. This same arrangement continues during the plant shutdown.
- Both SFS trains are used during normal refuelling operations. One train is aligned for SFP cooling and purification throughout the refuelling. The other train performs various functions during the refuelling (purify IRWST, fill the Integrated Head Storage Tank (IHST), drain IRWST to refuelling cavity etc.). Once flooded, the second SFS train is used to initially purify the water in the refuelling cavity before switching to the SFP when fuel (and hence decay heat) is transferred to the SFP. Once refuelling is complete the second SFS train is used to transfer the refuelling cavity water back to the IRWST, along with the other water transfers necessary.

604 Overall, the SFS can take suction from the SFP, IRWST, refuelling cavity, fuel transfer canal, cask loading pit and cask washdown pit. Returns can be made to all of these locations.

605 One train of RNS cooling can also be used to support or supplement normal SFS cooling as required based on the heat load in the SFP. The SFP contains dedicated RNS suction and discharge lines.

606 Despite performing similar functions, both the filters and demineraliser in the SFS are generally much larger than those used in the CVS (approximately a two fold increase). The design basis is that each SFP demineraliser has been sized to provide 6 months of service without media replacement with each demineraliser containing around 2.1 m^3 of ion exchange resin. The outlet filter uses the same housing as those in the CVS but the filter porosity is likely to be higher (5 μm), requiring replacement on around an annual

basis. The SFS is designed to be able to treat the SFP volume around twice every 24 hours (depending upon SFP occupancy), which is significantly up-rated from existing Westinghouse designed PWRs. Measurements of flow, pressure drop and temperature ensure correct operation of the SFS. The SFS piping includes individual sampling points to allow sampling of water upstream and downstream of the demineralisers to verify the performance of the demineraliser resin.

607 This design of the SFP cooling and clean-up system is functionally very similar to those currently in use at other PWRs. I consider that an adequate case has been made by Westinghouse in this area for normal operations. The chemistry assessment of the AP1000 safety case for loss of cooling faults is discussed further in Section 4.3.2.4.

4.3.2.2 Operational Chemistry

608 During normal operations Westinghouse propose chemical specifications for the SFP water, in order to:

- Control pond reactivity.
- 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.

609 Westinghouse provides guidance on the expected values for various species in the SFP water in the ‘*Westinghouse Supplement to EPRI PWR Primary Water Chemistry Guidelines Rev. 6 for the AP1000™ Standard Plant*’ (Ref. 26). While the EPRI Guidelines provide guidance for monitoring spent fuel pool chemistry, the Westinghouse supplemental guidance requires more stringent control of spent fuel pool chemistry and specifies limits for some additional species. This results in controls for boron, aggressive anions (such as chloride) and zeolite forming elements. These are monitored by sampling of the SFP water using the PSS connections. I consider the additional requirements specified by Westinghouse to be beneficial to AP1000 chemistry both in the SFP and the primary circuit.

610 Despite the importance of adequate chemistry control in the SFP, neither the Step 4 PCSR (Ref. 1) nor the EDCD (Ref. 22) contained any reference to the expected SFP chemistry for AP1000. It is normal good practice to define the chemistry expected for Spent Fuel Pools in the safety case and I consider this to be an Assessment Finding, **AF-AP1000-RC-30**. This should also define requirements for sampling.

611 Water losses and transfers from the various pools require provisions for make-up, both of demineralised water and borated water of the correct concentration and purity. The CVS provides the normal makeup source of borated water for the SFP via a connection to the SFS pump suction pipe. The CVS is assessed in Section 4.2.2. Demineralised water is provided by the Demineralised Water Transfer and Storage System (DWS) via a normally closed connection to the SFS pump discharge piping. The DWS is assessed in Section 4.4.2.1.8. The principal water requirements are:

- Compensation for losses during transfers; CVS or IRWST.
- Compensation for losses due to evaporation; DWS.
- Compensation for losses of borated water from the SFP; CVS.

612 Unusually, the SFS is able to provide some borated water to the Reactor Coolant System (RCS) if the normal supply of borated water from the CVS is not available and the SFS water is compatible with the RCS requirements. Westinghouse claims this is a "*non-safety defense in-depth function*". This provision may be needed if the CVS boric acid tank is out of service for maintenance or has been drained empty. The SFS pump suction line from the SFP has a connection to the CVS that allows the CVS make-up pump to take suction from the SFP; this is the same line which is used to enable the CVS make-up pumps to supply borated water to the SFP. The available water is limited by the SFS suction level. Should the SFP be drained below this level, and hence the SFS no longer function, cooling would be performed by the RNS.

613 An important characteristic of the SFS water is that it is part of reactivity control for the pools during fuel movements and for the refuelling cavity during refuelling activities. It is necessary during refuelling 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). 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. These requirements are common to the pools at many reactors. The criticality control aspects of the AP1000 safety case are assessed elsewhere (Ref. 66), as are the potential SFP faults (Ref. 67).

614 The soluble boron present in the AP1000 SFP was claimed to maintain sub-criticality for fuel stored correctly in the racks. This is not common in SFPs, although has been used in the past. This is the subject of GDA Issue **GI-AP1000-RP-01** affecting many GDA assessment areas, including fault studies, radiation protection and Reactor Chemistry (see Ref. 66). As described more fully in Ref. 66, ND considers that a design for a new plant which relies on a non-fixed neutron absorber during normal conditions does not meet the expectations of the SAP.ECR1 (Ref. 3).

615 The exact concentration required depends on the fuel storage racking controls used, which are discussed as part of the Westinghouse response to RO-AP1000-73 (Ref. 7). Westinghouse calculate that the minimum required boron concentration in the SFP would be less than 50% of the normal operating concentration, which is controlled by an operating limit. Nevertheless this puts requirements on the measurement and control of boron, due to the necessity of ensuring boron is always present in the SFP in sufficient quantities.

616 The response to RO-AP1000-73 (Ref. 7) states that the AP1000 relies on grab sampling of the SFS, at a minimum frequency of once every 7 days. The argument is made that a reduction of boron is an unlikely event requiring multiple operator errors. An analysis is presented for the events which could introduce non-borated water to the SFP, with dilution times calculated between 8 and 50 hours. It is further argued that consequential effects, such as SFP overflowing, would initiate alarms which would indicate to the operator that there was a problem with the SFP. Assessment of these claims and arguments is outside the remit of the Reactor Chemistry assessment. I am not convinced that such arrangements are commensurate with relevant good practice for similar situations, where on-line meters have been used.

617 Overall, for a case which relies on soluble boron in the pond, I did not consider the arrangements for boron control to be sufficient to control the risks posed by loss of boron from the SFP. Fundamentally there is no mechanism to assure the soluble boron is present between sampling. A more frequent sampling regime would be required if this claim is retained. I consider this to be an Assessment Finding, **AF-AP1000-RC-31**,

dependent on the outcome of the Radiation Protection GDA Issue, **GI-AP1000-RP-01**, which requests a justification for adoption of a design based on non-fixed controls.

618 The spent fuel pool storage racks within the AP1000 SFP utilise a neutron absorber material, Metamic^{TM}, which is a proprietary aluminium / boron carbide composite. This material is novel to the UK, although has been used in recent years at a number of US plants including Diablo Canyon, Arkansas Nuclear One and Clinton. The reactivity control provisions of this material are assessed in Ref. 66; the main Reactor Chemistry interest is in relation to the behaviour of the material in the SFP chemistry environment which is an above ambient temperatures potentially mildly corrosive aqueous environment for a long period of time (60+ years). TQ-AP1000-594 (Ref. 8) requested more information on this material, including potential susceptibilities. The response provided a report summarising the behaviour of Metamic^{TM} under typical operating conditions (Ref. 68). From the response it appears that the main driver for selection of this material for AP1000 is the 'efficiency' of Metamic^{TM} compared to other materials for the relatively small AP1000 SFP. The Metamic^{TM} in the AP1000 SFP racks is sheathed in the stainless steel racking hence cannot be examined or replaced. For degraded material, options would be limited to replacement of entire racks or insertion of additional neutron absorbing material. I commissioned TSC support to examine the behaviour of this material (Ref. 69).

619 The evidence presented by Westinghouse is based upon information provided by the manufacturer, which is based upon both EPRI (Ref. 70) and in-house (Ref. 68) testing of the material. The tests differ in several aspects from the expected AP1000 conditions and are of only limited duration, but are a reasonable approximation and were conducted at higher temperatures. While there appears to have been a general 'simplification' of the conclusions as they have passed from EPRI, to the manufacturer and finally to Westinghouse, the general consensus seems to be that, provided the SFP environment is maintained within normal bands, the material is not expected to degrade significantly in the short term. For the purposes of neutron absorbency and shielding protection, the Metamic^{TM} appears to perform adequately based on the work already conducted. Where corrosion has been noticed, there has been no reduction in ^{10}B density and neutron attenuation tests have shown that there is no loss in performance. Due to the highly homogeneous nature of the material localised corrosion should not pose a significant threat to this behaviour.

620 The position regarding the long-term behaviour of the material is less clear. The EPRI review states that "*it is expected that coupon weight loss would not be detected after a simulated 40 years service life*", although Westinghouse claim sufficient evidence exists for the full 60 years of service expected. The Westinghouse approach is to provide coupons to monitor the condition of the Metamic^{TM} within the SFP environment over time. I assessed the suggested scheme in the context of SAPs EAD.1 to EAD.4 and consider that it is heavily front-end loaded, which may not be the most appropriate. I consider that the monitoring scheme for this material should be reviewed by the Licensee to more suitably address the longer term performance associated with the material. I consider this to be an Assessment Finding, **AF-AP1000-RC-32**, to be addressed before fuel is delivered to site, to facilitate the location of measurements or coupons.

621 The surface finish of the Metamic^{TM} may be an important parameter in determining long-term performance. The EDCD (Section 9.1.2.2.1, Ref. 22) states that "*the panels are not anodized, but will be cleaned via glass bead blasting and washing with demineralised water to ensure removal of surface contamination prior to installation*." It is notable however that the EPRI review states that "*The test program has identified the need to either thoroughly clean and/or anodize the surfaces of Metamic^{TM} scheduled for wet*

storage applications." Further justification may be necessary for the decision not to anodise the panels given the long life expectancy. I consider this to be an Assessment Finding, **AF-AP1000-RC-33**.

622 Overall, I consider that adequate evidence has been presented to support the choice of Metamic^{TM} for AP1000 for normal operations. The potential effects of loss of cooling conditions on Metamic^{TM} are considered in Section 4.3.2.4.

623 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 and lower levels of neutron radiation. This resulted in very high levels of silica contamination in the SFP, and hence the RCS during refuelling. Silica is difficult to remove by ion exchange processes and would require discharge and make-up if the contamination became significant. 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, due to the increased potential to form deleterious precipitates on the fuel heat transfer surfaces. Although AP1000 uses Metamic^{TM} for the SFP rack neutron absorbers, which is not a source for silica, Westinghouse still specify a silica limit for the SFP water. Further design features in AP1000, such as the improved make-up water systems should mean that this limit is rarely approached.

624 The other materials used in the SFP systems should not experience significant degradation, provided the SFP chemistry and cooling are well controlled.

4.3.2.3 Control of Radioactivity

625 An important function of the SFS 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.

626 An important input to minimising ORE and wastes during refuelling operations is the shutdown chemistry, which is discussed in Section 4.2.11.

627 Nevertheless, during refuelling a large amount of radioactivity is transported and relocated around the various plant systems. AP1000 has a number of features which should minimise these effects, such as:

- The water transfer sequence has been developed to improve water clarity in the refuelling cavity during refuelling operations, which avoids filling the refuelling cavity by flooding up through the reactor vessel using the RNS.
- The SFS 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.

628 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-AP1000-1236 (Ref. 8) was raised to clarify these aspects for the AP1000 design. The response stated that while a standard finish for the structural module steel would have a

surface finish of around 12 μm roughness, Westinghouse have specified a much smoother finish of around 0.6 μm for the refuelling cavity. This is the only pool which will be routinely filled and drained and thus be subjected to personnel access. A calculation (Ref. 71) considers the potential further benefits of Electropolishing (EP) to be insufficient on an ALARP basis. I consider this to be a acceptable. I do however judge that further consideration should be given to specifying a similar finish for the SFP walls which are subject to level oscillations. I consider this to be an Assessment Finding, **AF-AP1000-RC-34**.

629 Minimising 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. The pool purification systems are assessed in Section 4.3.2.1.

630 ND requested further details of the source terms for AP1000 in RO-AP1000-83 (Ref. 7). The response provided details of the calculation methodologies, inputs and results for the standard plant design. A number of detailed codes were used in the derivation of the AP1000 source term, including ORIGEN (ORIGEN2 or ORIGEN-S), FIPCO, SSP, TRICAL, CORA and SECONS. A number of these codes were developed by Westinghouse. The principal codes of interest to the Reactor Chemistry assessment and their functions are:

- ORIGEN; calculation of time-dependent concentrations and radiation source terms of a large number of isotopes, which are simultaneously generated or depleted through neutronic transmutation, fission, and radioactive decay.
- FIPCO; calculation of design basis fission product activity levels by assuming 0.25 % fuel cladding defect level. The release from defective fuel is based on element-dependent escape rate coefficients.
- CORA; calculation of generation and transport of corrosion product activity concentrations in the primary coolant, CVS demineralisers and surface deposits.
- TRICAL; calculation of the generation and transport of tritium considering leakage, evaporation and various in-plant dilution and mixing schemes.

631 The bulk of the source terms for the AP1000 were calculated around 10 years ago and compiled into a single document, the "*AP1000 Radiation Analysis Design Manual*" (Ref. 31), also called the "*radiation manual*". Westinghouse claim that the data compiled in the *"radiation manual"* is conservative and is used for the sizing of many components in AP1000. The *"radiation manual"* is referenced in both the EDCD and PCSR.

632 The principal sources of activity within the SFP can be broadly considered as tritium, fission products and fuel crud. In the *"radiation manual"* Westinghouse provided estimates for the radioactivity within the SFP. The activity in this pool is different from other systems in the reactor in that they generally receive an increase in activity only when connected to the RCS (i.e. they do not have a large permanent source), but this additional activity is gradually removed during the cycle both by natural decay and purification by the SFS. 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.

633 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-AP1000-807 (Ref. 8) requested information on the likely head lift criteria to be applied in AP1000. The response to this TQ is discussed in Section 4.2.11, under primary circuit shutdown chemistry. As with all limits and conditions, Westinghouse has not presented any such criteria to ND during Step 4, resulting in the cross-cutting GDA Issue **GI-AP1000-CC-01** (see Section 4.1.3.3). Tritium during shutdowns is also 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, Westinghouse proposes no specific controls for tritium during a shutdown. Tritium is unique in that it will not be removed by the SFS purification systems.

634 The tritium concentration in the SFP is reduced, if necessary, by transferring a portion of the SFP water to the WLS for discharge and replacing it with non-tritiated water. Westinghouse estimates in the *"radiation manual"* indicative values based on both no discharge and discharge of one RCS volume per cycle. Both "*best estimate*" and "*design basis*" values are given. In both cases the tritium concentration builds to an equilibrium level after a number of cycles due to both decay and evaporative losses. This takes between 15 and 25 cycles depending upon the extent of discharge, with more discharge resulting in establishment of an earlier equilibrium. The values are projected as:

	Discharges	**Cycle 1 SFP tritium concentration / MBq t^{-1}**	**Equilibrium SFP tritium concentration / MBq t^{-1}**
"Best estimate"	1 RCS volume per cycle	5,500	37,000
"Design basis"		13,000	110,000
"Best estimate"	None	15,000	165,000
"Design basis"		33,000	370,000

Table 10: AP1000 Spent Fuel Pool Tritium Concentration

635 Tritium control was also the subject of RO-AP1000-84.A1 (Ref. 7) which requested details of the controls in AP1000 to ensure an ALARP concentration of tritium would be produced in the SFP and associated systems. As for head lift limits, as discussed in Section 4.2.11, the Westinghouse position is that the Licensee should specify limits for the SFP tritium concentration, if appropriate. The response stating that; "*…the choice of applying or not and the definition of operational limits on tritium concentration in large volume open water sources is the responsibility of each operating utility. As plant designer, Westinghouse does not place operational limits on the tritium concentrations for the AP1000 standard plant design.*"

636 This is a reasonable position, and would meet UK expectations regarding the responsibilities of a Licensee, however it potentially completely neglects assumptions made elsewhere in the AP1000 safety case, which are in the remit of Westinghouse, for example on aerial discharge levels or ORE. Contradictions also exist with other safety case documentation, for example:

- The SFS SSD (Ref. 65) states that; "*The concentration of tritium in the SFP water is maintained at less than 9.3 KBq g^{-1}* [9,300 MBq t^{-1}] *to provide confidence that the airborne concentration of tritium in the fuel handling area is within 10 CFR* [Code of Federal Regulations] *20, Appendix B limits*."

- Chapter 12 of the AP1000 *"chemistry manual"* (Ref. 25) states that the expected SFP tritium concentration is less than 18,500 MBq t^{-1}.
- Chapter 12 of the EDCD (Ref. 22, Table 12.2-24) assumes a SFP tritium concentration of 37,000 MBq t^{-1} for determining the FHA airborne tritium concentration.

637 Westinghouse went on to state in the RO-AP1000-84.A1 response that concentrations "*would only become a significant concern*" (to ORE) at levels above 93,000 MBq t^{-1}. I find the multiplicity of tritium levels and safety claims confusing. Either the operational safety documentation is consistent or the safety case should explain why the different limits exist and which take precedent. I consider this to be an Assessment Finding, **AF-AP1000-RC-35**.

638 Further information in the response indicates that the 'expected' end of cycle 1 concentration in the SFP is around 260 MBq t^{-1}, with an equilibrium level of around 1,000 MBq t^{-1} reached in 5 cycles. This is significantly lower than the concentrations predicted in the AP1000 *"radiation manual"* or elsewhere. This variation is clearly related to the assumed dilution rate used in the analysis, which must be significantly higher than the one RCS volume per cycle assumed in the *"radiation manual"*. No details are provided in the response on this assumption. The same tritium concentration values are also suggested for the IRWST concentration, which follows logically given that the IRWST water is fully mixed with the SFP during refuelling. The response to TQ-AP1000-809 (Ref. 8) indicates that the IRWST is essentially sealed from the containment atmosphere during normal operations which should minimise the release of tritiated water to the containment and hence plant vent throughout the cycle.

639 The remainder of the RO-AP1000-84.A1 response provides details of the measures that can be taken to control the tritium level in the SFP, which involve dilution of the RCS tritium concentration as part of normal boron dilution required for the primary circuit reactivity control. This is standard practice in all PWRs which do not recycle the primary effluent, as is the case in AP1000. In general terms these are reasonable arguments. The response does show that the RCS tritium concentration at mid-cycle may peak at 120,000 MBq t^{-1}. The effect of shutdown at this point is not discussed but would lead to higher levels than predicted by allowing the cycle to complete, although this is likely to be offset to some degree by the volume of water added to borate the coolant.

640 As the AP1000 SFP is a relatively small volume the combined volume of the RCS refuelling cavity, fuel transfer canal and SFP is similarly small compared to other reactors. This means that the dilution of the RCS tritium activity that occurs during refuelling is also relatively modest and hence more stringent controls on RCS tritium activities prior to refuelling may be warranted.

641 Overall, I consider that a reasonable case has been made by Westinghouse to demonstrate that tritium control in the AP1000 SFP may be possible. However by not defining any limits or controls the case presented does not demonstrate how other assumptions in the safety case, for example on aerial discharges, can be met without a limit on the SFP and/or IRWST tritium concentration. In addition the cases presented do not consider 'abnormal' events which may cause tritium concentrations over and above those estimated. Fundamentally, I consider that a limit or condition for tritium activity in the SFP, and potentially in the IRWST, is required for AP1000. This is related to Assessment Finding **AF-AP1000-RC-35**.

642 RO-AP1000-84.A2 (Ref. 7) requested evidence that the AP1000 design could adequately control fuel crud throughout the nuclear island systems. The Westinghouse response

(Ref. 116) covered the release and accumulation of crud and provided a roadmap to the methodology applied by Westinghouse to analyse core fuel crud levels, using BOA. These aspects are assessed in Sections 4.2.3.3.1 and 4.2.5. The response also provides a summary of fuel crud properties, based on fuel scraping data. A description of the CORA modelling to calculate transport of activity (be that as fuel crud or other soluble or insoluble forms) to other connected systems including the RCS, SFS and IRWST is provided. As with action 1 under this RO, the response is weak in links to the PCSR and safety analysis specific to AP1000. While the data provided by CORA may bound radioactivity in normal operations it does not estimate fuel crud specifically. Importantly, Westinghouse declined to estimate the fuel crud loading expected in the AP1000 SFP, either during normal operations or during faults (as would be required during loss of cooling faults, See Section 4.3.2.4). The AP1000 *"radiation manual"* (Ref. 31) provides some information on expected SFP and IRWST sources, but again does not distinguish fuel crud. Westinghouse made reasonable arguments regarding this approach as, although much information is available on fuel crud properties and characteristics, a holistic model for its transport around a nuclear plant does not exist and much information is instead gained from OEF. However, they do present results for the BOA analysis which indicates the expected quantity of crud in typical AP1000 cores. While I accept this is only an estimate, and is not intended to calculate crud for transport purposes, it does provide an estimate of crud on which a bounding safety demonstration could be based using appropriate uncertainties and factors.

643 As part of the updated response to RO-AP1000-55.A5 (Ref. 7), Westinghouse supplied a calculation estimating the fuel crud levels in the AP1000 SFP (Ref. 117), including a comparison of these results to those calculated by CORA, and hence used in the AP1000 *"radiation manual"* (Ref. 31). As described in the next subsection, the assessment of this revised response to RO-AP1000-55.A5, including the main references, is incomplete due to delivery late in Step 4. However, this calculation does appear to be based on reasonable assumptions.

644 ND has raised a cross-cutting GDA Issue **GI-AP1000-FS-01**, refer to the next section of my report, which requires Westinghouse to develop a safety case for SFP faults and reports to ND on its consequences for each assessment area, including chemistry (see Ref. 67). Therefore, the radiological source term arising from SFP faults has still to be assessed during GDA.

645 As described earlier (para. 607) the fundamental design provisions to control activity in AP1000 appear reasonable, so there is no reason to suggest AP1000 should be more prone to fuel crud accumulation in the fuel pond and associated systems, provided adequate chemistry control is maintained during operations by the Licensee. The Licensee will thus need to demonstrate that control of such contamination is adequate in a UK AP1000, including consideration of many factors outside of the GDA assessment, such as detailed operating and shutdown chemistry regimes, limits and conditions and operational procedures. I consider this to be an Assessment Finding, **AF-AP1000-RC-36**.

646 During Step 4, ND noted that the AP1000 SFP ventilation system (VAS) did not include any filtration prior to discharge under normal operations. The original Westinghouse design of the Fuel Handling Area HVAC (Heating, Ventilation and Air Conditioning) system (part of the VAS) had the exhaust air going to the plant vent without filtration but switching to the Containment Ventilation System (VFS) upon detection of radiation. The VFS system has both HEPA (High Efficiency Particulate Air) filters and charcoal filters on the exhaust. Due in part to concerns of active particulate (fuel crud) by-passing this system ND raised RO-AP1000-43.A5 (Ref. 7). As a result Westinghouse implemented a

design change to include HEPA filtration to the exhaust going to the plant vent. However, AP1000 will retain the switching to the VFS train upon detection of radiation to ensure that radioiodine isotopes are absorbed in the VFS carbon bed.

647 RO-AP1000-84.A3 (Ref. 7) requested evidence for the control of other nuclides expected in the SFP. Westinghouse provided a response to this ROA (Ref. 131) which, while providing a discussion of the various systems used to minimise transfer of activity during refuelling, does not provide any estimates for the activity in these systems during a cycle. Overall, I do not consider that the AP1000 design should be more prone to retaining contamination within the SFP in comparison with existing PWRs, in fact due to some of the design differences the AP1000 may in fact perform better in this respect.

648 A notable assumption in the AP1000 design is that the CVS will be available to purify the refuelling cavity during the outage. As discussed in Section 4.2.2, the design of the CVS includes two mixed bed units, one duty unit and one on stand-by. It is likely that the duty unit will need to be changed during the outage, leaving only the stand-by unit available; however should this be needed early in the operating cycle, and hence exhaust during the cycle, there may be no capacity available for SFP purification, thus putting further requirements on either the second SFS train or prolonging outages to attain the required clean-up level. I consider this an unlikely event and it should not impose additional safety concerns, provided suitable controls and limits are in place to stop the outage schedule taking priority over other safety factors. This is related to Assessment Finding **AF-AP1000-RC-26**, described in Section 4.2.11.7.

4.3.2.4 Loss of Cooling

649 For AP1000, Westinghouse claim that the active portions of the SFS are not required to continue normal SFP cooling following design basis events. In the event of an accident involving loss of normal SFS cooling, the spent fuel cooling is provided by the heat capacity of the water in the pool plus make-up from safety-related supplies when pool boiling begins. The water sources available depend upon the accident conditions; however they potentially include the fuel transfer canal, cask washdown pit, cask loading pit and Passive Containment Cooling Water Storage Tank (PCCWST). A relief panel in the wall of the fuel handling area (FHA) will be passively actuated at elevated ambient air temperatures to provide a relief path for steam generated in a SFP boiling event. Further details of the faults considered are provided in the response to RO-AP1000-54 (Ref. 118). The original Westinghouse evaluation concluded that such an event would occur approximately once every 6 years, although the most recent revision to the response has reduced this frequency to less than once every 2,000 years. While Westinghouse claim that the SFS design is such that a total loss of cooling is extremely unlikely, the system is designed to restart after a boiling event and restore the pool to a controlled state. This has been a significant area of assessment for ND during Step 4.

650 Westinghouse claim that this approach is acceptable, and ALARP, on the basis of calculated doses for a boiling SFP with steam venting via the relief panel in the FHA wall (Ref. 72). Westinghouse claims that this analysis is conservative. There are a number of significant chemistry assumptions in this analysis, including:

- All of the activity released is in the form of ^{131}I, with an increased fuel release rate coincident with the accident and an assumed 1% volatile fraction
- The SFP activity is taken to be at a level which would produce the 25 μSv hr^{-1} surface dose rate limit assumed in the safety case

651 In Ref. 72, no attempt was made to relate these assumptions to the more realistic consequences of such events, for example damage to fuel may mean the assumptions on iodine release are not bounding and the actual SFP dose rate is most likely dominated by fuel crud attached to fuel, dissolved in the water or stagnant on the base of the pond, which could potentially be mobilised and released. I consider these aspects further in the assessment that follows.

652 Assessment in this cross-cutting area has been led by Fault Studies and has resulted in some suggested design changes to AP1000, which are not yet complete. The Reactor Chemistry assessment of this area has concentrated on evaluating the consequences of such events on the pool chemistry and hence the SFP systems and stored fuel. Ultimately these factors may affect the resulting doses from the accident and I have reviewed the chemistry aspects of the Westinghouse dose assessment. The concerns I have can be summarised as:

- Effect of make-up water sources and boiling on SFP chemistry.
- Damage to stored fuel, SFP or connected systems.
- Adequacy of the dose assessment for the accident; specifically the potential for unabated releases from the FHA via the vent panel, especially of fuel crud.

653 I raised RO-AP1000-55.A5 (Ref. 7) to understand the evidence Westinghouse had to support the chemistry aspects of this approach. Westinghouse responded in October 2010 (Ref. 119), however on review I found the response unsatisfactory as it failed to fundamentally address a number of the concerns I raised; the principal deficiency was that the response failed to account for the chemistry effects that could potentially occur during pond boiling and hence did not adequately justify the source term used for the consequence analysis. For these reasons this response is not discussed further.

654 Assessment of chemistry in the SFP was further complicated by the discussions that were occurring simultaneously with ND fault studies inspectors on the overall safety case for loss of cooling faults in AP1000, especially the calculated frequency and potential design changes. Westinghouse provided a revised and final response to the Chemistry observation RO-AP1000-55.A5 (Ref. 120) at the end of January 2011, which summarised the final safety case and design changes, the Fault Studies Inspector raised a similar Observation RO-AP1000-54. For these reasons assessment of this aspect of the AP1000 safety case is not yet complete, although it is clear that the final response is much improved. Due to the safety significance of this issue, I consider this to be a GDA Issue, and this is part of the cross-cutting GDA Issue in this area, led by Fault Studies **GI-AP1000-FS-01** (see Ref. 67). I judge that this Issue is resolvable from a chemistry perspective. While assessment of SFP faults is not yet complete, the following paragraphs summarise the chemical aspects of frequent pool boiling to date. This may be superseded by a satisfactory response to **GI-AP1000-FS-01.**

655 During a pond boiling event water will be lost as steam, leaving in-volatile species in the remaining reduced water volume thus concentrating the in-volatile species. Importantly this applies to both boron and impurities in the pond. As described above, para. 614, a minimum boron concentration must be maintained in the AP1000 SFP for reactivity control purposes. During such an event Westinghouse claim that the boron concentration in the pond will increase, potentially to over 13,400 mg kg^{-1}, although this assumes additional borated water sources are added and evaporated. This concentration is still within the solubility limit for boric acid. Even if only pure water were added to the pond as make-up the boron present in the original SFP volume would mostly be retained and hence the pond should not experience a significant boron reduction, if any, caused purely

by boiling. There are potentially other mechanisms for this to occur, such as excessive addition of make-up sources or chemical precipitation, although these are considered unlikely.

656 Westinghouse have reviewed the conditions that the fuel cladding will experience during boiling and consider that the clad temperature will remain low, significantly below the temperature at which localised dry-out or clad failures would be expected, provided it remains covered with water. Reasonable arguments appear to have been presented for this aspect.

657 As part of the TSC review of Metamic^{TM} for use in the SFP racks (Ref. 69) the behaviour of Metamic^{TM} under boiling conditions was considered. However, the assessment used the data provided in the original RO-AP1000-55.A5 response (Ref. 119) for the final pool chemistry conditions after boiling (8,500 mg kg^{-1} boron et al), while the final response (Ref. 120) provided significantly higher values (13,400 mg kg^{-1} boron et al) . Of particular concern is the much elevated chloride level that would be caused by evaporative losses of water, which could accelerate the localised corrosion typical of aluminium based alloys.

658 In the final RO-AP1000-55.A5 response (Ref. 120) Westinghouse have attempted to quantify the potential for fuel crud release during a boiling event (Ref. 117) and consider this to be bounding by the current dose assessment. Further mitigation has been proposed by the design change to include filtration on the FHA blow-out panel discharge.

659 The validity of these assumptions can be revisited, once the response **GI-AP1000-FS-01** has been received. This may supersede the assessment paragraphs above.

4.3.2.5 Summary

660 Based upon the evidence presented during GDA, the main conclusion I draw for the assessment of the Spent Fuel Pool in AP1000 are:

- The AP1000 spent fuel pool systems are functionally very similar to current PWRs and the design and material choices are conventional. Westinghouse have outlined the expected spent fuel pool chemistry, but outside the PCSR. The chemical requirements for such systems are well known and AP1000 has systems for monitoring, controlling and purifying the pool water which can be considered generally adequate. While not assessed as part of this report, the current AP1000 safety case relies on the presence of soluble boron in the SFP as part of the criticality control arrangements. The monitoring of this important safety parameter is not considered adequate and I have raised this as an Assessment Finding.
- The use of Metamic^{TM} neutron absorber material has been demonstrated to be acceptable, under normal operating conditions. The long-term behaviour of this material and its behaviour outside of normal conditions is subject to some uncertainty and further work is required in these areas.
- The control of radioactivity within the large volume spent fuel pool is important from an ORE, waste and discharge perspective. I see no reason why AP1000 should not be at least as capable as current PWRs in controlling the activity in the pool, and may be better due to larger treatment systems in comparison to the SFP volume. I have highlighted a number of findings in this area where further justification and evidence is still required. I consider that limits or conditions will be required on tritium in the AP1000 spent fuel pool, and potentially the IRWST.

- The chemical implications and consequences for loss of cooling faults were a significant area of assessment, across ND. The safety case in this area was initially deemed inadequate and Westinghouse has worked to resolve my concerns and improve the safety case during Step 4. This resulted in a revised case being presented too late in GDA for a complete assessment. On the basis of information reviewed to date and on-going discussions with Westinghouse I am satisfied that a case can be made for AP1000 in this regard. However, as this is a safety significant area, with potential impacts on the design, I support the cross-cutting GDA Issue in this area.

661 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA, subject to successful resolution of the GDA Issue and Assessment Findings.

4.3.2.6 Assessment Findings

662 Based upon the assessment of spent fuel pool chemistry in AP1000 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-AP1000-RC-30*** *– 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-AP1000-RC-31*** *– The Licensee shall review the adequacy of the sampling arrangements for boron in the spent fuel pool, including justification for the choice of continuous on-line instrumentation versus grab sampling. This Assessment Finding should be completed before fuel is brought on to site and boron is required for reactivity control purposes; Target milestone – Fuel on-site.*
>
> ***AF-AP1000-RC-32*** *– The Licensee shall review and document the justification for the corrosion monitoring scheme for the Metamic*^{TM} *material in the spent fuel pool racks. This Assessment Finding should be completed before plant fuel is delivered to site, to permit the location of coupons or measurements; Target milestone – Fuel on-site.*
>
> ***AF-AP1000-RC-33*** *– The Licensee shall review and document the justification for the surface treatment to be applied to the Metamic*^{TM} *material in the spent fuel pool racks. This Assessment Finding should be completed before fuel is brought on to site and the pools are filled, but should be considered during manufacture; Target milestone – Fuel on-site.*
>
> ***AF-AP1000-RC-34*** *– The Licensee shall review the surface finish to be applied to areas of the spent fuel pool subject to level oscillations and produce a justification for the finish specified. This Assessment Finding should be completed before fuel is brought on to site and the pools are filled, but should be considered during manufacture; Target milestone – Fuel on-site.*
>
> ***AF-AP1000-RC-35*** *– 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.*

> ***AF-AP1000-RC-36*** *– The Licensee shall generate evidence that controls over radioactivity (excluding tritium) in the spent fuel pool and connected systems, including the IRWST, are adequate for UK AP1000. This should include consideration of those factors out of scope for the GDA assessment, such as detailed operating and shutdown chemistry regimes, limits and conditions and operational procedures. This should include consideration of both operator radiation exposure and discharge considerations. This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated; Target milestone – Initial Criticality.*

4.3.2.7 GDA Issues

663 Based upon the assessment of spent fuel pool chemistry in AP1000 described in Section 4.3.2 above, I support the following cross-cutting GDA Issue that require resolution before nuclear island safety-related construction of a reactor could be considered (see Ref. 67). This topic is also relevant to the cross-cutting Issue on Limits and Conditions described in Section 4.1.3.

> ***GI-AP1000-FS-01*** *– Spent Fuel Pool Safety Case – The design basis case developed in GDA Step 4 for the spent fuel pool for the Fault Studies topic area needs to be cascaded into other technical areas and any new claims clearly identified in the PCSR. The design change process needs to be followed to incorporate the various physical modifications identified and all the affected documents need to be updated. Fault Studies concerns on the availability of the RNS and the protection of fuel above the spent fuel racks are to be addressed.*

4.4 Secondary Circuit

664 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.

665 The secondary coolant passes through the Steam Generators (SG) in order to extract heat from the primary circuit. Corrosion from the outside of the steam generator tubing could potentially cause a leak and mixing of primary and secondary coolants. This might have consequences dependent on the direction of leakage flow, and flow in both directions is possible as the reactor often shuts down following such events:

- If the primary coolant leaks into the secondary circuit, there could be a release of radioactive material. Various protection and clean-up systems exist to mitigate and prevent this occurrence.
- If the secondary coolant leaks into the primary circuit, this could dilute the boron and there could be an ingress of chemicals that are harmful to the integrity of the reactor and its fuel.

666 Due to the high flows of water and steam, the chemistry of all secondary circuits must be tightly controlled to prevent the build-up of sludges, chlorides or other harmful materials inside the SGs on the secondary side. A large quantity of sludge is potentially very harmful for several reasons including vibration of SG tubing or because sludge can

harbour corrosive elements like chloride. A large number of systems outside the steam generators contribute to the chemical conditioning of secondary coolant to avoid such problems.

667 Corrosion and other faults in the secondary circuit outside of the steam generators can result in structural failures which may be matters of conventional safety outside the scope of GDA. However, the consequent loss of service (e.g. loss of feedwater or loss of heat-sink) could test nuclear safety systems, especially if they happened suddenly.

668 The design of all of the secondary circuit systems must account for the operations required during start up, normal operation (including power changes), shut down, 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.

669 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. Consequently these areas were further assessed during Step 4.

670 A complication in the assessment of the AP1000 secondary circuit is the close tie between many of the secondary circuit systems and the site specifics. Furthermore, Westinghouse initially stated that all of the secondary circuit was within the scope for GDA, however much of the detailed design for these systems is not yet available. In addition the AP1000 ‘standard plant’ assessed as part of GDA has been designed on the basis of an “*estuarine*” cooling water source to the secondary circuit, hence seawater cooling is considered outside the scope of GDA. It is notable that the plant does include some features consistent with a seawater cooled plant, such as a leak tight titanium tubed condenser. While this aspect is clearly site specific, any deviation from this basis may require an assessment of the implications during site licensing. I consider this to be an Assessment Finding, **AF-AP1000-RC-37**, because significant plant and equipment outside of the nuclear island, such as for condensate polishing, could be needed at a seawater site.

671 The following systems were included in the Step 4 assessment of the AP1000 secondary circuit:

AP1000 Abbreviation	Description
BDS	Steam Generator Blowdown System
CDS	Condensate System
CFS	Turbine Island Chemical Feed System
CPS	Condensate Polishing System
DTS	Demineralised Water Treatment System
DWS	Demineralised Water Transfer and Storage System
FWS	Main and Start-up Feedwater System
MSS	Main Steam System
SGS	Steam Generator System
SSS	Secondary Sampling System

Table 11: AP1000 Secondary Circuit Systems included in GDA Scope

672 The assessment of secondary circuit chemistry during GDA has sampled a number of interrelated areas which, when taken as a whole, cover a large part 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 Westinghouse approach and expectations for secondary circuit chemistry in AP1000. This included a determination that the plant can safely support the anticipated chemistry. The areas sampled were:

- Materials, Design and Chemistry.
- Integrity.
- Sampling Systems.

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

4.4.1 Overview

673 As the secondary circuit is a complex arrangement of many systems, a brief discussion of the AP1000 design is given below. A number of the main systems described were subject to more detailed assessment in the subsequent sections.

674 The main interfaces between the primary and secondary systems are the SGs. Chemically conditioned feedwater is fed to the SGs. The bulk coolant in the SG is heated to saturation temperature (approximately 270 °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 within the steam generator. The dried steam at saturation temperature exits the steam generator at around 58 bar and passes to the turbine, where it transfers energy to the turbine.

675 Simultaneously, a small flow of coolant (< 0.6 % of the SG steam output at full power) is extracted by the Steam Generator Blowdown System (BDS). The BDS system purifies the extracted coolant and returns this to the bulk condenser supply, thus minimising the coolant impurity levels. In AP1000 the BDS uses an Electrodeionisation (EDI) process to purify the coolant which is a novel approach for a PWR. This feature of the AP1000 secondary circuit design is discussed in greater detail in Section 4.4.2.1.

676 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 downstream pipework and components that receive wet steam 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 Reheaters (MSR). While this provides dry steam to the subsequent turbines the MSRs themselves operate under wet steam conditions and so are again potentially vulnerable to damage. Low temperature wet steam conditions develop at some stage within the LP (Low Pressure) turbine, which can lead to a risk of droplet erosion of the turbine blades, and condenser tubes, if the latter are not adequately protected.

677 The detailed design of systems associated with the AP1000 turbine systems are not within the GDA scope and as such no assessment of these systems has been undertaken. The hazards associated with these systems are mainly associated with conventional, rather than nuclear, safety.

678 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, such as estuarine water, 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.

679 Condensate is collected and stored before pumping through four stages of low pressure (LP) feed heating. During normal operation there is no purification of the condensate during this stage; however the AP1000 include a Condensate Polishing System (CPS) which is used during plant start-ups and during "*abnormal*" chemistry conditions, as described in Section 4.4.2.1.3. This approach is not uncommon for PWRs, especially in the US, but it does place 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 (BDS).
- Condenser tube integrity.
- Quick detection of condenser tube leaks.

680 Feedwater passes into the Deaerator tank where it is sprayed through steam, removing non-condensable gases. A deaerator is not a common addition to PWR secondary circuits with most relying 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 AP1000 secondary circuit design can therefore be viewed as a valuable addition to the means available to the operator for controlling feedwater oxygen concentrations. It also provides a reservoir of treated feedwater that may be valuable under fault conditions.

681 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 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.

682 The principal water (blue) and steam (red) systems and components in this arrangement, of relevance to Reactor Chemistry, are shown below (Ref. 108):

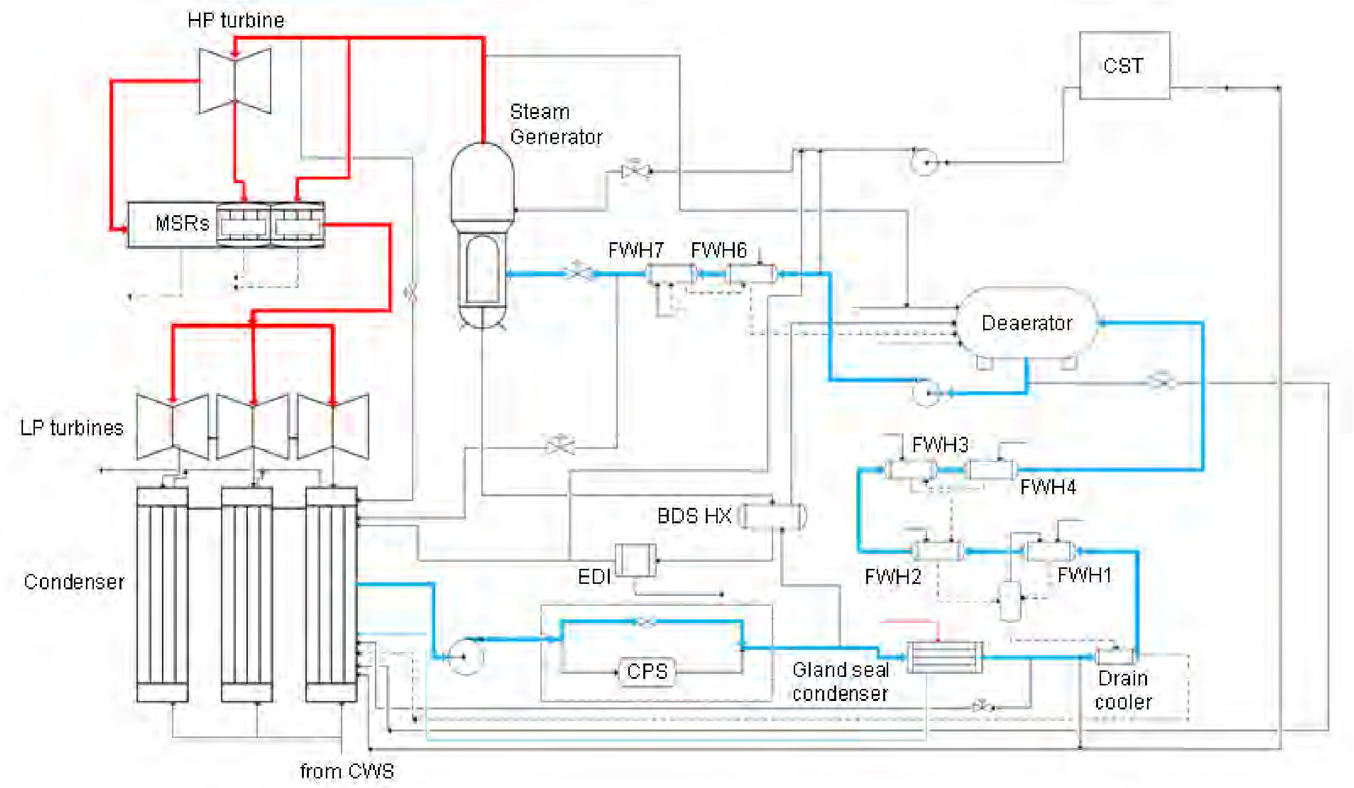

Figure 10: AP1000 Secondary Circuit

4.4.2 Assessment – Materials, Design and Chemistry

683 The 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.

684 Assessment during Step 4 has concentrated on demonstrating these aims have been realised in the AP1000 safety case. My assessment was supported by a TSC contract which reviewed both relevant good practice in secondary circuit chemistry (Ref. 231) and the AP1000 design specifically (Ref. 187). My assessment that follows is consistent with these reviews.

4.4.2.1 Materials and Design

685 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 design and materials is required. The following sections concentrate on the main chemistry

related systems in the AP1000 secondary circuit, and the factors which influence the chemistry.

4.4.2.1.1 Steam Generators

686 The Steam Generators (SG) are the interface between the primary and secondary circuits of a PWR. The AP1000 has two SGs which are similar to Westinghouse model Delta-75 and Delta-94 replacement SGs that are already in service in several plants. These are described in the PCSR (Ref. 1, Section 6.3.2.4.), with further details in the RCS SSD (Ref. 44). The main differences in comparison to the previous designs are an increase in secondary side water volume, an increased number of SG u-tubes and the incorporation of the RCPs in the channel heads. 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 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. The AP1000 SGs are shown below (Ref. 22):

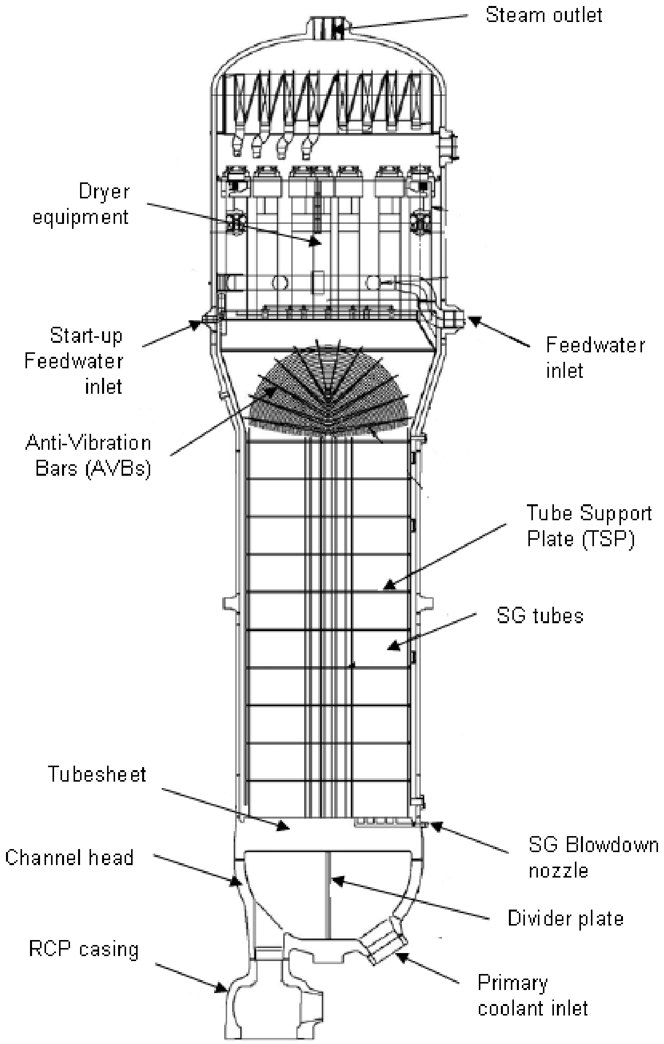

Figure 11: AP1000 Steam Generator

687 Many design differences exist between SG designs of different reactor 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.

688 During Step 3, I was content with the SG features described for AP1000, 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 AP1000, during Step 4.

689 TQ-AP1000-1237 (Ref. 8) requested OEF feedback for the AP1000 SG design, specifically aimed at demonstrating that the major degradation mechanisms that have affected previous SG designs had been considered for AP1000. While recognising that no direct OEF exists for the AP1000 design, significant experience exists for progenitor designs. The Westinghouse response included a specific OEF report which identifies problems recognized by the industry, both nuclear and non-nuclear, with steam generators and similar heat exchanger components, and describes the steps taken by Westinghouse to improve the AP1000 design to address these. In addition to a detailed description of the AP1000 design, the report highlights OEF from industry bodies such as Nuclear Energy Institute (NEI), EPRI, US Nuclear Regulatory Commission (NRC) and the Institute of Nuclear Power Organisations (INPO). The main threats to AP1000 (and other) SGs are summarised by Westinghouse as:

- Tube damage induced by loose parts.
- Material loss as a result of erosion or corrosion.
- Cracking of structural components in the secondary shell, tube support plate ligaments, wrapper, feedwater nozzle, and other component parts.

690 Reactor Chemistry can influence the occurrence and extent of the second and third of these and the provisions made by Westinghouse to address these are assessed in the following paragraphs.

691 The most significant choice made for the AP1000 SGs is the use of Inconel 690 tubing in the thermally treated condition. This is almost the standard choice for SG tubing material and is used in the latest replacement SGs. Protection of this material is a determining factor in any chemistry regime. While accepted that, overall, this material has much better corrosion behaviour than Inconel 600, and comparable performance to Alloy 800, Westinghouse recognise a number of environments still pose risks to Inconel 690 as discussed in the response to RO-AP1000-55.A2 (Ref. 108). These are environments which contain caustic lead, lower valence sulphur species and acidic solutions that are slightly oxidising, 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 Westinghouse has provided responses to my questions in each of these areas, as described in Section 4.4.2.2.

692 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.

693 The SG tubes are welded to the primary side of the tubesheet cladding to inhibit coolant leakage from the primary to secondary side. After welding the tubes are full length

expanded into the tubesheet. The design specification for the AP1000 SGs (Ref. 45) provides some details of the process for AP1000, including requirements for the maximum crevice widths and depths. This joint is an important area in SG design as a number of SGs have experienced corrosion issues here due to the crevices left between the tube and tubesheet. The AP1000 SGs are expected to have a diametrical clearance between the tube outer surface and the tubesheet hole of less than [redacted] mm, over a maximum depth of [redacted] mm, with much smaller crevices expected on average. This is much improved on earlier SG designs and should minimise the potential areas for crevice type corrosion to occur in AP1000.

694 Stress introduced into the SG tubes during the expansion process can cause sensitivity on affected tubes. Westinghouse propose to specify a (to be confirmed) procedure that will result in reduced residual stresses, with the specification stating that "*the expansion process shall be carefully controlled so as to produce as low a residual stress in the tubes as is reasonably achievable*". Provided OD residual stresses are indeed kept low, along with adequate chemistry control, this should not impose additional corrosion concerns.

695 A novel feature of the AP1000 SG tubesheet design is the integration of the Steam Generator Blowdown System (BDS) manifold within the tubesheet. The [redacted] mm diameter blowdown holes are drilled vertically into the tubesheet secondary face to intersect with a manifold which terminates at the SG pressure boundary in the BDS nozzle. Previous SG designs have a series of pipes and nozzles located above the tubesheet to feed the blowdown system. Westinghouse state the reason for this change is to leave an unobstructed tube-free lane for inspections and maintenance (e.g. sludge lancing). The BDS is assessed in discussed further in Section 4.4.2.1.2.

696 The tubes are supported on the secondary side by ten trefoil broached tube support plates (TSP) made of Type 405 stainless steel. Trefoil TSPs were chosen due to size constraints on the SG requiring a triangular pitch. The TSPs are supported vertically by 56 stayrods, made of 2-1/4Cr-1 Mo steel. These high chromium steels should provide adequate corrosion resistance except if hostile environments are allowed to develop, although these would damage the more sensitive SG tubes first.

697 Westinghouse claim that the trefoil-shaped broached TSP (Tube Support Plate) used in AP1000 will 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 CANDU (CANadian Dueterium-Uranium reactor) Recirculating Steam Generators (RSG) and Babcock and Wilcox (B&W) PWR Once-Through Steam Generators (OTSG). The response to RO-AP1000-55.A2 (Ref. 108) suggests there are no reasons to believe a trefoil TSP should be more susceptible to blockage than any other support shape in current use, and should be much improved over earlier designs. The blockage process is complex and may involve deposition of both particulate and soluble iron, hence depends on many factors. The AP1000 TSP design is the latest evolution and it should perform at least as well as current replacement SGs in this respect.

698 The AP1000 SG tube bundle U-bend supports comprise 6 sets of anti-vibration bars (AVB) made from Type 405 stainless steel and some Inconel 690 components. The design is an evolution from the latest replacement steam generators (Arkansas Nuclear One Unit 2 and Waterford 3). Again, these materials should offer suitable corrosion resistance in typical secondary chemistry environments.

699 The AP1000 SG has separate main and start-up feedwater nozzles, both in the upper shell. The main feedwater inlet nozzle has an all welded, Inconel 690 thermally treated liner that leads into an upper chromium molybdenum steel alloy feedwater ring. The feedwater flows from the feedwater ring into the steam generator through top exiting spray nozzles, made of Inconel 690 TT pipe. The start-up feedwater nozzle is also fabricated with an all welded Inconel 690 liner that turns vertically upward and terminates in a spray nozzle. These materials are chosen for increased resistance to erosion and corrosion, based upon OEF.

700 Surrounding the SG tube bundle, along the SG shell periphery, is the downcomer annulus which takes the feedwater and recirculating coolant mixture towards the tubesheet. The entire SG pressure boundary shell is made from machined ring forgings of SA-508 low alloy steel. The primary channel head and the torispherical upper head are also made from SA-508 forgings with integral nozzles.

701 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. Sludge accumulation and deposition 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 (Ref. 110), which led to difficulties with level control. TQ-AP1000-816 (Ref. 8) queried several points in this area related to quantities, location and provisions for sludge removal in AP1000.

702 The response provided details of the AP1000 design provisions in this area, which include:

- Two [redacted] mm diameter secondary manways in the upper shell.
- Four [redacted] mm and three [redacted] mm inspection ports. The larger ports are located at the tubesheet 90 degrees apart. Two of the smaller ports are located at the highest TSP level. The final port is provided for “*chemical cleaning*” of the SG. Together these allow inspection of the tubesheet and upper tube bundle.
- A “*sludge collector*”.

703 The AP1000 design has a dedicated sludge collector which previous SG designs have not included. The sludge collector provides an area above the primary separator lower deck through which a portion of the coolant flows, from the centre to the periphery. The feature provides an area of low flow velocity such that particulate matter suspended within the fluid tends to settle out. During outages the material trapped in the collector can be removed. Westinghouse claims that it tends to reduce the amount of sludge that accumulates on the tubesheet and tube bundle surfaces by approximately 50%. This is a significant claim and TQ-AP1000-817 (Ref. 8) was raised to understand this further. The response provided a calculation note (Ref. 46) for the fluid flows to ensure sedimentation of particles in the collector using Computational Fluid Dynamics (CFD) analysis. A number of assumptions were used for the analysis, such as the properties of the coolant were taken as equal to water at 100 °C and the particles were assumed to be 12 μm diameter carbon steel. Even with these significant assumptions the calculated efficiency was closer to 5% (cf. originally claimed 50%). While it may not prove to be as efficient as claimed, and will only really be proved in operation, the inclusion of the sludge collector should pose no detriments to the AP1000 SG. It is also clear however that the sludge collector cannot be used as an argument to ‘relax’ sludge controls in the secondary circuit.

704 Westinghouse confirmed that no assessments of likely sludge accumulation in the AP1000 SG have been performed, although they do perform thermal hydraulic flow analysis in all SG models. I found the former somewhat surprising, as this information would be an input to determining the surveillance and cleaning programmes and the location and number of BDS nozzles. Westinghouse claims that no BDS nozzle design can completely prevent sludge accumulation, so they have designed AP1000 to provide maximum sample representivity and minimum obstructions for SG lancing. These are reasonable arguments.

705 Westinghouse claims 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 Westinghouse has considered this possibility. It is notable that Westinghouse does not anticipate use of a dispersant for chemical sludge mitigation in AP1000, but have not ruled out this possibility later in plant life.

4.4.2.1.2 Steam Generator Blowdown System

706 The Steam Generator Blowdown System (BDS) 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, purifying it and returning it to the condenser. For AP1000 this system is very important to maintaining an adequate water quality in the secondary side.

707 In existing plants the steam generator blowdown flow is typically of the order of 1% of the feed flow, which implies the concentration of in-volatile impurities in the SG water should be approximately two orders of magnitude higher than those in the feedwater assuming no other processes occur (e.g. hideout). This means that, overall, it is easier and more efficient to remove the relatively high concentration of impurities from the SG than to try and further clean-up the already much reduced feedwater impurities. Most PWRs, with the exception of Ringhals 2 in Sweden, use conventional ion exchange processes to purify the blowdown flow. The major difference between existing PWRs and the AP1000 BDS design is the use of an Electrodeionisation (EDI) process.

708 Assessment of this system started during Step 3, although very limited information was available at the time, with the Step 3 PCSR containing no specific arguments for the selection of this technology over more conventional ion exchange. Westinghouse themselves confirmed that they have no previous experience of use of this technology for BDS treatment. I noted particular concerns related to:

- Use of an electrolytic process for routine secondary circuit chemistry control, particularly faults with the EDI units.
- Process concerns, namely; iron fouling, release of ionic contaminants or release and retention of radioactive species under fault conditions.
- Compatibility of the technique for likely secondary circuit chemistry conditions (e.g. use of dispersants, alternative amines).
- Maintenance requirements for the EDI and the disposal route for contaminated units.

709 Continuing assessment occurred throughout Step 4 focussing on the evidence to support the system functions, to address the concerns listed above and to provide me with confidence that the use of this technology is justified and appropriate. Due to the novel

nature of EDI I raised RO-AP1000-55.A7 (Ref. 7) and a number of TQs during Step 4. The most relevant of these are discussed below.

710 The AP1000 BDS is described in the PCSR (Ref. 1, Section 6.6.9) and the corresponding SSD (Ref. 47). The BDS has two 50% trains, one for each SG. Each train includes a regenerative heat exchanger, a flow control valve, and an EDI unit. Each EDI unit consists of a filter (duplicate 2 x 100%) for removal of suspended solids and particulate matter prior to being processed through an EDI demineraliser for removal of ionic impurities. Each EDI demineraliser is actually a collection of many smaller EDI membrane cells. Each cell consists of alternating pairs of cation and anion membranes, ion-exchange resins, polymeric flow channel spacers and a pair of electrodes. During operation a small voltage is applied across the ion exchange membranes resulting in a purified effluent and a concentrated waste, or "*brine*", stream. The EDI process maintains the resins in a regenerated state thus the resins are not exhausted in the process. Westinghouse has not yet specified the precise design of the EDI to be used in AP1000. The BDS SSD (Ref. 47) states that; "*Electrodeionization (EDI) package details, including configuration of internal components, maximum allowable operating temperature, instrumentation and control, operational limitations, material selection, and testing and maintenance requirements are preliminary and likely to change based on vendor selection and finalization of EDI design with vendor*." The AP1000 BDS is shown below (Ref. 47):

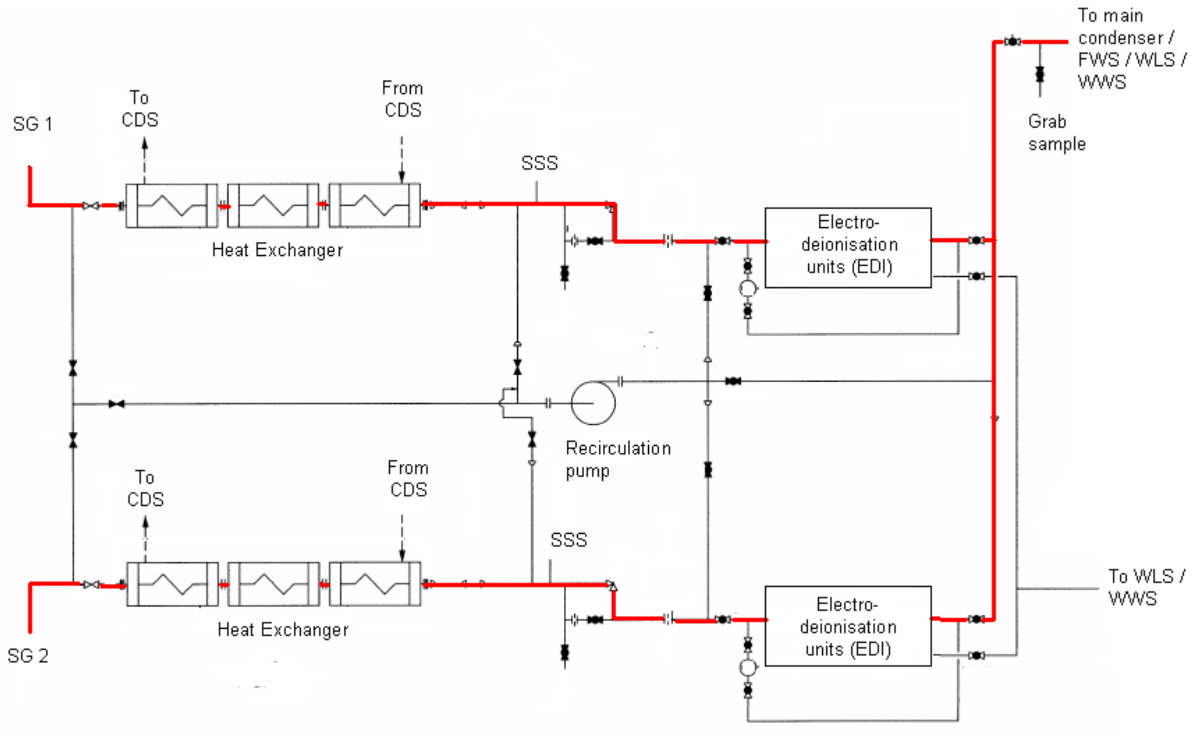

Figure 12:AP1000 Steam Generator Blowdown System

711 Each SG has a separate blowdown line which is attached to the BDS nozzle described in Section 4.4.2.1.1. Flow control valves adjust the blowdown flow rate from each SG and depressurise it. A flash tank is not included in the AP1000 BDS design. Therefore, to prevent flashing, the blowdown fluid is cooled before the pressure is reduced by the flow control valves. The blowdown flow is cooled by means of a regenerative heat exchanger

fed with feedwater from the condensate stream prior to the LP feedwater heaters with the exhaust passing into the Deaerator, thus recovering the BDS flow thermal energy. The cooled blowdown flow then passes through the EDI unit, which removes impurities. Downstream of the EDI unit, both trains combine into a common header, which contains a relief valve for providing overpressure protection for the low-pressure portion of the system (including the EDI).

712 The BDS also includes a recirculation pump which, with the SG at low pressure, allows:

- SG cooling by recirculation of the SG contents through the BDS regenerative heat exchanger.
- Establishing and maintaining steam generator wet lay-up conditions during plant outages by injecting chemicals to the recirculation flow from the turbine island chemical feed system (CFS).
- Draining the secondary side of the steam generators for maintenance.

713 The system is fitted with various monitors which measure temperatures, pressures, flows and levels (via the SG level detectors). Abnormal conditions result in automatic isolation of the affected BDS train.

714 In AP1000 the maximum continuous BDS flowrate which can be treated is expected to be 0.6% of the main SG flow at full power, which even at this maximum is low compared to other PWRs. Operational values are expected to be between 0.06 and the maximum 0.6%, which reflects Westinghouse's expected low secondary coolant impurity concentrations. Due to the construction of the EDI demineralisers the flow is reduced by isolating a number of cells rather than reducing the flow to all; half of the maximum flow in each operating cell is required to stop overheating of the cell. Higher flowrates of 0.9% are possible for reduced durations and the extracted coolant can be sent to the Liquid Radwaste System (WLS) dependant upon the available capacity. TQ-AP1000-534 (Ref. 8) indicated that Westinghouse had looked at increasing the BDS flowrate to 1% [redacted], but this was ultimately rejected [redacted].

715 The BDS is located within the Turbine Building in AP1000. TQ-AP1000-633 (Ref. 8) queried the implications of this location on ORE, both during normal operation and in fault conditions. The response provides details of the automatic isolations and actions triggered by high activity levels. The blowdown flow and the ion exchange waste stream (brine) flow are both continuously monitored for radioactivity, either due to primary leakage or as an indication of a steam generator tube rupture. Detection of high levels results in alignment of the Liquid Radwaste System (WLS) to process the blowdown and ion-exchange waste effluent. If radioactivity should exceed a higher preset level, the blowdown flow control valves and the isolation valves would automatically close. Provisions exist for the installation of extra shielding to the BDS if dose rates increase too much. Westinghouse has incorporated a number of design changes in this area during Step 4 (Refs 48, 49 and 50). Together these changes allow for continued sampling of the BDS when isolated, transfer of drainage to WLS and isolation of the BDS area ventilation system thus minimising unintentional activity release and transfer. I consider reasonable steps have been taken to control potential activity transfer to the non-active turbine building areas, but still have concerns regarding sampling of the BDS with the Secondary Sampling System (SSS) in case of high activity levels; see Section 4.4.4.

716 To monitor the chemistry of the BDS, continuous blowdown samples are collected from each blowdown line and are analysed within the secondary sampling system (SSS), see

Section 4.4.4. The chemistry of the dilute product recycled to the condenser from the EDI is also monitored by dedicated EDI conductivity instruments.

717 RO-AP1000-55.A7 (Ref. 7) asked for further evidence in relation to a number of aspects of the EDI choice for AP1000. Some of these are related to system design, while others are related to the chemistry; this later group are discussed in Section 4.4.2.2 where the BDS is vital to the secondary circuit chemistry in AP1000. As highlighted in the response (Ref. 111), the main 'design' concern with the use of EDI is the temperature at which the system will operate in AP1000. High temperatures are liable to result in degradation, and ultimately failure of EDI modules if not detected. It is notable that the only other proven application of EDI in the BDS at Ringhals 2 has a much lower inlet temperature of 15°C to 35°C, whereas the AP1000 BDS temperature should be normally maintained at 54°C, but can experience infrequent excursions up to 60°C. These high temperatures are at the limit for conventional ion exchange resins. It is common for 'standard' EDI cells not to operate continuously at a higher temperature than 40°C although recent advances in technology may allow higher temperatures of around 50°C (Ref. 51). To address this issue Westinghouse contracted a potential EDI supplier for AP1000 to perform testing of EDI modules at temperatures ranging from 57.2°C to 60°C. No failures or leakage due to the raised temperature were recorded during the two month testing period. The outlet from the cell produced water of [redacted] μS cm^{-1} quality from a [redacted] μS cm^{-1} inlet. While this provides reassurance of no gross loss in performance during the test, reliance on conductivity rather than more detailed measurements does not necessarily constitute proven performance at the low outlet levels required. In reality, I consider it unlikely that any UK AP1000 would reach such elevated temperatures for a significant duration, with the temperature ultimately driven by the site conditions and the BDS flow. The test does show the resilience of the EDI to minimal periods of elevated temperature operation. I consider reasonable arguments have been presented for operation of the AP1000 BDS at temperatures above 40°C for short periods. This will need to be reviewed once an EDI design is finalised and site conditions are known. I consider this to be part of Assessment Finding **AF-AP1000-RC-41**, to be addressed in time for alterations to its temperature-protection system or other improvements.

718 Only limited information is available on the materials in the BDS. The heat exchangers are of welded construction with stainless steel tubes and a carbon steel shell. The BDS piping material from the steam generator to the EDI and downstream of the EDI is specified as "*corrosion resistant alloy steel*". The piping inside the EDI is "*vendor supplied*" and is currently specified as CPVC (Chlorinated PolyVinyl Chloride). The influence of material choices in the secondary circuit is discussed further in Section 4.4.3.

4.4.2.1.3 Condensate Polishing System

719 The Condensate Polishing System (CPS) is a relatively common feature of PWR secondary circuits and is used to chemically clean the condensate by passage through ion exchange resins to remove corrosion products (by filtration) and ionic impurities.

720 Chapter 5 of the "*chemistry manual*" (Ref. 25) provides further details of the CPS; the CPS removes corrosion products, dissolved solids, suspended solids and other impurities from the condensate system by use of a deep bed resin ion exchanger. Westinghouse acknowledge that the selection of a system type and mode of operation is site specific depending on the secondary chemistry and Circulating Water System (CWS) water quality design basis, noting that "*A full condensate flow CPS may be specified for an AP1000 plant that uses seawater as the CWS cooling medium*". While outside the scope of GDA, recognition of this possibility is important.

721 The AP1000 CPS is described in the PCSR Section 6.6.13 (Ref. 1). The system consists of two trains of 50% capacity deep bed ion exchange polishers containing 2:1 cation:anion resin with the total capability to accept 33% of main condensate flow. Also included is a tank and mechanism for removing and exchanging the spent resin, although it is notable that the media is not regenerated on-site. This is claimed by Westinghouse to minimise the potential for impurity ingress. Westinghouse states that the system is capable of providing sufficient polishing capability to deal with a 'continuous leak' in the condenser of around 0.227 litres per hour or a "*faulted*" leak of up to 22.7 litres per hour; this is assessed further in Section 4.4.2.2.1. The AP1000 design basis is that this system will not be used during normal operations (only during start-up, shutdown and during 'abnormal' chemistry conditions).

722 Experience has shown that such systems require careful attention by operators to achieve their full value. During operation the CPS ion exchange resins will rapidly become saturated with the pH additive and consideration needs to be given to when the media is replaced, either on amine or impurity breakthrough.

723 No SSD is yet available for the AP1000 CPS, so information on the design and materials is very limited. The EDCD (Ref. 22, Section 10.4.6.2) states that the vessel itself is carbon steel, with a rubber lining. Resin traps are provided after the resin bed to minimise transfer of resin fines.

4.4.2.1.4 Condensate Systems

724 The condensate system is the first stage in returning condensate, of acceptable chemical quality, to the feedwater systems and ultimately the SGs. 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 inadequately conceived or poorly controlled. The AP1000 Condensate System (CDS) is described in the PCSR in Section 6.6.1 (Ref. 1). Further details are provided in the SSD (Ref. 52).

725 The CDS condenses steam from the turbines and turbine bypass valves (in addition to other minor sources) and collects the condensate in the main condenser hotwells. Three 50% capacity condensate pumps connected in parallel provide flow in the CDS, extracting condensate from the condenser hotwell and transferring it to the LP feed heaters and deaerator tank. The two lowest pressure feedwater heating stages (1 and 2) are divided into three trains of heaters, with each train associated with one condenser shell. Feedwater heater stages 3 and 4 are divided into two trains. Condensate is delivered to the deaerator at the required flow rate for use in the main and start-up FeedWater System (FWS). Automatic controls are provided to maintain levels and flows in the system to match plant requirements.

726 The condenser in the CDS in AP1000 acts to condense steam discharge from the final (LP) stages of the turbine, by-pass steam or other steam sources. This system contributes 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. The main condenser is a three shell, multi-pressure, deaerating type, surface condenser located below the exhausts of the three low-pressure turbines of the Main Turbine System (MTS). Each condenser shell contains two parallel, single pass tube bundles which pass cooling water from the circulating water system (CWS). CWS water passes through shell A first and is

then directed through shell B and C. Details of the condenser are related to site specific characteristics, such as cooling water supply, and as such many details regarding the precise condenser design were 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. Westinghouse claims that the AP1000 design will use a ‘leak tight’ approach with titanium tubing fixed to titanium lined steel tube sheets. A cathodic protection system is provided to protect against corrosion between the titanium tubes/tubesheet and the carbon steel. In addition, several design features are claimed to minimise impurity ingress:

- Use of “*flash boxes*” outside the condenser for high energy input streams thus minimising tube bundle impact.
- Inclusion of “*dummy tubes*” for sacrificial steam impingement.
- Isolation provisions allowing some tubes to be isolated during leakage.

727 I am content that the use of titanium tubing is an appropriate choice for AP1000 and should provide reliable condenser performance.

728 The use of a ‘leak tight’ condenser is an important part of the overall AP1000 secondary chemistry philisophy. As suggested in TQ-AP1000-810 (Ref. 8), this feature is an important part of the justification for not including a condensate polishing plant (or similar) in AP1000 for use during normal operations. This is discussed further in Section 4.4.2.2.1.

729 Connections to the Condensate Storage Tank (CST) in the Demineralised Water Transfer and Storage System (DWS) allow the CDS to maintain the secondary circuit coolant inventory. The DWS is discussed in Section 4.4.2.1.8.

730 Westinghouse also claims that the AP1000 CDS contributes to deaeration in both the main condenser and the deaerator. Non-condensable gases are concentrated and collected in the air removal sections of the condenser and removed under vacuum by the Condenser Air Removal System (CMS). The expected condensate oxygen concentration is $< 10\ \mu g\ kg^{-1}$ during normal operations.

731 The addition of a deaerator tank is a valuable addition to the AP1000 secondary circuit. This feature is not common in many PWRs. The AP1000 deaerator is in fact used as a fifth stage of LP feedwater heating. Turbine extraction steam is passed into the deaerator, underneath a series of deaerating trays. Condensate is sprayed onto the trays and passage through the steam causes non-condensible gases to be extracted. The expected feedwater oxygen concentration is $< 2\ \mu g\ kg^{-1}$ during normal operations.

732 Although no details of the design were provided for GDA, I queried the potential impact of this feature in TQ-AP1000-1207 (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 deaeration. The tank also provides a useful store of feedwater for transient and accident conditions.

733 Condensate polishing is performed downstream of the condensate pumps discharge header. As described in Section 4.4.2.1.4, during normal operations the CPS is bypassed.

734 Chemical injection into the CDS is accomplished in the main condensate piping downstream of the polishing equipment and into the deaerator. These connections are

provided to inject both an oxygen scavenging agent and a pH control agent as part of the Turbine Island Chemical Feed System (CFS); see Section 4.4.2.1.7.

735 Sampling is provided at several locations within the CDS as part of the Secondary Sampling System (SSS); see Section 4.4.4, in addition to grab sampling locations. These locations include the main condenser, the discharge piping from the condensate pumps, the main condensate supply piping to the deaerator and the water stored in the deaerator. A connection for sampling the effluent from the condensate polishing unit is provided as a part of the CPS.

736 All of the heaters and heater drain coolers have carbon steel shells and tubesheets and 439 ferritic stainless steel tubes. The heaters have internal impingement baffles at the extraction steam inlets. The deaerator shell is fabricated from carbon steel. Most of the deaerating chamber, including the deaerating trays, water sprinkling box, and spray valves are constructed of stainless steel. In general, CDS piping is fabricated of carbon steel. In segments of piping that may be subjected to flashing conditions and/or a two phase mixture, alloy steel is used for increased resistance against erosion.

4.4.2.1.5 Feedwater Systems

737 The feedwater system transfers condensate from the deaerator, through various stages of heating and pressurisation, to the SG inlet. As with the CDS, design and materials used in this system are important in defining the secondary circuit chemistry regime. The AP1000 Main and Start-up Feedwater System (FWS) is described in the PCSR in Section 6.6.1 (Ref. 1). Further details are provided by the SSD (Ref. 53). Feedwater is supplied whenever the level is required to be maintained in the SGs (i.e. during start-up, shutdown and normal operations); the use of the FWS during plant start-up and shutdown is discussed in Section 4.4.5.

738 During normal operations the feedwater is sourced from the CDS deaerator. The FWS consists of three identical (50%) feedwater pump trains, with each train consisting of a booster pump and a HP feedwater pump. The main feedwater pumps are each preceded by a booster pump, to pressurise the inlet and thereby prevent cavitation. Feedwater from the three trains of booster/main feedwater pumps join into a common discharge line for supply to the two parallel strings of two stages of high pressure feedwater heaters. After exiting from the last stage of feedwater heaters, main feedwater flow is delivered through a single line (called the main feedwater header) to a point where the flow splits into individual lines to the two steam generators. The individual feedwater lines to the steam generators are part of the FWS until the Steam Generator System (SGS) / FWS interface at the turbine building wall. The SGS contains the Main Feedwater Control Valve (MFCV), a Main Feedwater Isolation Valve (MFIV) and a main feedwater check valve.

739 During unavailability or failure in the FWS, feedwater can be supplied to the SGs in AP1000 using the start-up feedwater system, which is part of the FWS. While the system is not claimed or credited by Westinghouse in the safety analysis (although this may change as a result of RO-AP1000-52), in these circumstances the start-up pumps are fed from water stored in the Condensate Storage Tank (CST). Flow from these pumps pass through separate Start-up Feedwater Control Valves (SFCV), to the dedicated SG feedwater nozzle. Flow can also be provided by the main feedwater pumps via this route. Injection occurs downstream of the HP feedwater heater trains.

740 The feedwater heaters are shell-and-tube heat exchangers with feedwater flowing through the tube side. Heater drains from the feedwater heaters are collected and controlled by the Heater Drain System (HDS).

741 All of the heaters have carbon steel shells and 439 ferritic stainless steel tubes. The tubesheets are of carbon steel and HP heaters 6 and 7 have a stainless steel overlay. Features of the heaters include impingement baffles at the extraction steam inlet, integral flash chambers at the flashed drain inlets and integral drain coolers, as appropriate.

742 In general the FWS piping is fabricated in carbon steel, except for areas subjected to flashing conditions and/or a two phase flow where alloy steel is generally used. This means that alloy steel, or equivalent erosion resistant material, is used downstream of the deaerator recirculation control valve and downstream of the long cycle recirculation control valve. Alloy steel is used for most of the piping downstream of the booster/main feedwater pump miniflow control valves. The SGS portion of the main feedwater piping material is alloy steel (SA-335, Grade P-11) to minimise potential erosion-corrosion concerns.

4.4.2.1.6 Steam Systems

743 The system that transfers steam generated in the SGs to the turbines is called the Main Steam System (MSS). The MSS is designed to ensure the supply of steam to the Main Turbine System (MTS) and to various steam consumers in the turbine hall during power operation. This system is described in Section 6.6.2 of the PCSR (Ref. 1). Further information is provided in the SSD (Ref. 54).

744 This system consists of the pipes and valves that take the steam from the SGs to the HP turbine. The MSS includes the two main steam lines, one connected to each SG outlet. The system also diverts a proportion of the steam to the Moisture Separator Reheaters (MSR) for steam drying and reheating. There is also a turbine bypass connection, which allows (up to 40% of) the steam to be dumped directly into the main condenser without passing through the turbine. The role of the bypass 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 main steam relief valves.

745 An 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 condensates produced in the steam systems, especially in drain lines. The material choices are an important aspect of this process, as they offer another potential mitigation route.

746 In AP1000 the main steam lines are constructed SA-335 Grade P-11. Grade P-11 low alloy chromium-molybdenum steel has material properties which significantly reduce the effects of erosion-corrosion and flow accelerated corrosion in piping systems. Carbon steel remains to be used for hot reheat piping, turbine bypass piping, and other piping that is used intermittently, passes high-quality or superheated steam, or has low velocities. Low alloy steel is used for cold reheat piping, extraction steam and low point drains. The MSR tube bundles and internals exposed to wet steam or flashing liquid are constructed of stainless steel.

4.4.2.1.7 Chemical Dosing Systems

747 Chemical additions must be made to the secondary circuit in order to maintain the coolant chemistry within the required bands. The AP1000 design incorporates a Turbine Island

Chemical Feed System (CFS) which injects chemical reagents to ensure that the water in the secondary systems and in the auxiliary systems has the required chemical properties. No details are provided in the PCSR (Ref. 1) on this system nor is a SSD available.

748 Some information of the reagent injection points in the secondary circuit are provided in the response to RO-AP1000-55.A2 (Ref. 108) and Chapter 5 of the "*chemistry manual*" (Ref. 25). The AP1000 secondary system is designed to provide chemical injection locations in the main and start-up feedwater and condensate. Additionally, a chemical injection location is also provided in the blowdown recirculation and drain lines for use during wet layup of the system. The AP1000 design includes chemical injection of pH control agents and oxygen scavengers based on an AVT (All Volatile Treatment). Other chemical additives such as dispersants, boric acid treatment and inhibitors are considered plant specific and therefore not considered. The main locations for chemical injection into the secondary circuit are at the CDS pump discharge (downstream of CPS), for pH additive, and into the deaerator tank, for pH additive and oxygen scavenger. Both will be controlled automatically based upon deaerator inlet and HP feedwater heater outlet measurements respectively.

749 No final information is yet available on the materials used in the CFS. Due to the corrosive nature of the strong chemical stored and delivered by the CFS, all equipment subjected to the action of chemical products (pipework, vents, valves, etc.) will need to be made of a suitable corrosion resistant material. Similar consideration needs to be given to gasket materials.

4.4.2.1.8 Demineralised Water Systems

750 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 in the plant. This is the first step in ensuring impurity levels are met. The AP1000 has a two stage approach to treatment of the raw water, first using the Raw Water System (RWS), which is site specific, followed by the Demineralised Water Treatment System (DTS) which provides final clean-up to a high purity. The DTS is closely associated with the Demineralised Water Transfer and Storage system (DWS) which stores and distributes DTS product to the plant systems. These systems are described in the PCSR (Ref. 1, Section 6.5.8 and 6.5.9) and the corresponding SSDs (Ref. 112 and 113).

751 The DTS treatment systems consist of two 100% cartridge filters, two 100% reverse osmosis units and four 25% Electrodeionisation (EDI) units. The reverse osmosis units undertake most of the purification with final polishing left to the EDI units. Typical outlet specifications for the demineralised water are $< 0.08\ \mu S\ cm^{-1}$, $10\ \mu g\ kg^{-1}$ Na and $100\ \mu g\ kg^{-1}$ dissolved oxygen, which are reasonable targets.

752 The associated DWS is designed to provide storage capacity for demineralised water and condensate that is sufficient to support plant needs under all modes of operation. Demineralised water from the DTS is stored in the Demineralised Water Storage Tank (DWST), while condensate is stored in the Condensate Storage Tank (CST). The CST is sufficient for 8 hours of hot standby conditions followed by a normal cool down, while the DWST volume is sufficient to support normal plant operations. The DWST supplies many important plant systems including the RCS, SFP, Component Cooling Water System (CCS) and CVS Boric Acid Mixing Tank. Both tanks have immersion heaters for freeze protection.

753 Control of oxygen in the stored water is important in most of the fed systems. Both tanks are vented to the atmosphere, however the CST has a floating stainless steel cover to minimise absorption and both the CST and DWST are fitted with a Catalytic Oxidation Reduction System (CORS) to remove dissolved oxygen from the water via reduction with hydrogen gas over catalytic resin. The response to RO-AP1000-55.A2 (Ref. 7) provided more information on these devices. In the CORS water is pumped to and from the tanks in a recirculation loop. Hydrogen is injected into the loop from the Plant Gas System (PGS) just prior to the CORS mixing chamber, controlled automatically by a system which takes into account the resin bed inlet oxygen and hydrogen levels, the outlet hydrogen level and the flow rate. These systems are initiated automatically on detection of high oxygen levels and are novel for UK nuclear plants. Westinghouse claim that these systems are sufficient to reduce dissolved oxygen in the inlet, which could be saturated at around 8 mg kg^{-1} to less than 20 μg kg^{-1}, maintaining the bulk tank level at less than 100 μg kg^{-1}. The outlet from the CORS resin vessel is filtered to stop any resin fines passing further downstream. The system is vented to a specific degassing vessel, which is continuously purged with air to stop a build-up of hydrogen gas. The DWST CORS vents outside the plant, while the CST CORS vent to the TDS (Turbine Drains System). Westinghouse considers it likely that both CORS will be used almost constantly, at reduced flow, during operations.

754 I consider that the use of CORS is a beneficial addition to the CST which, along with the tank floating cover, should maintain adequate oxygen control. Similarly the DWST should also experience similar benefits. It is also notable that the CORS will not remove other non-condensable gases such as nitrogen, see Sections 4.2.3.4.3 (on ^{14}C), 4.2.11 (on start-up) and 4.2.9 (on primary sampling) for my assessment of the effect of nitrogen and oxygen in various systems.

4.4.2.2 Chemistry

755 Definition of a secondary circuit chemistry operating regime is a difficult task in a PWR. Many factors should be considered including material compatibility, corrosion control, environmental impact and economic viability. The nature of secondary circuits, involving many systems and components and a range of thermo-hydraulic conditions, further complicates the decision as a particular chemistry is often not ideal for all parts of the circuit. The nominally non-active nature of the secondary circuit does mean that options are not restricted by the consequences of contamination.

756 Neither the PCSR (Ref. 1), nor the EDCD (Ref. 22) discusses the secondary water chemistry treatment in any detail. Section 10.3.5 of the EDCD does note, however, that the secondary circuit will be copper free, which allows for the option of operating with a high pH All Volatile Treatment (AVT) in the secondary circuit. This is advantageous for secondary chemistry as it avoids a number of limitations on options for the secondary circuit water chemistry when copper alloys are present. Although there is little discussion of the secondary circuit chemistry the EDCD does tabulate secondary circuit chemistry specifications for the condensate, feedwater and steam generator blowdown for the AP1000 reactor. It is notable that these are inconsistent with the guidelines presented in the AP1000 *"chemistry manual"* (Ref. 25) and are also less restrictive than most current secondary chemistry guidelines used in existing PWRs, a point also noted in the EPRI review (Ref. 55) of the secondary circuit chemistry specifications in the US AP1000 Design Control Document, Revision 17, which contains the same values as the EDCD. For the purpose of the assessment that follows the information given in the EDCD is considered superseded by the "*chemistry manual*". This discrepancy needs to be rectified

in future revisions of the safety case, should the EDCD be retained as reference documentation. I consider this to be an Assessment Finding, **AF-AP1000-RC-38**.

757 Due to the lack of information and justification in the safety case on secondary chemistry, I issued RO-AP1000-55.A2 (Ref. 7) to Westinghouse requesting evidence in this area. Westinghouse provided a response to this RO (Ref. 108), providing a main summary report and several specific, detailed supporting references. The response covered many areas of secondary circuit chemistry including:

- Chemistry regime.
- Impurity control.
- Redox control.

758 Overall, these responses provide a reasonable overview of the AP1000 secondary chemistry regimes and appear to include the main considerations. However, for a number of reasons discussed more fully below, the response is inconclusive in a number of areas and further justification and evidence will be required as licensing progresses and as designs for AP1000 become more developed. A number of more detailed Assessment Findings follow in the subsequent paragraphs, where each principal aspect of the proposed regimes is discussed.

759 As described in Section 4.1, and in the response to RO-AP1000-55.A2, Westinghouse do not specify the operating secondary chemistry regimes for AP1000, leaving such decisions to the Licensee. While ultimately the responsibility for defining a safe secondary chemistry regime would rest with the Licensee in the UK, this approach does not provide a basis for a full and detailed assessment during GDA. For this reason this is an ‘out of scope’ item for the Reactor Chemistry GDA assessment and has been raised as an Assessment Finding, **AF-AP1000-RC-01**.

760 Westinghouse does specify that the AP1000 is designed and operated within the guidelines specified by EPRI (Ref. 16). The EPRI guidelines and “*chemistry manual*” effectively require an All Volatile Treatment (AVT) chemistry to be used, which consists of:

- Addition of a volatile pH raising additive.
- Addition of a reducing agent.
- Minimisation of impurities.

761 The EPRI guidelines recommended by Westinghouse are the latest guidelines publicly available from EPRI (Revision 6) but are not the latest revision and as such are around six years old. These guidelines were last revised in 2009 (Revision 7) and are revised regularly. The use of the EPRI guidelines is mandatory for PWR operators in the US. Unlike the corresponding primary chemistry guidelines, the secondary chemistry guidelines offer the operator greater freedom and require the Licensee to carry out a “*plant specific optimisation*” to define the secondary water chemistry for their particular plant design. This complicates the assessment of a generic design, as a key component of the regime, specifically the identity and concentration range for the secondary circuit conditioning agent, is not specified. This in turn means the pH_T around the secondary circuit is also not yet defined. This is an essential aspect of the secondary chemistry regime and also has knock on consequences for the control of ionic impurities. An immediate consequence of this approach is that a Licensee in the UK will be required to justify the secondary chemistry they choose to operate, even within the framework of the EPRI guidelines if they choose to adhere to these guidelines. None of these comments

imply that an AVT secondary water chemistry regime based on the EPRI guidelines or others would necessarily be unsatisfactory. This is part of Assessment Finding **AF-AP1000-RC-01**.

762 Similarly, as described in para. 670, the ‘standard plant’ assessed as part of GDA is based on “*estuarine*” cooling of the secondary circuit. Westinghouse themselves recognise that some design changes to the ‘standard plant’ secondary circuit may be necessary, but such decisions are site specific. As such all of the assessment that follows is based upon the ‘standard plant’. The assessment will need to be reviewed if an alternative cooling source is used. This is related to Assessment Finding **AF-AP1000-RC-37**.

763 As such, without a more specific chemistry regime during Step 4, I have assessed the impact of the system designs on potential chemistry regimes for AP1000 and their subsequent potential effects on safety. A number of design features described in Section 4.4.1 will influence the chemistry that will and can be operated on AP1000 and the response to RO-AP1000-55.A2 is influenced by these.

764 The important system design choices affecting the AP1000 is the omission of a Condensate Polishing Plant (CPP) (or similar) for normal operations and the use of EDI for the BDS at a relatively low flow rate of 0.6%. While the former is not uncommon, the latter is novel and these design choices do potentially influence the secondary chemistry regimes that are available.

765 These design choices mean that under normal operations the only system available to clean-up the secondary coolant is the BDS. This requires the BDS EDI units to reduce impurities in the blowdown flow to very low levels if the impurity levels in the steam generator are to be maintained within the limits specified by the EPRI guidelines, namely < [redacted] $\mu g\ kg^{-1}$ sodium and < [redacted] $\mu g\ kg^{-1}$ each of chloride and sulphate. Typical OEF from operating plants indicates that levels much lower, of the order of < 1 $\mu g\ kg^{-1}$, are typically achieved using conventional ion-exchange BDS designs.

766 Functionally EDI is a promising technology for the treatment of waste water stream and has developed significantly in recent years. As an option for BDS designs EDI offers a number of potential advantages over conventional ion-exchange systems, including:

- The plants can operate on an almost continuous basis, unlike resin beds that require regeneration at a frequency dependant upon the operating chemistry.
- The lack of regeneration means that concentrated acid and alkali chemicals are not stored, discharged or potentially transferred to the treated water in minute quantities.
- The plants require a smaller area for installation than an equivalent ion exchange system and are claimed to require less maintenance, assumining both systems work as expected.

767 However, as mentioned at the beginning of Section 4.4.2.1.2, operational experience of EDI systems in nuclear power applications is limited and full scale application as blowdown treatment is limited to Ringhals unit 2 in Sweden. Thus the main disadvantage of EDI at present is related to a lack of operating experience in this type of application. Before discussing the chemistry related concerns with EDI it is worth summarising the operational experience at Ringhals (Ref. 56) as there are a number of features of this experience which are different to that proposed for AP1000. In 2001, a pilot plant was installed as a side stream to the existing ion exchange blowdown treatment system. Within this arrangement 20% of the blowdown was passed through the pilot EDI plant. After successful results of the pilot plant, where the EDI produced “*high quality*” effluent, a

full scale EDI system was installed in 2005. It is assumed that this system achieves similar values to those specified by EPRI, as the plant effectively operates to EPRI PWR guidelines. The EDI unit, however, was installed upstream of a final ion-exchange mixed bed which ensures a very high purity for the blowdown effluent. In addition a (amine saturated) cation bed was retained upstream of the EDI, acting as an upstream filter.

768 RO-AP1000-55.A7 (Ref. 7) was raised to understand further the justification and evidence for the AP1000 application of EDI. One of the main concerns regarding EDI is the fouling of the EDI membranes with precipitates. The BDS flow will undoubtedly contain some quantity of metallic, oxidic, ionic and colloidal species, many of which could potentially deposit inside the EDI cells, hindering performance of the units. It is notable that Ringhals retains an upstream cation bed to act as a filter, whereas AP1000 relies on the two 100% redundant mechanical filters. During Step 4 a design change (Ref. 57) added the second filter in order to maintain operation during filter blockage. Using iron (magnetite) as an example Westinghouse estimates that the EDI input may be 8 $\mu g\ kg^{-1}$ of iron during normal operations, with typical specified EDI maximum inputs of 10 $\mu g\ kg^{-1}$. This estimation is subject to much uncertainty, but Westinghouse also claims an improved sludge removal from the SG to the BDS in AP1000. The effects of particulate iron will be more pronounced during start-up and shutdown periods, where BDS discharge of iron may increase by many orders of magnitude. It is notable that Westinghouse has not performed any testing for this aspect. While I consider that this process poses a risk to the EDI units, it is not considered to be a significant safety concern as, even if the upstream filters are inefficient, any degradation should be gradual and should result only in a decrease in the lifetime of the EDI cells rather than a rapid failure. I consider that an adequate case has been made for this aspect.

769 Another concern with EDI is the potential for retention of radioactivity within the cells. Westinghouse claims this as a benefit over conventional ion exchange which will retain more radioactivity than an EDI system. However disposal of contaminated ion exchange resins is an accepted practice in the UK. It is not expected that significant activity will be passed through the EDI, even during an SGTR, due to the automatic isolation of the EDI package upon high activity detection. Nonetheless, activity will pass through the BDS as a result of normal primary to secondary leakage; it is this process that creates active ion exchange resins in a conventional ion exchange based blowdown system. In the response to RO-AP1000-55.A7 (Ref. 7), Westinghouse argue that some accumulation is likely within the EDI cells, but this is uncertain as it depends on the prevailing redox conditions, but is expected to be mostly influenced based on selectivity as in a conventional ion exchange system. Westinghouse is calculating the shielding requirements for the BDS system based upon a constant leak from the primary side equivalent to the "*technical specification*" limits. No significant retention has been reported at Ringhals (Ref. 56), lending further confidence that there should be no gross retention compared to ion exchange systems. I am content this should not pose a significant safety concern, provided the waste EDI cells can be shown to be disposable. I have shared this concern with my radwaste colleagues during Step 4.

770 However, if not retained in the EDI units themselves, radioactivity must pass to the concentrated "*brine*" discharge. This is disposed to the Waste Water System (WWS) under normal conditions, which is not designed to operate with radioactive contamination. As described above the extent of this transfer is unknown. The BDS includes a radiation monitor on the reject stream which directs the reject flow to the Liquid Radwaste System (WLS) upon high activity detection. I am content with this approach, but this needs to be factored into the WLS design.

771 I also queried the potential for gas build-up in the EDI modules. Westinghouse makes reasonable arguments in this respect, taking credit for gas extraction in the boiling SG environment. I am satisfied by these arguments, but the design of AP1000 without a BDS flash vessel makes this more of a potential risk.

772 Unlike Ringhals the AP1000 design does not incorporate a final ‘polishing’ mixed bed, so I asked for a justification for this design choice. To date the evidence from Ringhals relies on direct conductivity measurements (Ref. 56), which are not sufficiently sensitive to determine impurity levels in the low μg kg^{-1} range. PWRs that operate with conventional ion-exchange clean-up of the steam generator blowdown typically replace the resins when sodium, chloride or sulphate impurity levels in the blowdown effluent exceed 1 to 2 μg kg^{-1}. These levels are at the limit of detection if direct conductivity measurements are used to determine their presence. Westinghouse does not consider that further downstream processing is justified based on the expected EDI outlet concentrations and consider that the specific BDS design of AP1000, which allows direct discharge to waste, transfer of BDS flow to one EDI, removal of some of the EDI cells from an individual unit or operation at reduced flow, offer suitable contingency in case of operational failures. The additional advantage of a downstream step would be in case of gross failure of all or part of an EDI unit. Based on the claimed outlet concentrations a small ion exchange bed would last many cycles before exhaustion and could be non-regenerable, but would provide a useful contingency. Overall, I consider that a fuller justification for excluding further downstream polishing should be provided once a final chemistry regime is available. I consider this to be an Assessment Finding, **AF-AP1000-RC-39**.

773 As an electrolytic process there is a possibility of applying too high a voltage to the EDI cells or operation at reduced flow compared to the applied voltage. Westinghouse provided a useful description of the controls in place for these faults, which is ultimately limited by the capacity of the voltage supply and flow sensors. Similarly, over pressure protection is provided in the EDI packages to limit the potential for membrane rupture at excessive pressure.

774 The main gap in the safety case provided by Westinghouse for the use of EDI is the compatibility of the technology with likely secondary chemistry conditions. Ringhals PWR operates under a high pH AVT regime with 8 - 10 mg kg^{-1} of ammonia and 100 μg kg^{-1} of hydrazine in the main feedwater. The operation of the EDI in the blowdown system has been safe and trouble free for five years (Ref. 56). In contrast AP1000 will also operate under AVT conditions; however the exact chemistry has not yet been defined and operation under the EPRI guidelines allows significant freedom in choosing a pH additive. As such the EDI needs to be clearly demonstrated to function with the amine chosen to control the secondary circuit pH. This was raised with Westinghouse during Step 4 and they have subsequently commissioned a series of tests into the compatibility of the EDI with three potential secondary coolant amine additives; ethanolamine, methoxypropylamine and morpholine. Testing is also underway on a SG polyacrylic acid dispersant, although its application is not within the design basis for AP1000. The intention is to add degradation products from the organic amines at some point during the testing to ensure no detrimental effects. Results from this testing were not available during the GDA assessment. I take comfort from the experience at Ringhals and consider that fundamentally the use of ammonia with EDI has been satisfactorily demonstrated. In the worst case this testing will place limitations on the potential chemistry regimes that can be used in AP1000. A demonstration of system operation with the chosen operating chemistry should be provided once a chemistry regime is developed. I consider this to be an Assessment Finding, **AF-AP1000-RC-40**.

775 If the EDI failed to achieve its claimed performance, the secondary circuit may operate with impurity levels just below the acceptable limits. This could impact on the frequency of corrosion damage, including tube rupture. Therefore, I believe that the safety case would benefit greatly from testing of the AP1000 EDI system under actual secondary chemistry conditions, in a similar manner to that undertaken at Ringhals. This would potentially resolve many of the concerns conclusively. Information may be available from other AP1000 plant operated before any UK AP1000. I consider this to be an Assessment Finding, **AF-AP1000-RC-41**.

776 Overall, while an EDI system has considerable prospective merits for clean-up of the steam generator blowdown its operation has yet to be demonstrated under the conditions it will operate under in an AP1000 reactor. While I am content that a suitable case has been made in this area for GDA, further work is required on this aspect of the design and I have identified a number of Assessment Findings that should be taken forward.

777 Many of the potential chemistries available to an AP1000 Licensee 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. The impact of these on the EDI units is part of the testing described above. 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_T within the secondary circuit in certain locations, although less so with amines than ammonia, and is relevant to the discussion of Flow Accelerated Corrosion (FAC) that follows below.

778 A further consideration in defining a suitable chemistry regime is to counter potential corrosion threats to the secondary circuit materials. This can be a complex area, with many materials and environments present around the secondary circuit as a whole and needs to consider a range of corrosion mechanisms such as general corrosion, Stress Corrosion Cracking (SCC) and FAC. An assessment of these effects needs to consider both the materials and the environments within the secondary circuit, as explicit in the optimisation suggested in both the "*chemistry manual*" (Ref. 25) and the EPRI guidelines (Ref. 16). As Westinghouse do not specify the chemistry for AP1000 it is not possible to complete such an assessment during GDA. The "*chemistry manual*" provides a reasonable overview of these aspects, while the referenced EPRI guidelines provide detailed technical background in this area to aid decision making by the Licensee. Chemistry impacts on FAC are considered further in Section 4.4.3.3.2.

779 Some commentary on the current AP1000 safety case in relation to the operating chemistry regime is provided below.

780 Despite improvements in the design of the SG internals or secondary feed systems, transport of iron to the SG is inevitable. A particular consequence of this iron transport can be sludge pile accumulation on the tubesheet and blockage of tube support plates, both of which can result in corrosion or flow restrictions. This can be reduced by maintaining a high pH_T with operating experience suggesting a low value seems to be a contributory factor. Experience from other PWRs reinforces this position. Westinghouse recommends that a minimum pH_{25} of 9.5 is maintained, which should reduce concerns of such effects by minimising general corrosion rates of carbon and low alloy steels in the feed system, although many plants operate at higher values than this.

781 Westinghouse has taken the positive step of removing copper sources from the AP1000 secondary circuit. The exclusion of copper and copper alloys, as well as being consistent with OEF, means that high pH regimes needed to mitigate copper alloy corrosion are not necessary. Westinghouse state that the only copper alloy (0.5Cu-Ni-Cr steel) in the main secondary circuit of AP1000 is part of the turbine pressure shell, although this alloy has been used previously and is not considered a significant source.

782 Westinghouse expect that AP1000 will operate with hydrazine addition to produce a reductive environment in the secondary circuit, at the EPRI levels of at least [redacted] $\mu g\ kg^{-1}$ or eight times the condensate oxygen level. Westinghouse claim that AP1000 has been designed to operate at $< 5\ \mu g\ kg^{-1}$ and $< 10\ \mu g\ kg^{-1}$ dissolved oxygen in the feedwater and condensate respectively. The Licensee will need to specify the precise hydrazine control bands. Hydrazine is universally used in commercial PWRs and the values suggested appear reasonable, albeit potentially higher than may be necessary in reality for AP1000 with a deaerator. While a small residual of oxygen is beneficial for FAC purposes it must be removed before entering the SG, where it can be highly corrosive.

783 A principal aim of secondary circuit chemistry, as acknowledged by Westinghouse, 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. The minimum pH_{25} of 9.5, reducing environment and impurity control arrangements should minimise risks from these mechanisms.

784 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. Westinghouse claim that the use of materials containing these species is strictly controlled during operations, and more likely during construction, commissioning or maintenance.

785 TQ-AP1000-813 (Ref. 8) queried several points related to lead contamination in AP1000. On the evidence presented I am satisfied that, provided appropriate controls are put in place by the Licensee of AP1000 during construction, commissioning, maintenance and operations, there is no reason to suggest that this should be a risk for AP1000. This is related to Assessment Finding **AF-AP1000-RC-04**.

786 A similar TQ was raised on reduced sulphur contamination. The response to TQ-AP1000-814 (Ref. 8) is comprehensive and concludes that; "*proper foreign material intrusion control, and ALARP chemistry practices relative to sulphate (and sulphur) and caustic ingress, material of the AP1000 secondary system are not expected to be challenged by normal perturbations of sulphur throughout the design life of the secondary system*". A number of design choices, including Inconel 690 tubing and non-continuous CPS make sulphur contamination issues less likely in AP1000.

787 In addition to the controls on impurities discussed above, Westinghouse also propose controls on chloride, sulphate, silica and oxygen in AP1000. The arguments and evidence presented for these species are reasonable and are consistent with operating plant experience.

788 While adherence to the EPRI chemistry guidelines should provide a general level of protection, a full and detailed justification for the operational chemistry needs to be provided at a later stage of licensing. The fact that this is not yet available is unsurprising given the current incomplete status of the design. This is related to Assessment Finding **AF-AP1000-RC-39**.

789 Overall, while I am satisfied that the chemistries suggested can be safely operated in AP1000 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-AP1000-RC-42**.

4.4.2.2.1 Fault conditions

790 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 fault chemistry conditions in the secondary circuit; however, the behaviour of the plant during a condenser leak can be considered a representative case.

791 The expected effect of a condenser leak in AP1000 is described in the response to RO-AP1000-55.A2 (Ref. 7). Westinghouse has considered leakage at various rates; below 0.227 litres hr^{-1} and up to 22.7 litres hr^{-1}, with the corrective action dependant upon the prevailing chemistry conditions. Westinghouse claim that a small condenser leak of 0.227 litres hr^{-1} or less can be tolerated while still maintaining the feedwater quality within the EPRI guidelines (Ref. 16). In order to do this the CPS is brought on-line (treating 33% flow, 66% by-passed) and the BDS letdown is increased to the maximum of 0.6% (if not already) or can be increased to 0.9%, with the blowdown discharged to the Waste Water System (WWS), bypassing the EDI units. Condenser leakage greater than 0.227 litres hr^{-1} requires the plant power level to be reduced to approximately 30% and the BDS along with the CPS is sufficient to support continued plant operation while the affected condenser water box is isolated and repaired. When the condenser repair is completed, the plant can return to normal operating conditions. The AP1000 CPS has ion exchange capacity to tolerate a "*faulted*" condenser leak of up to 22.7 litres hr^{-1} for up to 8 hours.

792 I queried the basis for these calculations in a technical meeting and Westinghouse provided the AP1000 estimate which supports these (Ref. 58). Summary information is also provided in the response to TQ-AP1000-1226 (Ref. 8). The calculation shows that the EPRI guideline values of [redacted] $\mu g\ kg^{-1}$ sodium and [redacted] $\mu g\ kg^{-1}$ chloride in the BDS blowdown may be exceeded. Notable assumptions are that the BDS operates at 0.9% blowdown and the influent leak contains 3,000 mg kg^{-1} NaCl (i.e. a 'brackish' water; seawater would be around 10 times higher). The determining factor in this case is the time taken to amine saturation of the cation resin as operation beyond this would result in higher CPS outlet concentrations of sodium. Based upon a nominal secondary chemistry using ethanolamine, Westinghouse estimate the bed will operate for around 8 to 10 days before exhaustion; a similar calculation for chloride would indicate several hundred days before exhaustion. The calculation to show the ability to tolerate a "*faulted*" leak of up to 22.7 litres hr^{-1} for up to 8 hours is not included, however based upon the same input assumptions this could be demonstrated. A design change to modify the CPS to have two 50% trains each with an upstream cation and polisher vessel is also discussed. This may also necessitate changes to the CPS materials to account for the acidic effluent from the upfront cation bed.

793 Overall, the calculation shows that it may not be possible to operate AP1000 for long periods with anything above very minor condenser leakage, without having to reduce power and fix the leak. This is routine practice in many PWRs, although such leaks are rare. This will need to be reviewed once a chemistry regime, a site specific cooling water source and operating limits and conditions are available, noting that I consider it unlikely

that such an arrangement at a seawater cooled plant would be satisfactory. I consider this to be an Assessment Finding, **AF-AP1000-RC-43**.

794 The responses to RO-AP1000-55.A2 (Ref. 7) and TQ-AP1000-1226 (Ref. 8) also include details of detection systems for condenser leakage. These are part of the Secondary Sampling System (SSS), which is assessed further in Section 4.4.4. The main features for mitigation of condenser leaks are continuous monitoring of cation conductivity and specific conductivity in the condenser hotwells (shells A, B, and C), at the condensate pump discharge, at the deaerator inlet, at the high pressure feedwater heater outlet and in the BDS lines. Continuous monitoring of sodium concentrations is provided at the same locations. Provisions exist for grab sampling of cation conductivity and sodium at the condenser tubesheets by grab sampling. These are reasonable arrangements and should allow for quick detection of impurity ingress.

795 As described in Section 4.4.2.1.4, Westinghouse claims several features of the AP1000 condenser design will limit the likelihood of condenser leaks.

796 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 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 and the time available for mitigation actions in a PWR is longer for a comparable ingress. TQ-AP1000-1233 (Ref. 8) queried if AP1000 had any automatic controls in case of a major condenser leak. The response indicates that, aside from MCR (Main Control Room) alarms triggered by high condensate conductivity or sodium, all mitigation actions for a major condenser leak (or other gross impurity ingress) are manually operated. This arrangement 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-AP1000-RC-44**.

4.4.2.3 Summary

797 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of secondary circuit materials, design and chemistry are:

- The basic approach for AP1000 secondary water chemistry and corrosion control is acceptable. The design, operation and operational chemistry regimes of the AP1000 secondary circuit are not yet defined, however, the information currently available does not suggest there would be any fundamental problems that would prevent safe operation of the secondary circuit of an AP1000. Definition, justification and optimisation of the chemistry would need to be undertaken by the Licensee during plant licensing.
- The design of the AP1000 secondary systems and components incorporate a number of features and design provisions which have been derived based upon OEF from US PWRs and elsewhere. Positive features include the addition of a deaerator, titanium 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 main difference in the AP1000 design, compared to current operating plants is the use of an EDI system instead of conventional ion exchange technology to purify

the steam generator blowdown. During normal operation, the EDI unit is the only means by which water in the secondary circuit will be purified. Westinghouse have provided reasonable arguments to cover my initial concerns with this system, although several areas still remain open for further work as Assessment Findings. The main gap in the case presented is the compatibility of the EDI system with the operational chemistry regime, although I note that a similar system has been used safely elsewhere under a different specific chemistry. It is also notable that while some limited laboratory testing has been undertaken, no testing has been performed under actual plant conditions for the specific AP1000 arrangement. I am content that these pose mainly commercial risks to the Licensee rather than safety concerns. Overall, I am content that an adequate case has been made for the use of this technology for GDA, provided the Assessment Findings are resolved.

- The secondary coolant chemistry regime, should be developed in conjunction with complete and cohesive analyses which optimise the operating regime, material choices, corrosion threats and plant design amongst others. This should form part of the safety case moving forward, but I am content this can be addressed at the site-specific stage .The chemistry optimisation and limits placed on some impurities should be developed once the site is chosen.
- 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.
- The Licensee will specify detailed procedures for the minimisation of contamination in the secondary circuit during construction, commissioning and maintenance operations as part of their normal business; see **AF-AP1000-RC-04.**

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

4.4.2.4 Assessment Findings

799 Based upon the assessment of secondary circuit materials, design and chemistry in AP1000 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-AP1000-RC-37 – *The Licensee shall produce evidence that the secondary cooling water source chemistry is within the design basis for the AP1000 'standard plant' assessed as part of GDA. This Assessment Finding should be completed before operation of the plant; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-38 – *The licensee shall update the safety case documentation to reflect the defined secondary chemistry regime. The Licensee shall ensure that chemistry parameters are consistent, wherever mentioned in safety documentation. This Assessment Finding should be completed before operation of the plant; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-39 – *The Licensee shall conduct a design review for post-electrodeionisation (EDI) treatment in the steam generator blowdown system, based upon the site operating chemistry. This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-40 – *The Licensee shall generate evidence for testing of the AP1000 electrodeionisation (EDI) system with the intended operating chemistry. This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-41 – *The Licensee shall generate evidence for the performance of the steam generator blowdown electrodeionisation (EDI) system under representative site operating conditions, including chemistry regime and at representative temperatures, or shall document the justification for why such evidence is not required to support the safety case. This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-42 – *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. 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-AP1000-RC-43 – *The Licensee shall review the condensate polishing system (CPS) performance requirements once an operating chemistry regime, cooling water source and limits and conditions are defined. Documentation for the review should include justification for the final performance specification. This Assessment Finding should be completed before plant operations, but should be considered during the design finalisation stage for the secondary circuit, as this may indicate design changes are necessary; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

AF-AP1000-RC-44 – *The Licensee shall review the requirements for automatic actions in case of significant ingress of impurities that could damage Steam Generator (SG) 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, but should be considered during the design finalisation stage for the secondary circuit, as this may indicate design changes are necessary; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*

4.4.2.5 GDA Issues

800 Based upon the assessment of secondary circuit materials, design and chemistry in AP1000 described in Section 4.4.2 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.4.3 Assessment – Materials Integrity and Corrosion

801 Integrity of the secondary system is an important consideration for secondary circuit chemistry; for many components an inadequate chemistry regime would result in rapid deterioration and potential for failure. 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.

802 The assessment during Step 4 sampled three 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 material choices throughout the main circuit for the major components.

4.4.3.1 Overview of Secondary Circuit Material Choices

803 In addition to detailed information in individual system SSDs, Westinghouse provided an overview of material selection for the AP1000 secondary systems in the response to RO-AP1000-55.A2 (Ref. 108). The response states that; "*The selection of AP1000 materials has been based upon industry guidance, operating experience, best practices, and lessons learned from operating plants. For materials selection and equipment design, sources such as ANSI standards, ASME code requirements and EPRI Guidelines have been utilized as industry standards for developing the AP1000 plant*." Key documents cited include Chapter 5 of EPRI NP-2294 (Ref. 59) and the URD (Ref. 38). Overall material requirements for AP1000 are detailed in "*Mechanical Design Criteria*" (Ref. 60) which is consistent with the above.

804 An overview of the main material choices made for the AP1000 secondary circuit is given below, as per the response to RO-AP1000-55.A2 and described in Section 4.4.2;

Component	**Recommended Material(s)**		**AP1000 Specified Material**
	EPRI NP-2294 (Ref. 59)	**EPRI URD (Ref. 38)**	
SG tubes	-	-	Thermally treated Inconel 690
TSPs	-	-	405 stainless steel
AVBs	-	-	405 stainless steel
SG shell	-	-	SA-508 low alloy steel
MSR tubes	Modified 409 or 439 Ferritic stainless steel	[redacted]	Ferritic stainless steel
MSR chevrons	-	[redacted]	Stainless steel
MSR shell	-	[redacted]	Carbon steel with stainless steel overlays or impingement plates
Condenser tubes	Stainless steel, AL-6X or	[redacted]	Titanium

Component	**Recommended Material(s)**		**AP1000 Specified Material**
	EPRI NP-2294 (Ref. 59)	**EPRI URD (Ref. 38)**	
	titanium depending upon water source	[redacted]	
Condenser shell	-	[redacted]	Carbon steel with impingement plates
Condenser tubesheets	-	[redacted]	Titanium clad carbon steel
FW heater tubes	Austenitic stainless steel	[redacted]	Type 439 Ferritic stainless steel
FW heater shells	-	-	Carbon steel with impingement plates
FW heater tubesheets	-	[redacted]	Carbon steel, Stainless steel clad for HP heaters
Piping	Carbon steel, Cr-Mo alloy steel or stainless steel	[redacted]	Carbon steel, Cr-Mo alloy steel or stainless steel
Steam lines	-	-	SA-335 grade P-11

Table 12: AP1000 Secondary Circuit Component Material Choices

805 The main material choices appear consistent with industry experience and OEF. The only significant difference from the recommendations made in the EPRI and URD documents is the use of Type 439 Ferritic stainless steel for the FW (FeedWater) heater tubes. I queried this choice with Westinghouse who believe this material is justified by industry experience, with it offering increased resistance to erosion-corrosion and increased hardness compared to austenitic steels. From a chemistry viewpoint this argument is reasonable.

4.4.3.2 Steam Generator Tube Integrity

806 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 SG tube integrity are assessed further below.

4.4.3.2.1 Denting Corrosion

807 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 led 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 inbetween the tube support holes and the secondary flow distribution holes causing distortions in the tube bundle to occur.

808 Based on the AP1000 design, this type of corrosion should be ruled out, due to:

- Replacement of carbon steel components 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.

809 I am content risks posed by this type of corrosion in AP1000 are ALARP.

4.4.3.2.2 Pitting Corrosion

810 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 and an oxidant (usually copper) and temperatures in excess of 150 °C to occur. 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.

811 Based on the AP1000 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.

812 I am content that risks posed by this type of corrosion in AP1000 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

813 Outer Diameter (OD) Intergranular Attack / Stress Corrosion Cracking (IGA/SCC) has been known to affect SG u-tubes under certain circumstances. Based upon the description of the relevant chemistry parameters given in Section 4.4.2.2, and the materials and design choice described in Section 4.4.2, I am content that AP1000 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

814 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 circuits 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 and accumulation in the secondary circuit and importantly in the SGs.

815 In reality, FAC susceptibility can be reduced using (or a combination of):

- Flow conditions.
- Materials selection (especially chromium content).
- Water chemistry.

816 During Step 3, Westinghouse provided some limited information on consideration given to FAC in AP1000. This suggested that consideration had been given to this degradation mechanism in the AP1000 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.

817 Westinghouse provided an overview of the AP1000 approach to FAC in the response to RO-AP1000-55.A2 (Ref. 108) and in numerous TQs during Step 4. The main arguments and evidence from these is summarised below. The overriding argument from Westinghouse is that they have designed AP1000 to be "*resistant*" to, but not "*immune*" from FAC, mainly due to economic considerations. This is a reasonable position, and is consistent with operating plants, but does put emphasis on assessing and ultimately monitoring and reviewing FAC during operations.

818 Westinghouse claim that FAC mitigation for AP1000 starts with piping design, with the "*AP1000 General Layout Criteria*", Ref. 61, imparting some requirements which act to minimise FAC susceptible geometries such as short radius bends and tee connections. This is a reasonable argument but has not been assessed in detail due to the complexity of the secondary systems.

819 During technical meetings, and as part of TQ-AP1000-1227 (Ref. 7) I asked Westinghouse to provide information on how FAC has been assessed in AP1000. Westinghouse confirmed that they have not assessed FAC in AP1000 as a whole; rather their approach is based on OEF and engineering judgement to inform which parts of the AP1000 design are potentially susceptible. An additional ("*informal*") review by US operators, for which there is no record or report available to ND, indicated only one area where a material change was required to a carbon steel piping section. This change was implemented. This is a reasonable basis for the status of the design at present, with some design and chemistry choices still to be decided. However, this is contrary to that stated in many of the SSDs, for example the FWS (Ref. 53) and CDS (Ref. 52), which state (or similar); "*FWS piping that is potentially susceptible to flow accelerated corrosion is evaluated by modelling the piping and predicting wear rates using the EPRI CHECWORKS computer program or equivalent software. In general, carbon steel piping is modelled when it transports water/steam at operating temperatures of 200°F* [93 °C] *or higher. If the predicted wear rate for a piping segment results in reaching minimum wall thickness prior to the end of plant design life, that segment is modified to achieve the design life. The principal methods for modifying a piping segment to reduce wear rates are changing the layout geometry, changing the piping size to reduce velocity, or*

changing to a more resistant piping material such as alloy steel. Piping segments that have the potential for significant wear over the life of the plant are also reviewed to ensure that the layout facilitates an inspection program." Clearly this is the aspiration for the design, but this has not yet been realised and appears more related to operating plants. This is related to Assessment Finding **AF-AP1000-RC-42**.

820 An important consideration for FAC mitigation at any reactor in operation is the definition of a suitable monitoring/surveillance programme, as required by SAP EAD.3 and EAD.4. This requires full details of the local chemistry and material choices and as such is not expected during GDA. I asked Westinghouse if any formal consideration had been given to such a scheme in AP1000, in terms of accessibility and practicality. This had not been considered. This should be defined and assessed once full details of the plant chemistry and materials are available and a subsequent assessment is complete. I consider this to be an Assessment Finding, **AF-AP1000-RC-45**.

4.4.3.3.1 Material Mitigation

821 Some information has been provided on the material choices for components in the AP1000 secondary circuit that are potentially subject to FAC. For example:

- Ferritic stainless steels for MSR tubes, stainless steel for MSR chevrons and chrome or stainless steel overlays for the MSR shell.
- 439 Ferritic stainless steel for feedheater tubing and corrosion resistant or stainless steel overlays and impingement plates to protect the heater shells.
- Use of SA-335 P-11 grade low alloy steel main steam lines.

822 All of these are very desirable measures from an 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.

823 The position regarding other pipework in AP1000 is less clear. The principal 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, including for replacement components in existing reactors. The piping in AP1000 can be produced from "*Carbon steel, Cr-Mo alloy steel or stainless steel*". These materials are highly sensitive, sensitive and insensitive to FAC respectively, dependant upon the local environment. There is no systematic assessment of FAC in AP1000 available so it is not possible to assess if the selection of these materials has been appropriate. This would also require an understanding of the plant chemistry, which is not yet sufficiently defined. Some general considerations defined by Westinghouse include:

- Low alloy or stainless steels for some secondary circuit piping.
- A corrosion allowance of 80 mils (2 mm) for FAC damage in defined areas of carbon steel pipework.

824 Information in the RO-AP1000-55.A2 response on FAC (Ref. 114), the US operator review and details in the various SSDs suggest Westinghouse to be a suitably competent and experienced organisation that understands and should be able to adequately complete this task. Unfortunately, it appears that much of this is done on an individual basis without any specific guidance and there is no analysis to confirm this. This is related to Assessment Findings **AF-AP1000-RC-42** and **AF-AP1000-RC-45**.

825 TQ-AP1000-812 (Ref. 8) queried what consideration had been given to specifying a low residual chromium content for the carbon steel section in AP1000. Westinghouse responded, and indicated in meetings, that this was considered to be a viable and appropriate method for AP1000 but would be a choice made by the Licensee. I consider this to be a potential safety benefit and this should be reviewed at a later stage of licensing. I consider this to be an Assessment Finding, **AF-AP1000-RC-46**.

826 Overall, much of the detailed information on the choice and location of materials used in AP1000 that are resistant to FAC is not currently available, nor has an assessment for FAC around the AP1000 secondary circuit been provided. This is not surprising given the current incomplete status of the design and corresponding chemistry regime for AP1000, but will need to be addressed at a later stage of licensing. The responses provided in this area give confidence that this can be done. The main outstanding decisions relate mainly to the specification of material and/or residual chromium levels in piping which continues to use carbon steels. Ideally, an assessment should be carried out to evaluate the risk of FAC, which is part of a wider assessment of the optimum chemistry and pH regime required for the UK AP1000 secondary circuit. FAC continues to be a major problem in existing PWRs, and in many circumstances can be essentially eliminated by appropriate design and material choices. Hence, it is very important to take this into consideration when specifying the plant materials and optimum secondary circuit chemistry and pH regime. The production of comprehensive site specific chemistry documentation that addresses the relationship of the secondary circuit design and operation to the secondary circuit chemistry and corrosion risks would be beneficial in this respect, in addition to assuring consistency. This is related to Assessment Finding **AF-AP1000-RC-04**.

4.4.3.3.2 Chemistry Mitigation

827 As described in Section 4.4.2.2, Westinghouse does not specify a secondary chemistry regime for AP1000 although they do acknowledge the impact of both pH_T and dissolved oxygen on FAC.

828 For FAC mitigation this means that the pH_T at various points around the circuit cannot be defined and the degree of protection offered by the chemistry cannot be assessed. A variety of amines could potentially be used, alone, or in combination with other amines or ammonia. There are advantages and disadvantages with any such regime, but broadly speaking it is desirable to operate with the highest possible pH_T around the secondary circuit (as allowed by other factors) in order to minimise iron transport and FAC of carbon steels. The suggested minimum feedwater pH_{25} for AP1000 is 9.5. Operation at higher than pH_{25} 10 is not uncommon in existing plants, and may be possible in AP1000 without copper alloys. From an FAC perspective a pH_{25} 9.5 may be less than optimum, particularly with respect to iron transport and its adequacy with respect to FAC depends on the pH additive partitioning and the extent and location of carbon steel around the secondary circuit, both of which are not yet fully known. For example operation with ammonia at pH_{25} 9.5 may not result in adequate protection of some liquid lines and drains due to preferential partitioning into the steam phases; an alternative, lower partitioning amine at the same pH_{25} 9.5 may offer substantially more protection in these areas. ‘Adequate’ in this context is subjective, as inadequacy does not mean the plant is unsafe, rather further attention may be needed in monitoring/surveillance in these areas.

829 Westinghouse expects AP1000 to operate to EPRI recommendations regarding oxygen control in the feedwater systems. 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. Westinghouse support the EPRI position in this

respect 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.

830 Overall, Westinghouse has not been able to demonstrate that the secondary chemistry provides the appropriate degree of protection for FAC. While the basic approach is reasonable, a more detailed assessment of the AP1000 specifically will be needed as licensing progresses, both to demonstrate control of the FAC risks and as an input into the development of a monitoring/surveillance scheme for AP1000. This is related to Assessment Findings **AF-AP1000-RC-42** and **AF-AP1000-RC-45**.

4.4.3.4 Summary

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

- While many of the detailed material choices for AP1000 have yet to be made, Westinghouse have provided information on the principal material choices for the secondary circuit which are in contact with the coolant. These appear reasonable and consistent with operating experience from the latest generation of PWRs.
- In terms of SG tube integrity, Westinghouse has provided reasonable arguments to support A1000 for GDA. Many of the historically encountered integrity problems will be eliminated or reduced in AP1000.
- For FAC, the overriding argument from Westinghouse is that they have designed AP1000 to be “*resistant*” to, but not “*immune*” from FAC, mainly due to economic considerations; this is a reasonable position. While many of the main component material choices suggest that AP1000 should be adequately protected, the selection of piping materials is less clear and may come down to a Licensee decision between protection and mitigation.
- The lack of a detailed operating chemistry regime means that such an assessment cannot be undertaken at this time, but will be required later in Licensing. I have raised Assessment Findings to support these areas. 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.

832 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 an AP1000. I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.4.3.5 Assessment Findings

833 Based upon the assessment of secondary circuit integrity in AP1000 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-AP1000-RC-45*** *– 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 operation of*

the plant but with sufficient time to allow design modifications if necessary; Target milestone – Hot Ops.

AF-AP1000-RC-46 *– The Licensee shall review requirements for a minimum chromium specification for carbon steel pipework in the secondary circuit and ensure the relevant pipework and fittings are procured to the specifications made. This Assessment Finding should be completed before relevant metal surfaces are delivered to site; Target milestone – Mechanical. Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*

4.4.3.6 GDA Issues

834 Based upon the assessment of secondary circuit integrity in AP1000 described in Section 4.4.3 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.4.4 Assessment – Sampling Systems

835 For very similar reasons to those given in Section 4.2.9, sampling of the secondary coolant in AP1000 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 AP1000 were selected as an area for assessment during GDA.

836 Assessment of the AP1000 secondary sampling capabilities began during Step 3 and continued during Step 4. The overall assessment objective was to demonstrate that the AP1000 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.

837 During Step 3 I noted a number of beneficial features had been incorporated into the design, such as effluent recycle provisions and ‘on-line’ measurements for a number of important secondary circuit parameters. Overall, at the end of Step 3, I was content with the general approach demonstrated for AP1000 in the design of the secondary sampling 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.

838 As for the primary side sampling systems, my assessment has been informed by a TSC contract, which specifically reviewed the AP1000 design in this area (Ref. 34).

4.4.4.1 Secondary Sampling System

839 The Secondary Sampling System (SSS) is noted in the PCSR (Ref. 1, Section 6.5.20) but no details are provided on the system as Westinghouse claim that the system is “*non-safety*”. The EDCD (Ref. 22) provides further limited information on the SSS in Section 9.3.4. The sampling locations are given in Tables 9.3.4-1 and 9.3.4-2 of the EDCD. Overall, details on the SSS are very limited within the Westinghouse safety submission. Further information was provided in the responses to RO-AP1000-55.A2 (Refs 108 and 115) and in the SSD (Ref. 62).

840 Westinghouse states that the function of the SSS is to establish and maintain control of secondary plant water chemistry. The SSS consists of equipment used to collect and analyse samples from specified secondary plant systems during all plant operational

modes including cold shutdown, wet layup, heat-up to low power operation and normal operations. Samples from selected secondary plant systems are conditioned and routed to the secondary sampling panels located within a dedicated turbine building sampling room. The main systems served include:

- Condensate.
- Main feedwater.
- Main steam.
- Steam Generators.

841 The SSS sample lines are made from stainless steel. Flow rates are selected to ensure turbulent sample flow (Reynolds number > 10,000) and deliver around 0.2 litres per minute to each on-line analyser.

842 The SSS includes a total of 11 main continuous sample streams from the secondary circuit. The main samples include:

- Condenser hotwells (shells A, B and C).
- HP feedwater heater outlet.
- BDS (one line per train).
- Main steam system (one line per steam pipe).
- Condensate pump discharge.
- Deaerator inlet.
- A shared common sample line which can be used for a number of sample points including; MSR heater drains, auxiliary steam system (feedwater, boiler drum, condensate), CPS outlet, heater drains, deaerator outlet and start-up feedwater

843 In addition grab sampling is available for a number of other secondary sample sources including; Condenser Tube Sheets (CDS), Condensate Storage Tank (CST), Demineralised Water Transfer and Storage System (DWS), Circulating Water System (CWS), Component Cooling Water System (CCS) and the Demineralised Water Treatment System (DTS). However these provisions are not part of the SSS.

844 In most cases the pressure of the system being sampled provides the driving force for sample flow. The condenser and LP feedwater heater samples do not have sufficient back pressure and are pumped to the SSS panel. Each of the three condenser shells includes a pump skid located at the corresponding condenser shell (A, B, or C), while the LP heater pumps are located in the corresponding panel. The sample panel reduces the sample temperature and pressure before the instruments and grab sampling using shell and tube heat exchangers, valves, pressure and flow controllers, and associated piping and instrumentation. Depending upon the sample source, up to two stages of cooling may be needed. The first stage is cooled by the Turbine Building Closed Cooling Water System (TCS) and the Central Chilled Water System (VWS), and then by the VWS alone. These are used to achieve a steady temperature of 25 °C.

845 Once conditioned, analysis is performed using continuous on-line analysers or laboratory analysis of grab samples. The on-line meters dedicated to each sample depend on the sample source, but include meters for dissolved oxygen, hydrazine, sodium, conductivity and pH. Ion chromatographs are also provided in the analyser racks to determine the anion, cation and metal concentrations in the BDS sample streams. Analyser filters are

provided to minimise plugging of the analysers with 140 μm filtering capacity. Usually, 40 μm or finer filtration is required to adequately protect on-line instrumentation, but this is a minor discrepancy. Data collected from the on-line analysis is displayed on the Plant Data Display and Processing System (DDS) and signals from continuous and selected on-line analysers are transmitted to the Plant Control System (PLS) for plant process monitoring. The data from the continuous and selected on-line analysers and the grab samples analysis are used to control secondary system water chemistry using the Turbine Island Chemical Feed System (CFS), see Section 4.4.2.1.7; these control the chemical feed for dissolved oxygen concentration and pH in the condensate, main feedwater and the SGs.

846 Sample flows from the sodium, hydrazine and ion chromatograph analysers are directed to the Waste Water System (WWS). These sample flows cannot be returned to the secondary systems due to possible contamination of chemical reagents or other impurities. All other sample flows are directed to a dedicated recovery tank for recycle to the main condenser, unless determined to be contaminated in which case the tank outlet is also directed to the WWS. The recovery tank level is controlled with an ultrasonic level detector which supplies a signal to open or close an exit valve and thus maintain a preset level. The recovery tank is vented to the atmosphere. A conductivity sensor is used to direct the recovery tank contents to either the condenser hotwell or the WWS. Oxygen ingress and non-condensable gases are controlled by injection of the water to the condenser at an elevation in the condenser where deaerating of the samples can be accomplished in the normal manner. The recovery tank has a volume of approximately 380 litres. The tank is constructed of stainless steel.

847 As described in Section 4.4.2.1.2, the AP1000 BDS is located within the turbine hall and as such Westinghouse has chosen to incorporate the BDS sample lines into the SSS. One sample line is taken from each SG outlet, downstream of the BDS cooler and upstream of the EDI units, and is directed to the SSS. Sampling after the EDI units is undertaken locally as a grab sample from the common BDS discharge header. In conventional ion exchange based BDS designs sampling is often undertaken at multiple points in the train. The EDI units in AP1000 have built-in dedicated conductivity meters to detect abnormal outputs, negating the requirement for grab sampling for the most part. Under normal operating conditions, with minimal primary to secondary leakage, this arrangement appears reasonable. In cases of enhanced leakage, such as during an SGTR, the BDS lines are automatically isolated on high activity detection. Westinghouse has incorporated a design change (Ref. 50) to allow continued sampling of the BDS in such circumstances. See also Section 4.2.9. The design change separates the BDS parts of the SSS to a separate panel, provides shielding for the resin columns and includes provisions to redirect the waste to the Liquid Radwaste System (WLS). The BDS sample panel will vent to the non-active Turbine Building Ventilation System (VTS). Even with this design change this would contaminate the BDS SSS equipment. Under such circumstances, routing the BDS samples without using the SSS equipment to the primary sampling laboratory or somewhere else outside the turbine building that is designated and designed for radioactive waste should be considered. I consider this to be an Assessment Finding, **AF-AP1000-RC-47**.

848 The build up of organic degradation products in the secondary coolant due to use of an organic amine conditioning agent leads to higher cation conductivity values that obscure detection of any ingress of strong acid anions, such as chloride and sulphate (See Section 4.4.2.2). I queried the consideration given to this in TQ-AP1000-808 (Ref. 8). The response provided feedback from US plants which dose amines. Westinghouse suggests an approach whereby increases over the ‘baseline’ BDS cation conductivity will be investigated by sampling to determine the cause of the increase. This approach is used

elsewhere. This assumes that the EDI units in AP1000 will remove the organic acids in a similar manner to conventional ion-exchange resins. This is part of the EDI testing currently underway by Westinghouse, which is as yet incomplete (also in Section 4.4.2.2) and should be reviewed once available, see also Assessment Finding **AF-AP1000-RC-41**. The addition of a deaerator in AP1000 may further reduce any impact of this effect. Provided the EDI does not alter the plant performance from conventional BDS systems, I am content that this effect can be adequately managed in AP1000 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-AP1000-RC-48**.

849 In response to TQ-AP1000-803 (Ref. 8) Westinghouse confirmed that the steam samples in AP1000 will be isokinetic. This is standard industry practice for sampling of main steam lines. It is notable that the SSD (Ref. 62) does not state this, and it is in fact listed as an "*open item*".

850 As described in Section 4.4.2, control of particulate and soluble iron is important. TQ-AP1000-634 (Ref. 8) queried how this would be achieved in AP1000. The response provides an overview of the approach suggested by Westinghouse for managing SG deposits in AP1000, including particulate iron from the feedwater, which is based upon both EPRI (Ref. 63) and Westinghouse documents (Ref. 64). The response also includes a general description of those features in the SSS 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. In general, the features for monitoring iron and particulates 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.

851 The sampling approach adopted within the AP1000 feedwater and steam systems is consistent with US sampling practices and can be considered adequate. However, specific practices adopted in European PWRs, and recommended in EPRI guidelines (Ref. 16), that may increase sample consistency and accuracy include temperature conditioning in close proximity to the sample point for all plant systems and the use of local sample panels and short sampling lines where practicable. These are particularly relevant to those samples which control the addition of hydrazine or are used to measure iron transport. Consideration should be given to these effects in the final SSS design. I consider this to be an Assessment Finding, **AF-AP1000-RC-49**.

852 Overall, the SSS design is considered to be satisfactory for the systems to be sampled and the measurements required in diagnosing plant chemistry problems. The secondary circuit as a whole has sufficient capabilities to sample the secondary systems and control plant chemistry.

4.4.4.2 Summary

853 Based upon the evidence presented during GDA, the main conclusion I draw for the secondary circuit sampling assessment of AP1000 is:

- The AP1000 secondary circuit sampling system has taken due account of operating experience and relevant good practice in its design. Many of the incorporated design features, as described above, will provide improvements to the sampling capabilities and chemistry control. I note a number of areas where further consideration should be given, but these are relatively minor. The main query relates to the continued sampling of the BDS letdown in the case of elevated primary to secondary side leakage. I have raised Assessment Findings in these areas.

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

4.4.4.3 Assessment Findings

855 Based upon the assessment of the secondary sampling systems in AP1000 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-AP1000-RC-47** – *The Licensee shall specify arrangements for sampling of the secondary side of the steam generators in the case of a tube rupture, including evidence that the specifications are appropriate. This Assessment Finding should be completed before nuclear operations, but should be considered during design finalisation to allow for any changes as necessary; Target milestone – Initial criticality*.
>
> **AF-AP1000-RC-48** – *The Licensee shall review the implications of 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-AP1000-RC-49** – *The Licensee shall review the design of the secondary sampling systems and consider reasonably practicable measures that could be taken to improve the sampling capabilities, especially for those samples which are used for automatic control of the plant chemistry. This Assessment Finding should be completed before hot operation of the secondary side of the plant, but should be considered during design finalisation to allow for any changes as necessary; Target milestone – Hot Ops.*

4.4.4.4 GDA Issues

856 Based upon the assessment of the secondary sampling systems in AP1000 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

857 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.

858 No details were provided in the safety case on this topic during Step 3, so all assessment has been undertaken during Step 4.

859 A number of TQs and ROA responses provided information on the AP1000 start-up and shutdown chemistry in the secondary circuit. TQ-AP1000-815 (Ref. 8) provides a general overview of the steps during such transients and the response (Ref. 108) to RO-AP1000-55.A2 (Ref. 7) provides information on the chemistry. These are the principal responses in this area, in addition to the detailed SSDs for the affected systems.

860 During a shutdown from normal operating conditions heat is first removed by the SGs, via steam dumping to the condenser, and subsequently by the RNS 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 (< 5% power) the SG feedwater supply is switched to the start-up part of the Main Feedwater System (FWS); refer to Section 4.4.2.1.5 for details of the FWS. The start-up feedwater section connects to the main FWS upstream of the HP feedwater heater trains and consists primarily of two 100 % feed pumps with connects to the Condensate Storage Tank (CST) for feed supply, See Section 4.4.2.1.8, and the start-up feedwater nozzles of the SGs for output. Cross connections allow the main feedwater pumps to supply start-up feedwater to the SGs (from the deaerator) via the start-up nozzle. Irrespective of whether the main or start-up pumps are used the feedwater is supplied via the start-up lines during low flow conditions to avoid thermal stresses on the main feed lines at low flows.

861 The assessment of the AP1000 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

862 The Steam Generator Blowdown System (BDS) is operated during the cool down in accordance with the desired cooling rate. The BDS is assessed in more detail in Section 4.4.2.1.2. Westinghouse claim that this allows for more stable feed control and more rapid cooling of the SG should maintenance be required. The Electrodeionisation (EDI) modules may be by-passed in these circumstances. The BDS is not used following the shutdown cooling phase, other than providing a recirculation and drain path and pipework connections to the SGs.

863 AP1000 includes a Condensate Polishing System (CPS) which can be used during shutdowns, although only if chemistry requirements dictate so. The CPS is described further in Section 4.4.2.1.3, and later in this section for start-up periods as this is the time when the CPS will be used most.

864 Chemical dosing of the various systems is fulfilled by the Turbine Island Chemical Feed System (CFS). Further assessment of the CFS is described in Section 4.4.2.1.7. Specific provisions exist for the addition of the plant pH control agent and oxygen scavenger to the start-up feedwater pump influent and to the BDS during SG wet lay-up and recirculation.

865 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. Westinghouse states in chapter 5 of the “*chemistry manual*” (Ref. 25) that the process for such

determinations in AP1000 will follow EPRI guidelines (Ref. 16) and as such sampling for sodium, aluminium, potassium, magnesium, calcium, chloride, fluoride, sulphate and silica during shutdowns will allow for estimations of pH and precipitate formation in the crevices of the SGs. Assessment of the AP1000 secondary circuit sampling system is given in Section 4.4.4. The HOR process can be aided by increasing the BDS flow to the highest rate allowable or flushing the SG with clean, deaerated make-up water to enhance removal. While not expressly considered by Westinghouse, both of these options appear to be available in the AP1000 design, notwithstanding the fact that the BDS flow is relatively low in AP1000 compared to other PWRs.

4.4.5.3 Storage and Lay-up

866 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 response to TQ-AP1000-815 (Ref. 8) Westinghouse only consider wet lay-up and suggest following the EPRI guidelines (Ref. 16) which involve the establishment and maintenance of a high pH and hydrazine environment for periods over 7 days. This is a reasonable argument; however consideration needs to be given to those occasions when a wet lay-up is no longer appropriate, for example during man-access, especially in relation to the effects of condensation which can be very detrimental due to pollution from airborne contaminants. I am satisfied that there are no fundamental differences in AP1000 in this regard, although this needs to be addressed by the Licensee in the safety case moving forward.

867 The BDS is used to control the SG chemistry during cold shutdown conditions; the BDS is aligned to the SG contents using the BDS recirculation/drain pump to recirculate the secondary water through the blowdown system and back to the steam generators via the start-up feedwater nozzle, by-passing the heat exchangers, the flow control valves and the EDI units. Control of pH and dissolved oxygen is provided by chemicals which are injected into the BDS recirculation flow from the CFS. Westinghouse recommends wet lay-up chemistry aligned to the EPRI guidelines (Ref. 16); the current EPRI practice is to recommend anionic impurity levels less than [redacted] mg kg^{-1}. I agree that the approach suggested for AP1000 seems reasonable.

4.4.5.4 Start-up Chemistry Control

868 During plant start-up, the reactor is brought from the cold shutdown condition to normal, no-load operating temperature and pressure, and subsequently to full power operation. Careful control of plant chemistry, especially impurity levels, is required during this phase. 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 deaerator or the CST, which should provide minimum levels of dissolved oxygen. The condenser vacuum and deaerator systems, in addition to hydrazine dosing, are used to remove remaining oxygen and non-condensable gases during heat up. Westinghouse recommend adherence to the EPRI values (Ref. 16) during power escalation, although these are part of the "*site specific optimisation*". This limits the dissolved oxygen to [redacted] and [redacted] $\mu g\ kg^{-1}$ before rising above 5% and 30% power respectively. While I am content that AP1000 could meet more restrictive specifications this may impact upon outage duration and further justification may be needed once precise procedures are developed for AP1000.

869 AP1000 features a staged approach to conditioning the secondary coolant before raising power, progressively removing impurities from the secondary circuit. Three recirculation paths back to the main condenser are provided within the condensate and feedwater systems to facilitate system cleanup and adjustment of water quality prior to initiating feed to the steam generators. These paths are:

- The hotwell recirculation path, part of the CDS, which circulates the condenser hotwell contents.
- The deaerator recirculation path, part of the FWS, builds on the hotwell recirculation path and also includes the LP feedwater plant and the deaerator tank.
- The long cycle recirculation path, which includes all of the main secondary feedwater plant until immediately before the SG nozzle.

870 In all cases the clean-up is provided by the CPS as the coolant exits the condenser. The main function of the CPS in these instances is to establish the required chemistry before power operation of the SGs. The CPS is capable of polishing 33% of the normal condensate flow, which is equivalent to 100% at start-up. During start-up, the concentration of suspended solids in the condensate may reach several mg kg^{-1} and the CPS will also act as a filter for this material. The AP1000 design uses a deep bed, mixed ion exchange resin CPS which is common to many PWRs and offers a suitable compromise of filtration and exchange efficiency. As the CPS media is not regenerated on site this reduces the potential for secondary circuit contamination by regenerant chemicals. The CPS system has no operational role during normal power operations, except during ‘abnormal chemistry’ conditions (for example operation with a small condenser leak). The performance of the CPS is assessed further in Section 4.4.2.2.1 during operations with condenser leakage which are more demanding than those expected during start-up and shutdown.

871 I am encouraged by the introduction of the CPS into the AP1000 design and the flexibility that the secondary circuit allows during start-up. I believe these features will offer advantages for impurity control during start-up periods; additionally I am satisfied that failure or unavailability of the CPS should not result in significant safety issues, merely delays to the start-up duration.

872 At some point during the start-up sequence the capacity of the CPS will be exceeded and the BDS must be brought into service. Initially, with the SGs at low pressure, the BDS flow is directed to the condenser for processing by the CPS by the BDS recirculation pump without passing through the EDI units. The flow is maintained at the maximum 0.6% during this period. As the plant progresses to full power operation, feedwater flows to the SGs increase, and eventually the CPS is taken out of service and the duty is taken up by the BDS once the SG pressure is high enough; the BDS flow will be maintained at a rate within the flow range although a lower rate may be acceptable for limited periods, if required to achieve the heat up rate. If the concentration of dissolved impurities is high the blowdown can be discharged to the waste water system. When the secondary cycle water chemistry is within acceptable levels, EDI demineralisation and recycling of the purified blowdown to the condenser hotwell proceeds as normal. No details are available at present on how the EDI units will operate at start-up, although provisions do exist in the design to allow discharge of the EDI effluents to waste. I am content with these arrangements.

4.4.5.5 Summary

873 The overall approach suggested by Westinghouse 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 licensing progresses. I am content that an adequate case has been made for GDA in this area.

874 Based upon the evidence presented during GDA, the main conclusions I draw for the secondary circuit start-up and shutdown assessment are:

- Westinghouse has presented an approach for start-up and shutdown chemistry in the secondary circuit of AP1000. A number of features of the AP1000 can be shown to have a positive effect on the ability to control plant chemistry during these transient periods.
- Post GDA fully developed start-up and shutdown procedures should be developed for the secondary circuit of AP1000, building upon the sound basis presented for GDA. These should include due consideration of related topics such as limits and conditions, as appropriate. This is part of Assessment Finding **AF-AP1000-RC-01.**

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

4.4.5.6 Assessment Findings

876 Based upon the assessment of secondary circuit start-up and shutdown chemistry in AP1000 described in Section 4.4.5 above, I have identified no Reactor Chemistry Assessment Findings in this area.

4.4.5.7 GDA Issues

877 Based upon the assessment of the secondary circuit start-up and shutdown chemistry in AP1000 described in Section 4.4.5 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.5 Ancillary Systems

878 In addition to the 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 systems sampled during GDA are discussed further in the following sections.

4.5.1 Assessment – Radwaste Systems

879 The design of AP1000 includes a number of provisions in order to reduce off-site releases in normal operation. An assessment of the AP1000 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 assess these complex systems. These include the systems for processing both gaseous and liquid wastes.

880 Due to the close links with other assessment areas for these systems, I have supported colleagues in ND and EA (Environment Agency) in their assessments during Step 4.

4.5.1.1 Gaseous Waste Processing Systems

881 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 CVS. 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.

882 The AP1000 features a Gaseous Radwaste System (WGS), as detailed in the PCSR (Ref. 1, Section 15.4.1) and EDCD (Ref. 22, Section 11.3). Further details are provided in the SSD (Ref. 89). The WGS collects the hydrogen bearing gaseous plant wastes from the connected systems and processes the radioactive component so as to minimize personnel exposure to radiation, and to control their release to the environment. AP1000 also includes a number of other ventilation systems, which treat and discharge potentially radioactive gas but these are not part of the WGS and are not assessed here. The WGS is located in the auxiliary building.

883 The WGS consists of pipe connections to the Liquid Radwaste System (WLS) degasifier and Reactor Coolant Drain Tank (RCDT). Gases exiting the connected systems are passed through a cooler, fed by the Chilled Water System (VWS), to condense any moisture which is subsequently removed in a moisture separator, returning the liquid phase to the WLS. The separated gas phase then passes through a guard and two operational charcoal delay beds before passing to the plant vent (VFS) for discharge. The system also includes provisions for oxygen monitoring and sampling of the exhaust gas both before and after delay in the charcoal beds. Flow through the system is provided by the pressure of the influent sources.

884 The design basis for the WGS is for operations leading up to a shutdown, when discharges will peak. During this time RCS dilution and CVS letdown rates increase as the primary coolant chemistry is controlled prior to entering a shutdown. It is assumed that the "*Technical Specification*" fuel defect level of 0.25% is present in the RCS, thus maximising the noble gas source term. The WGS is also designed to receive all of the potentially hydrogenated and radioactive gases produced during operation of the WLS. Westinghouse claim that, based on the maximum input gas volumes, the WGS is expected to operate approximately 70 hours per year but is designed to operate continuously if required. According to the SSD (Ref. 89), the main inputs are given as:

- RCS letdown, nominally for CVS letdown during shutdowns.
- RCDT venting, either due to tank high pressure or for flushing.

885 WGS influents are therefore hydrogen or nitrogen, or a mixture of the two. A major difference in the AP1000 WGS is the absence of a VCT input to the system. In other PWRs which have a VCT, unlike AP1000, the off-gas is routed through the gaseous waste system as it contains radiogases which collect in the VCT headspace. As the VCT is purged almost continuously to maintain the RCS hydrogen concentration this provides the major input flow. The AP1000 WGS was not increased in size from the original AP600 design, so the system flows in AP600 and AP1000 are comparable.

886 The first function of the WGS is to ensure that flammable or explosive hazards are controlled. As described above, the WGS influent streams will contain hydrogen, often in levels over that which, if mixed with air, could combust. A number of features are present in the WGS to counter this possibility. Primarily the WGS operates at a positive pressure (0.014 MPa) to prevent ingress of oxygen into the waste streams. Design features to prevent ignition include continuous oxygen monitoring, nitrogen purge connections, spark proof valves, electrical grounding, and isolation of the system discharge to prevent hydrogen build-up in the VFS exhaust duct on loss of ventilation flow. During operations a constant sample of gas is drawn off the main process flow for monitoring for hydrogen and oxygen content before being returned to the process. A high oxygen alarm stops the WLS vacuum pumps and injects nitrogen into the WGS inlet. The WGS also has provisions for taking grab samples of the gas streams. I consider that reasonable steps have been made in the design to control this hazard in AP1000. However, despite these provisions the tolerance of the WGS to explosive hazards should be reviewed, to determine if any further reasonably practicable measure could be taken to further reduce this risk and potential consequences. I consider this to be an Assessment Finding, **AF-AP1000-RC-50**.

887 The second main function of the WGS, conditioning of the gaseous waste before discharge is fulfilled by the carbon delay bed system. 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.

888 Westinghouse have calculated the hold-up times in the delay beds as 38.6 days decay for xenon isotopes and 2.2 days for krypton isotopes (Ref. 90). These calculations are based upon a constant WGS influent flow of 0.85 $m^3 hr^{-1}$, which is significantly above that predicted for the period of maximum usage during shutdowns. The maximum instantaneous flow can be above this value, with the WLS degasifier able to produce around 1 $m^3 hr^{-1}$ with an assumed primary coolant hydrogen concentration of 45 cc kg^{-1}, but such conditions are intermittent. Increasing the delay bed temperature (from 25 to 40 °C) decreases the retention times to 35.5 and 2 days. The pressuriser vent line modification, discussed in Section 4.2.2.3.3, (Ref. 30) has negligible impact on these calculations. Although Westinghouse claims that a single bed provides adequate performance, the same calculations show that the retention time is halved, meaning that releases would be larger, dependant upon the half-life of the isotope; for example ^{131}Xe releases would be around three times larger. The total mass of carbon in the delay beds in AP1000 is around 2,000 kg, which is small compared to comparably sized plants. However, as described a few paragraphs above in this section, the omission of a VCT removes much of the constant gas flow and hence less carbon is required. Water entrainment to the delay beds would impair the function of the system. This process is reversible by drying the beds and is avoided during operations by the guard bed, which is not credited. The carbon bed sizing appears reasonable given the flow constraints outlined above and it is considered unlikely that a delay time of less than 40 days for the limiting ^{131}Xe isotope would be achieved. A more rigorous assessment of the system performance when a fully developed outage schedule is prepared should be undertaken to confirm this. I consider this to be an Assessment Finding, **AF-AP1000-RC-51**.

889 Overall, the calculations for the WGS appear conservative. 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 WGS as part of GDA.

4.5.1.2 Liquid Waste Processing Systems

890 The AP1000 includes a dedicated system for the storage, treatment and monitoring of spent non-reusable liquid waste before it is discharged to the environment; the Liquid Radwaste System (WLS). In addition to the collection and disposal of radioactive liquid waste from the plant, the WLS includes a degasifier which can be lined up to the CVS to allow degasification of the primary coolant, mainly during shutdowns. This device is the primary means of removing dissolved hydrogen and fission product gases from the primary coolant during operation of the plant. See Section 4.2.2.

891 The AP1000 WLS is detailed in the PCSR (Ref. 1, Section 15.4.2) and EDCD (Ref. 22, Section 11.2). Further details are provided in the SSD (Ref. 91). The main processes which are used to condition the waste stream prior to discharge are degasification, filtration and demineralisation, with the treatment dependant on the waste type. A total of 15 tanks are part of the WLS design and include the RCDT, containment sump, auxiliary building sump, three effluent hold-up tanks, two waste tanks, one chemical waste tank and six monitoring tanks. With the exception of the RCDT and containment sump (which are in containment) and the monitor tanks (which are in the radwaste building) the WLS equipment is installed in the auxiliary building. The WLS equipment is made from stainless steel and fluoro-polymers are restricted in contact with primary coolant which may be returned to the RCS.

892 Preference is given to CVS letdown by the WLS, automatically isolating other inputs. An important operator action is to ensure that the effluent holdup tank which receives the reactor coolant is initially empty so that boron dilution or RCS contamination cannot occur, for those occasions when the coolant will be returned to the RCS.

893 Four main classes of waste are treated by the WLS, each with different chemical and radiochemical properties and each is treated differently depending upon the composition, although the following generally applies:

- RCS effluents (from the CVS, PSS, PXS, SFS and RNS) – degasification, filtration and demineralisation.
- Floor and equipment drains (mainly minor polluted primary coolant) – filtration and demineralisation.
- Detergent wastes – filtered, or treatment with “*mobile*” equipment if activity limits cannot be met.
- Chemical wastes – treatment with “*mobile*” equipment.

894 The storage tank capacity of the WLS for each waste class is different. RCS effluents have the largest capacity at around 270 m^3 (2 tanks at 106 m^3, 1 at 57 m^3). Each of the remaining tanks are 57 m^3 each, with the exception of the chemical waste tank which is 34 m^3 and the RCDT and sumps which are much smaller. Tanks have design features to minimise deposition or dead legs and allow recirculation of contents. Details of the volume of effluents expected to be treated by the WLS are subject to uncertainty as they depend heavily on plant operating parameters. Westinghouse have used OEF from US plants and have designed the WLS to provide a total storage capacity for over 40 days assuming the average daily liquid radwaste release rate is 8 m^3 per day (Section 3.4, Ref. 92). The storage period is reduced for operational transients associated with boron dilution and RCS heat-up following refuelling. Table 11.2-1 of the EDCD (Ref. 22) gives the input volumes for the various RCS effluent streams from CVS and PSS letdown as

equal to around 900 m^3 per year, or three RCS volumes, with two coming from CVS letdown. More detailed information is provided in the AP1000 Environmental Report (Table 3.4-1, Ref. 92). This is relevant to the discussion of tritium control given in Section 4.2.2. A notable assumption is that the AP1000 sampling activities will contribute less than 760 litres per day to the WLS input. This is a restriction on the plant design and is relevant to the discussion of the PSS in Section 4.2.9.2.3.

895 RCS effluents are processed through the degasifier, to remove dissolved hydrogen and fission gases to the WGS, before storage in the effluent tanks. Output from the RCDT is passed through a CCS cooled heat exchanger. The WLS degasifier is a single stage, stainless steel vacuum degasifier column. Influent is sprayed onto the top of a column of packing which breaks up and spreads the flow into a thin film as it cascades downward. Under vacuum the water boils and gases are removed to the WGS. The gas drawn off the degasifier vessel passes through a large diameter (0.9 m) mesh screen to trap any water droplets which are returned to the degasifier. The large screen area further helps to reduce water droplet entrainment to the WGS. Hydrogen is expected to be reduced by a factor of 40 assuming a 22.7 $m^3\ hr^{-1}$ flow rate at 54°C (i.e. to normally < 1 cc kg^{-1}). Hydrogen monitoring is provided in the effluent tank vents, with alarms at 25% of the flammability limit, with purging to the WGS possible if abnormal levels are detected. The contents of the effluent holdup tanks may be recirculated and sampled, recycled through the degasifier for further gas stripping, returned to the reactor coolant system via the CVS, discharged to a mobile treatment facility, processed through the ion exchangers or directed to the monitor tanks for discharge without treatment. Ion exchange processing is the normal route.

896 The AP1000 liquid radwaste system processes waste with an upstream filter followed by four ion exchange resin vessels in series. The vessels can in principle be filled with any media required for treatment, but the following is the AP1000 configuration specified for GDA. Any of these vessels can be manually bypassed and the order of the last two can be interchanged. The first vessel is somewhat different from the subsequent three and is not always used. As well as being larger (1.4 m^3), the top section of the bed is filled with activated carbon, to act as a filter. The bottom layer is a zeolite with high affinity for caesium and strontium radionuclides. The subsequent three vessels (0.85 m^3) are loaded with normal ion exchange resins (one cation bed and two mixed beds). Provisions for resin exchange and transfer are provided in the design. After purification the water passes through a further filter before entering a monitor tank. In the unlikely event that effluent still does not meet discharge levels it is recycled back to the corresponding effluent tank for a second treatment.

897 Westinghouse proposes the use of clinoptilolite for the zeolite component in the AP1000 WLS. This zeolite has been used previously in the UK nuclear industry at fuel reprocessing facilities for selective removal of caesium isotopes. It is understood to be used in a number of existing US plants. Westinghouse does not claim the decontamination factor of this material in mitigating radioactive plant discharges. However, this material is known to be very efficient at removal to an extent that care must be taken that the specific activity of the zeolite does not increase too much. Removing the zeolite out of the service vessel when the material is exhausted can be problematic. The coarse material is known to be friable and can break up into very fine particulates as it circulates through the spent resin transfer system. The fine particulates thus formed do not readily settle and are extremely difficult to dewater. Filtration immediately after the zeolite vessel should be considered to reduce the potential for fines transfer. Further justification for this treatment step will be required during licensing, if this media is

retained. This should include details of the effects of effluent chemistry on the media. I consider this to be an Assessment Finding, **AF-AP1000-RC-52**.

898 Floor and equipment drains are also processed using the filter and ion exchange systems. Chemical additives may be added to the waste tank before processing. Detergent and chemical wastes are not compatible with the ion exchange systems and are either simply filtered, disposed without treatment or transferred to "*mobile*" treatment facilities. Two connections for "*mobile*" equipment are available in the WLS, before the ion exchange vessels and at the outlet of the chemical waste tank. Arrangements for these activities are not within the scope of GDA; although it is notable that the WLS does not include the equipment necessary to process all of the AP1000 waste streams. Other plants operate evaporators or other treatment technology to deal with these 'difficult' waste streams.

899 For contaminated BDS processing and discharge, the operator aligns the BDS to the inlet of the selected waste holdup tank. The BDS waste is then processed in the same fashion as other radioactive wastes.

900 Samples are taken from local grab sample locations on the various tanks. No details are available on sampling provisions (for example; sample sink or filtered and vented enclosure), sample lines, precise locations, flowrates and effluent provisions. The sampling provisions need to be further justified when further details are available. I consider this to be an Assessment Finding, **AF-AP1000-RC-53**.

901 Further details should also be provided on:

- Filter monitoring for dose rate and pressure drop.
- Ion exchange media monitoring for dose rate and pressure drop.

Because inefficiency in these systems could increase radiological discharges or ORE, I consider this to be an Assessment Finding, **AF-AP1000-RC-54**.

902 Overall, The AP1000 WLS uses well proven techniques for chemical treatment of the liquid wastes. I am content with the design described from a Reactor Chemistry perspective, but note a number of areas where further information and evidence will be needed as licensing progresses.

4.5.1.3 Summary

903 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of Reactor Chemistry aspects of the radwaste systems in AP1000 are:

- The AP1000 radwaste systems for safely handling gaseous and liquid radioactive wastes are functionally very similar to many operating PWRs. The precise designs for AP1000 are somewhat different to other PWRs but the chemical processes and technology are well proven and should provide adequate controls. The impact of these systems on those they support appears to have been considered thoroughly by Westinghouse in the design.
- Further work is required in relation to these systems, once detailed operating procedures are available, but I have identified no fundamental safety concerns with the designs as presented. I have identified these areas as Assessment Findings.

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

4.5.1.4 Assessment Findings

905 Based upon the assessment of radwaste systems in AP1000 described in Section 4.5.1 above, I have identified the following Assessment Findings which need to be addressed, as normal regulatory business by a future Licensee, during the design, procurement, construction or commissioning phase of the new build project:

> ***AF-AP1000-RC-50*** *– The Licensee shall review the tolerance of the gaseous radwaste system (WGS) to explosive hazards and generate evidence that the specified flammable gas limits are appropriate. This Assessment Finding should be completed before the system is commissioned so that its performance can be verified; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.*
>
> ***AF-AP1000-RC-51*** *– The Licensee shall undertake a rigorous assessment of the gaseous radwaste system (WGS) performance when a fully developed outage schedule is prepared. This Assessment Finding should be completed before the system is commissioned so that its performance can be verified, but should be considered earlier; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*
>
> ***AF-AP1000-RC-52*** *– The Licensee shall conduct a review of the types of liquid waste ion exchange and absorbent media to be used in the liquid radwaste system (WLS). This will be based on developments in ion-exchange technology, estimated volumes and specific characteristics of the liquid radwaste to be processed. The review should also take account of ALARP considerations and provide evidence for the suitability of the chosen design. This Assessment Finding should be completed before radioactive waste is produced in the reactor; Target milestone – Initial criticality.*
>
> ***AF-AP1000-RC-53*** *– The Licensee shall generate evidence that the liquid radwaste system (WLS) sampling system is adequate. This Assessment Finding should be completed before the equipment monitoring radioactive waste is commissioned; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.*
>
> ***AF-AP1000-RC-54*** *– The Licensee shall generate evidence to demonstrate the adequacy of the arrangements for monitoring filter and ion exchange vessel pressure drops and dose rates in the liquid radwaste system (WLS). This Assessment Finding should be completed before radioactive waste is produced in the reactor, but should be considered beforehand to minimise any changes as necessary; Target milestone – Initial criticality.*

4.5.1.5 GDA Issues

906 Based upon the assessment of radwaste systems in AP1000 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

907 AP1000, 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 (CCS).

This system is described in the PCSR (Ref. 1, Section 6.5.5). The CCS is a closed loop cooling system that transfers heat from various plant components to the service water system (SWS) during normal phases of operation.

908 Detailed assessment of this system was not started During Step 3. During Step 4 the assessment of the CCS concentrated on the following aspects of the CCS design:

- Chemical conditioning regime; especially for the large range of corrosion mechanisms possible; general corrosion, localised corrosion (pitting, crevice corrosion, underdeposit), stress corrosion cracking (SCC), Microbiologically Influenced Corrosion (MIC) and Flow Accelerated Corrosion (FAC).
- Evidence regarding fouling and scale growth provisions.
- Chemistry control and addition provisions (e.g. sampling arrangements).
- Leaks into the CCS, especially from active sources (i.e. controls, mitigation, remedial actions), and leaks from the CCS, especially to sources where there is a risk of boron dilution or contamination with CCS conditioning agents.

909 The CCS cools a number of important components during normal reactor operations and shutdowns. During normal operation the CCS largest loads are from the Reactor Coolant Pumps (RCPs), Spent Fuel Pool Cooling System (SFS) heat exchangers, and Central Chilled Water System (VWS) high capacity water-cooled chillers. During plant shutdown this changes to the Normal Residual Heat Removal System (RNS) heat exchangers.

910 Further information on the CCS is provided in the SSD (Ref. 93). The AP1000 CCS consists of two separate trains, with each train including a pump, a heat exchanger (cooled by SWS), a vented surge tank and a single, shared chemical dosing tank. The CCS equipment is located within the turbine building, whereas the major users are distributed throughout the containment, turbine building and auxiliary building. Westinghouse claims that a single train is sufficient to provide the plant needs during normal operations, with the second train held in reserve. Both trains are required to achieve the normal shutdown; failure of a single train is still sufficient to cool the plant although the time is much increased. Connections allow either pump to use either heat exchanger. Component cooling water is distributed to the components by a single supply/return header arrangement. Components are grouped on branch lines according to their location in various areas of the plant; for example a single line enters containment and supplies the RCPs, the letdown heat exchanger, the PSS heat exchanger and the RCDT heat exchanger. Flow to each component is controlled manually by setting flow control valves and orifices.

911 Make-up to the CCS is provided from the DWS, into the surge tanks. Chemical dosing is manually performed by flushing chemicals into the system from the chemical dosing tank using the suction of the CCS pump. Sampling is performed locally from each CCS train, downstream of the CCS pumps.

912 The CCS pipework is made from carbon steel. The materials for the heat exchanger interfaces with the served systems is somewhat dependant upon site specific considerations, but will include copper, copper-alloys, stainless steel and potentially titanium for a seawater (or brackish water) cooled SWS. Towards the end of Step 4 it became apparent that the description of the SWS cooling provision, via two small cooling towers, was different to the information provided in the latest AP1000 Environment Report (Ref. 92) which described a system using once through sea water cooling. As with other ND assessments, I have based my assessment on the SWS described in the PCSR, using towers. This discrepancy needs to be corrected, as it potentially affects the

operational chemistry controls and limits for the CCS. This is related to Assessment Finding **AF-AP1000-RC-37**.

913 The PCSR contains no information on the CCS chemistry requirements. This is an omission from the safety case and needs to be rectified moving forward. I consider this to be an Assessment Finding, **AF-AP1000-RC-55**.

914 Westinghouse provided information on the CCS in response to RO-AP1000-55.A2 (Ref. 7). Additional information on the CCS chemistry requirements are provided in Chapter 6 of the “*chemistry manual*” (Ref. 25). As is common for other plant systems, Westinghouse do not specify a chemistry regime for the CCS in AP1000, instead referring to EPRI guidelines (Ref. 94) which expect the Licensee to perform a plant specific optimisation. These guidelines offer many possible treatment options, but essentially there is a requirement for up to four types of additive in addition to controls on impurity levels:

- Corrosion inhibitor.
- pH additive.
- Biocide.
- Fouling control.

915 Westinghouse has reviewed the EPRI guidelines and has further the potential corrosion inhibitors to nitrite, molybdate or hydrazine. This removes the possible use of chromate based inhibitors, which have known environmental impact. Of those selected by Westinghouse, only a regime based on hydrazine will offer suitable corrosion protection to the copper and copper-alloy components of the system. For a nitrite or molybdate regime an additional azole component will be required, with tolytriazole (TTA), benzotriazole (BZT) and mercaptobenzothiazole (MBT) being those highlighted by Westinghouse. The copper bearing components served are the Chilled Water System (VWS) chillers and the condensate (CDS) pump motors. pH control for nitrate or molybdate regimes uses either a buffer (such as sodium carbonate) or a strong alkali (such as sodium hydroxide). Hydrazine based programs can operate without pH additives or with an additional amine. Westinghouse leaves the choice of microbiological or fouling control agents to the Licensee, depending upon site specific requirements.

916 Westinghouse indicates the expected impurity levels in the CCS for AP1000 in the “*chemistry manual*”. These values are based on those recommended by EPRI (Ref. 94) so can be considered reasonable, but are notably higher than those imposed by Westinghouse historically for a nominally similar CCS system (EPRI, Ref. 94). The values for a hydrazine based programme are notably more restrictive, indicating that such a regime might not be suitable for a seawater cooled SWS. The allowable impurity levels will need to be justified once the system design is finalised and hence susceptibility to corrosion threats can be established. Similarly the susceptibility of the CCS to FAC should be assessed.

917 While Westinghouse has restricted the CCS chemistry, there is still much flexibility left to the Licensee and some information needed to define the precise regime is unknown at present, including materials of construction and SWS design. Westinghouse provides much useful information in the “*chemistry manual*” to aid decision making in this regard.

918 Despite these restrictions I am content that a suitable CCS chemistry could be defined and operated in AP1000 and the design should not be fundamentally different from other PWR plants in this respect; however this will need to be justified and reviewed once full details are available. This is part of Assessment Finding, **AF-AP1000-RC-55**.

919 TQ-AP1000-635 (Ref. 8) requested details of the CCS 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 CCS exist. The response to this TQ was included in the RO-AP1000-55.A2 (Ref. 7) response. This provided a description of the leakage sources to and from the CCS and the detection and mitigation approach.

920 The pressure of served systems is such that the CCS will mainly be leaked into, thus precluding the risk of boron dilution or contamination with CCS chemistry. Westinghouse indicate that only two sources of leakage from the CCS could occur; from the CCS heat exchangers to the SWS and from the CVS make-up pump miniflow heat exchanger. Detection would occur primarily through low level measurements in the CCS surge tank. Small, routine leakage and losses are made up automatically from the DWS.

921 A number of other served systems, principally those containing RCS coolant at high pressure will introduce active primary coolant into the CCS if leakage occurs. The principal risk of leakage into the CCS is from those sources with high flow rates at high pressure, which are those associated with the RCP external heat exchanger, CVS letdown heat exchanger and RNS heat exchanger. Detection of such leakage will be possible due to the CCS level measurements in the surge tank, via on-line activity monitoring, via CCS line flow measurements, or, in the case of the RCP heat exchanger, by abnormal temperature readings. In most cases the activity increase would be such that the on-line activity monitors would alarm within a few minutes triggering isolation of the source automatically, limiting any 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 CCS. In all these cases the ‘dilution’ of CCS chemistry would be relatively minor and would not cause a significant safety concern.

922 With the exception of the findings highlighted above, I am content that an adequate case has been presented for the AP1000 CCS for GDA from a Reactor Chemistry perspective, although further work is required in this area as the design progresses. The overall description of the control and management of leaks in the CCS appears reasonable.

4.5.2.1 Summary

923 Based upon the evidence presented during GDA, the main conclusion I draw for the assessment of the CCS in AP1000 are:

- Westinghouse has presented an adequate safety case in relation to chemistry consideration for the component cooling water system. This is based upon industry guidance for such systems, and the specifics of the AP1000 design.

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

4.5.2.2 Assessment Findings

925 Based upon the assessment of the CCS in AP1000 described in Section 4.5.2 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-AP1000-RC-55*** *– The Licensee shall include the safety aspects of the component cooling water system (CCS) 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

926 Based upon the assessment of the CCS in AP1000 described in Section 4.5.2 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.6 Accident Chemistry

927 The assessment of hazards 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.

928 The following sections summarize my assessment of the AP1000 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 AP1000 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 Westinghouse 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.

929 It is important to note that Westinghouse claims that severe accidents (i.e. those resulting in core damage) are "*virtually excluded*" by the AP1000 design and the design of AP1000 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

930 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.

931 AP1000 has been designed as a ‘passive’ plant whereby a number of the functions required in a post accident situation are provided by systems which do not need AC (Alternating Current) power inputs to function, instead relying on gravity draining, natural recirculation and other naturally occurring processes. These systems are described as part of the Passive Core Cooling System (PXS) and Passive Containment Cooling System (PCS). The safety functions provided by these systems are assessed elsewhere (Ref. 67), and the control of chemistry in these during normal operation was assessed in Section 4.2.8 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-Containment Refuelling 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 fill the reactor cooling annulus, flood the reactor cavity and could re-enter the core through a break.

932 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’. AP1000 is designed to retain the fuel material inside the reactor vessel even if it melts. This is known as In-Vessel Retention (IVR). To control releases in such an event, AP1000 is designed to:

- Provide and maintain a containment barrier, in the form of the containment building with a minimal leak rate.
- 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 hydrogen gas produced - in a controlled manner to avoid explosion.
- Condense and collect fission-products on the inside of the containment wall.
- Actuate a one-shot water spray within the containment building.
- Provide clean air for the operators in the Main Control Room.

933 The metal containment shell is designed to act as the final barrier to prevent the release of radioactive material to the environment. The metal containment shell can be cooled by air or by water draining under gravity over the outside. Steam that condenses inside the containment will collect radioactive particulates and transfer them down into the sumps via designed paths. The sumps are buffered with alkali to retain volatile iodine that drains with the particulates.

934 My assessment of accident chemistry spanned the full range of accidents that might occur in AP1000; 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. 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.

These are described in the following sections.

4.6.2 Assessment – Steam Generator Tube Rupture Events

4.6.2.1 SGTR Events in AP1000

935 The SG heat transfer tubes are effectively a barrier between the active primary circuit and the non-active secondary circuit of a PWR. The principal 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 (SGTR) 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.

936 Assessment of these events began during Step 3, and concentrated on gaining a general understanding of where chemistry was being applied by Westinghouse in the analysis. A significant conclusion from Step 3 was that the SGTR calculations for AP1000 had been performed by Westinghouse in order to show compliance with US NRC guidance. It was apparent from examining the Westinghouse radiological consequence assessment that the quoted consequences were unacceptably high (when compared to SAPs Target 4 limits, Ref. 3). This lead the ND fault studies inspectors to issue RO-AP1000-48.A1 (Ref. 7), which required Westinghouse to recalculate the consequence for design basis faults, including SGTR, using methods and assumptions consistent with relevant good practice in the UK.

937 A number of differences in the approach adopted for AP1000 compared to previous UK assessments were evident, and these were assessed further throughout Step 4, with the overall objective being to demonstrate that the treatment of chemistry during SGTR events in AP1000 was consistent and transparent and took adequate account of chemistry.

938 The Step 3 PCSR (Ref. 20) provided no details on the chemical assumptions used to derive the radiological consequences of the SGTR events. The Step 4 PCSR (Ref. 1, Section 5.3.5.8) again failed to provide any further details, referring to the EDCD (Ref. 22, Section 15.6.3) which, while providing a more detailed description of the accident sequence, does not indicate what chemistry effects were considered. This analysis considers a double ended rupture of a single tube coincident with a failed open Power Operated Relief Valve (PORV) (frequency 3.8 x 10^{-3} per year). Westinghouse 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. Radiological consequences for the accident are also presented in the EDCD (Ref. 22, Section 15.6.6.3).

939 Due to the lack of safety case information, I raised a number of detailed TQs with Westinghouse in this area (TQ-AP1000-595, 596, 597 and 598 (Ref. 8)). Westinghouse chose to integrate the responses to these TQs with the response to RO-AP1000-48.A1 (Ref. 121) for the most part. As such the RO response provided a revised analysis including details of the chemistry assumptions and formed the basis for the Step 4 assessment. SGTR faults were highlighted as the ‘test case’ for the overall response and

as such the analysis was provided to ND for assessment in July 2010. It should be noted that, in line with the Step 4 assessment plan (Ref. 5), my assessment did not consider other DBA sequences, such as LOCAs, which were also re-calculated as part of the response to RO-AP1000-48. The chemistry during these faults is different to that during an SGTR.

940 A TSC contract was undertaken on SGTR chemistry and produced two review reports; firstly to define ‘relevant good practice’ in iodine chemistry during SGTRs (Ref. 73) and then to review the specific treatment in AP1000 (Ref. 74). The results of these reviews are consistent and integrated with the assessment that follows.

941 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.

942 Chemistry is primarily concerned with the first of these, as the main chemistry consideration during an 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.

4.6.2.2 Fault sequences

943 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. 67). 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.

944 The AP1000 safety case does not consider multiple tube ruptures. In response to TQ-AP1000-819 (Ref. 8), Westinghouse argue 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 caused by earlier actuation of the primary side safety systems. The results in TQ-AP1000-819 (Ref. 8) do indeed show that the losses from the primary circuit were indeed lower than the single tube rupture considered for both 2 and 5 tube breaks, although it is notable that the break flow is higher in the earlier parts of the sequence with more broken tubes. The same argument is used to demonstrate that there is no chance of overfilling the SG.

945 TQ-AP1000-819 (Ref. 8) further queried whether the PCSR faults presented are bounding from the chemistry point of view. As described in Section 4.6.2.3 below, Westinghouse do not claim radiolytic oxidation of iodine in the primary circuit is inhibited during the fault, however they do claim that oxidation of iodine in the secondary circuit is prohibited. These claims are assessed in subsequent sections below. Note that these arguments are relevant to the RO-AP1000-48.A1 response and not the PCSR analysis.

946 A particular concern related to the possibility that SG dry-out could occur. The TQ-AP1000-819 response claims that, while the SG does boil down during the fault, dry-out conditions are not reached. The adequacy of claims made on preventing SG dry-out is assessed elsewhere (Ref. 67). Experimental evidence suggests that iodine releases from evaporating films can be significant. A notable assumption in this case is that it is the PRHR that assumes heat removal duties, stopping further steam releases. If dry-out cannot be discounted, the response regarding release is potentially unsatisfactory.

947 An important deficit in the case presented by Westinghouse is that the analysis of SGTR events stops once the pressure in the primary and secondary circuits are equalised and hence the break flow ceases. This occurs before the reactor is shutdown with the RCS and secondary sides still at elevated temperatures and pressures, above those at which the RNS can be actuated to complete the shutdown. This is not aligned with the ND definition of achieving ‘safe shutdown’ conditions for frequent faults. RO-AP1000-52 (Ref. 7) was raised with Westinghouse by ND fault studies inspectors to address this for SGTR faults, amongst others. The response suggested several routes by which this could be achieved for AP1000, at “*operators discretion*”, however several of these could potentially lead to additional releases which are not accounted for in the current analysis, including:

- Dumping steam from the affected SG to either the condenser or safety valves.
- Depressurise the RCS via the first stage ADS valves.
- Depressurise the affected SG via the BDS.

948 While the analysis presented for GDA uses the ‘anticipated’ sequence, these additional steps may be undertaken. Overall, I consider that Westinghouse have not presented evidence which shows that the analysis presented during GDA bounds these possible additional releases and have not considered the chemistry which occurs in the period between the end of the Westinghouse analysis and reaching safe shutdown (as defined in RO-AP1000-52). The use of ADS will contaminate the containment building and the BDS route is not safety qualified. Currently, Westinghouse claims the ADS to terminate an SGTR, but it is much more likely that a licensee would prefer to use the BDS. This will need consideration by the UK Licensee, once accident management procedures for AP1000 are finalised. I consider this to be an Assessment Finding, **AF-AP1000-RC-56**.

949 An additional suggestion was to use the ‘backfill’ method to depressurise the secondary side. This allows secondary coolant to enter the primary side. This method minimises radiological releases but the operator has to consider the adverse chemistry effects of secondary side water on the primary system components and the potential boron dilution. The response to RO-AP1000-52 (Ref. 157) provides further details on this operation, but I have not assessed the implication for this approach from a chemistry perspective. The ingress of unborated, treated water might have implications for primary circuit chemistry and I consider this to be an Assessment Finding, **AF-AP1000-RC-57**.

950 I particularly queried the role of the CVS systems during SGTR events in TQ-AP1000-598 (Ref. 8). The response referred to the RO-AP1000-52 response (Ref. 157), which now claims the use of the CVS as described further in Section 4.6.2.3, below. This is a new claim on the CVS system.

4.6.2.3 Source Terms

951 The source term used in the analysis of SGTR events presented in the PCSR (Ref. 1) is the standard AP1000 source term from the *“radiation manual”* (Ref. 31) with the assumption that the plant is operating at the maximum allowable concentrations from the

"*Technical specification*". These values are based upon operation with an assumed 0.25% fuel rod defect level, which is a significant conservatism based upon PWR operating experience and influences the fission product releases to the coolant. The corrosion product levels are based upon operating plant experience and are therefore independent of fuel defect levels, although no details are provided on the plants considered. This results in an initial primary coolant activity of 37 MBq kg^{-1} Dose Equivalent (DE) ^{131}I.

952 The response to RO-AP1000-48.A1 (Ref. 121) showed that the primary coolant activity level considered was too high, by a factor of around 4, to show compliance with Target 4 limits. This resulted in Westinghouse reducing the "*Technical specification"* limits by the same factor to an initial primary coolant activity of 9.3 MBq kg^{-1} DE ^{131}I.

953 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 considers two cases, the "*pre-accident*" and "*accident initiated*" cases. In the former an unspecified incident is assumed to increase the primary coolant activity prior to the SGTR event raising the concentration by a factor of 60. This results in a spike value of 2,220 MBq kg^{-1} DE ^{131}I. In the latter the SGTR is assumed to increase the iodine appearance rate by a factor of 335 for 8 hours. Westinghouse does not present figures for the maximum spike value in this case but based upon the data presented it can be estimated to be around 16,000 MBq kg^{-1} DE ^{131}I. It is notable that the Westinghouse model does not increase all of the activities during the spike; however this is expected to only have a negligible effect on the calculated consequences.

954 Similarly the response to RO-AP1000-48.A1 used the same spike models. However with the reduced primary coolant equilibrium activities the resultant spike values were consequently reduced by a factor of around four resulting in an activity of 550 MBq kg^{-1} DE ^{131}I for the pre-accident spike case.

955 Due to the way the transient is modelled in the Westinghouse analysis, the 'pre-accident' spike is not actually a spike but an analysis with an equilibrium coolant activity of 60 times the maximum equilibrium (i.e. there is no additional on-going input to the coolant from the fuel). This means that for around the first 160 minutes of the accident the 'pre-accident' case is more penalising, transferring more activity to the secondary coolant.

956 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 AP1000 bound these values. Earlier spiking should tend to be conservative, with higher volatility at higher temperatures. The EU (European Union) Utilities Requirement Document (URD) (Ref. 122) recommends values of 11 and 740 MBq kg^{-1} DE ^{131}I for equilibrium and spike iodine concentrations, in the absence of specific evaluations.

957 Irrespective of whether the PCSR or RO-AP1000-48.A1 values are used, the AP1000 source term appears to be very conservative. The high source terms have consequences for the chemistry considered, as described in Section 4.6.2.2. While it is expected that the AP1000 primary coolant activity levels should not raise to levels anywhere close to those used in the analysis no justification is given for the reduction, other than it allows Target 4 limits to be met. This approach could result in a Technical Specification that is close to a

legal limit. I consider that a UK Licensee would need to justify the appropriate source term for analysis of faults used to derive the Technical Specifications, although this is likely to result in reduced consequences compared to those presented by Westinghouse. I consider this to be an Assessment Finding, **AF-AP1000-RC-58**.

4.6.2.4 Chemistry Considerations

958 At a fundamental level the operating chemistry of AP1000 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 AP1000 (which is similar to comparable PWR) and the mass and chemistry of the make-up flows may mean that reducing conditions are removed by addition of dissolved oxygen.

959 In revising the SGTR dose analysis calculations for RO-AP1000-48.A1 Westinghouse incorporated elements of iodine chemistry defined in EUR 15615 (Ref. 75), which is a report summarising realistic methods for SGTR faults. This report was prepared shortly after the Sizewell B safety case in the UK and relies heavily on the methodologies used there. One of the main arguments used is that the primary circuit contains sufficient hydrogen, compared to oxygen (added from make-up sources) and iodine, to maintain the iodine in the primary coolant in a reduced and hence in-volatile state. As a result of radiolytic reactions occurring in the core, any oxygen introduced will combine stoichiometrically with hydrogen to form water. This process is favoured until all the hydrogen is consumed, in which case oxygen will be present. The presence of hydrogen ensures that reducing conditions are maintained with respect to iodine species, as hydrogen reacts with the oxidising OH radical which is the main route for the formation of oxidised forms of iodine. Westinghouse follows a similar argument in the RO-AP1000-48.A1 response (Ref. 121).

960 In AP1000, make-up flow to the primary circuit comes from the Core Make-up Tanks (CMT). Westinghouse claims that these are not a source of dissolved oxygen to the primary circuit during an SGTR. The CMTs are assessed in Section 4.2.8. The main source of oxygen ingress is from the CVS make-up flow, coming from the Boric Acid Storage Tank (BAST) which is assumed to be oxygenated. Westinghouse assumes the CVS is operational to “*maximise break flow*”. This is a very simplistic treatment and does not consider the actual oxygen ingress expected, although it may be conservative and is not a determining factor when consideration is given to the effects of the initial iodine concentration as discussed below.

961 The hydrogen concentration must be in sufficient excess of the iodide concentration in order to prevent radiolytic oxidation. The assumption used in EUR 15615, and hence RO-AP1000-48.A1, is that the iodine is reduced when the ratio of hydrogen to iodine is greater than 365,000. Using the minimum normal operating RCS concentration of 25 cc kg^{-1} for hydrogen it is shown that this criterion is no longer met when the primary coolant concentration of iodine exceeds 2.2×10^{-9} mol l^{-1} (around 160 MBq kg^{-1}). This is low compared to the primary coolant concentrations considered in the AP1000 source terms and means that reducing conditions are lost at time zero for the ‘pre-accident’ spike case and after only a few hundred seconds for the ‘accident initiated’ case. For simplicity Westinghouse therefore assumes no reduced iodine is present in the RCS for the duration of the SGTR transient.

962 In order to calculate the amount of iodine in the oxidised condition Westinghouse use data presented in EU 15615 (Figure 11) which gives the fraction oxidised as a function of temperature. At temperatures over 140 °C this is conservatively assumed to be taken as 0.1%, compared to the 0.07% presented. Westinghouse assumes that this fraction of the iodine that is transferred through the break is lost to the steam phase. This takes no account of potential scrubbing in the SG and is conservative. However, if the fault were to be analysed to safe shutdown conditions (as defined in RO-AP1000-52), the fraction of oxidized iodine at lower temperatures would be much higher. For example, the fraction of oxidized or volatile iodine at temperatures below 40°C is about 30%. It is therefore important that it can be confirmed that no releases occur at lower temperatures. This is related to Assessment Finding **AF-AP1000-RC-56**.

963 A more realistic assessment of the iodine concentration and oxygen ingress into the primary coolant may well show that reducing conditions are maintained. This would greatly reduce the iodine losses from this part of the accident.

964 Conditions in the secondary circuit are also important during the fault. Initially they will be alkaline reducing but this may change during the transient as primary coolant and emergency make-up water are introduced and steam is lost (along with volatile additions such as amines and hydrazine). Arguments are made in the response to RO-AP1000-48.A1 (Ref. 121) that no further oxidation of the iodine that is transferred from the primary circuit occurs. This is based on the claim that the SG is isolated following the accident, such that no feedwater additions are made. Although not stated, this implicitly assumes thermal and radiolytic oxidation in the secondary circuit is minimal, although no values are presented to substantiate this. 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. HI, for example, is volatile at higher SG temperatures. While oxygen may not be introduced from the secondary make-up sources, primary coolant is transferred through the break and this potentially contains oxygen. No values are presented to demonstrate that reducing conditions are maintained in the secondary side.

965 In addition to activity transferred to the secondary side from the break flow, activity may already be present in the SG coolant via ‘normal’ primary to secondary leakage. In the analysis presented Westinghouse assumes that this activity is at the maximum “*Technical specification”* limit, which is around 10% of the primary coolant concentrations. As with the primary circuit activities the values used here are conservative.

966 Overall, the arguments made for the secondary circuit iodine behaviour, as given above, appear overly simplistic but this is considered negligible compared to the assumptions made on the primary circuit side which dominates the released activity. These will need to be reviewed should less conservative assumptions be used for the primary side chemistry. This is related to Assessment Finding **AF-AP1000-RC-56**.

967 However, a significant assumption made in the RO-AP1000-48.A1 analysis for the secondary side is that “*Releases from the ruptured steam generator after break flow termination will not be considered*” due to this being “*unduly pessimistic*”. The EDCD analysis included steam dumping to atmosphere. As described in para. 947, Westinghouse proposes other methods to potentially achieve this (‘backfill’ or BDS let-down). After isolation, the ruptured SG slowly fills with contaminated primary coolant of high activity. This is a potentially significant assumption. It will be necessary to demonstrate that steam dumping can be avoided in all such circumstances for this assumption to be valid. This is related to Assessment Finding **AF-AP1000-RC-56**.

968 The second release mechanism given in para. 941, soluble species entrained in steam droplets, is accounted for by the entrainment factor used in the analysis. The PCSR originally used a value of 0.3%, consistent with the SG design value, while the RO-AP1000-48.A1 analysis uses 0.05% up to 3.83 hours into the transient and 0.4% afterwards. The former representing moisture carryover under recirculating conditions and the latter when the SG dryer level is reached (at 3.83 hours). These are taken from EUR 15165 (Ref. 75) and ultimately from Westinghouse model boiler tests (MB-2). These can be shown to be conservative values. It is notable that recirculating conditions are assumed even under reduced SG level. The MB-2 tests showed that low SG levels (under 50%) of the tube bundle resulted in non-recirculatory conditions.

969 The main influence for chemistry on the break location is whether mixing or flashing of the influent primary coolant occurs. The Westinghouse analysis assumes a submerged break which does not consider by-pass (flashing of primary coolant producing droplets of pure primary coolant). It could be shown that this is conservative given the assumed 0.1% volatile iodine release and the secondary coolant concentration.

970 The response also clarified that, as expected, 100% of noble gases are released during an SGTR.

971 Overall the case presented by Westinghouse in response to RO-AP1000-48.A1 includes the majority of the fundamental chemistry that I would expect to see in the safety case for SGTRs, although it some cases it has been simplified. The assumptions used appear to be very conservative for the most part, with the potential exception of not considering releases post break equalisation. These are subject to a finding in the Fault Studies report. I judge that if the post-equalisation releases were included the analysis would not meet Target 4 limits, although it could do with more realistic assumptions. I consider the cases presented are conservative and demonstrate that AP1000 is capable of meeting UK expectations for SGTR events. As it is currently presented I do not believe the analysis would be sufficient and there is insufficient clarity and consistency with the safety case made elsewhere (for example; regarding the achievement of safe shutdown conditions). I judge that this is a presentational issue rather than a fundamental shortfall in the design. This is related to Assessment Finding **AF-AP1000-RC-56**, requiring the Licensee to examine representative chemistry for the DBA faults analysed for the equivalent finding in the Fault Studies assessment.

4.6.2.5 Radiological Consequences

972 As with the fault sequence, assessment of the radiological consequences of SGTR faults is reported elsewhere (Ref. 67). As can be seen from the preceding sections the original analysis did not meet UK SAP Target 4 limits, while the later in response to RO-AP1000-48.A1 does. This change is primarily associated with the reduced source term.

4.6.2.6 Summary

973 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of SGTR events in AP1000 are:

- There are no novel chemistry differences in AP1000 compared with other PWRs, so there is no reason to consider different phenomena. 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.

- Westinghouse recalculated the consequences for SGTR events during Step 4. The original analysis presented did not meet SAP Target 4 limits. As part of this re-evaluation Westinghouse incorporated a more realistic model of the iodine chemistry that occurs during such faults; this is consistent with that previously used for UK Licensing. However, in order to show compliance with the SAP Target 4 limits, Westinghouse were forced to reduce the operating limit for iodine in the reactor coolant by a factor of four; no justification was given for this decrease. While the analysis can now demonstrably meet the appropriate SAP limits the large source term dominates the chemistry considerations applied, such that only wet oxidising SGTR faults are considered.
- I have noted a number of areas where the analysis does not meet my expectations or where further work is required and have raised these as Assessment Findings.
- The analysis presented by Westinghouse can be considered bounding with the assumptions used very conservative for the most part, with the potential exception of not taking the analysis through to safe shutdown. If releases during this period were to be included the analysis may again fail to meet Target 4 limits, although it could do so with more realistic assumptions used elsewhere. Overall, I judge that the case presented is conservative and demonstrates that AP1000 is capable of meeting UK expectations for SGTR events.
- While sufficient for GDA purposes, as it is currently presented I do not believe the analysis would be sufficient for Phase 2 due to a gap in the case made post-equalisation, and insufficient clarity and consistency with the safety case made elsewhere (for example; regarding the achievement of safe shutdown conditions). I judge that this is a presentational issue rather than a fundamental concern with the design.

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

4.6.2.7 Assessment Findings

975 Based upon the assessment of SGTR chemistry in AP1000 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-AP1000-RC-56 – *The Licensee shall analyse the chemistry of SGTR faults completely, to a safe shutdown state when all releases have effectively ceased. The analysis should consider all release paths using the most up to date knowledge of iodine chemistry, where appropriate. This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated, but should be considered prior to this to ensure SAP Target 4 limits can be met; Target milestone – Initial criticality.*

AF-AP1000-RC-57 – *The Licensee shall review use of the 'backfill' method for depressurisation in steam generator events, if this continues to be credited in the safety case. The review shall present evidence that safety implications of the backfill method, if used, have been considered. This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated; Target milestone – Initial criticality.*

> **AF-AP1000-RC-58** – *The Licensee shall consider a more appropriate source term for the analysis of steam generator tube rupture events and generate evidence that the source term is appropriate. Arbitrary reductions in source terms to meet limits are not appropriate without justification. This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated; Target milestone – Initial criticality.*

4.6.2.8 GDA Issues

976 Based upon the assessment of SGTR chemistry in AP1000 described in Section 4.6.2 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.6.3 Assessment – Hydrogen Control

4.6.3.1 Overview of Hydrogen Control in AP1000

977 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.

978 The potential for hydrogen build up in AP1000 under design basis or severe accident conditions comes from the possibility for water radiolysis, fuel cladding oxidation or metal structure corrosion, amongst others, which might produce large quantities of hydrogen. The AP1000 severe accident mitigation strategy is to contain molten core debris inside the RPV, thus precluding any ex-vessel phenomena if successful. This is described further in Section 4.6.5.

979 The AP1000 strategy for combustible gas control is described in the PCSR (Ref. 1, Section 6.5.2). The system is known as the Containment Hydrogen Control System (VLS). See also Ref. 95. The system is based upon the removal of hydrogen by reaction with oxygen in the containment atmosphere, ideally at low concentrations. The VLS consists of three main elements:

- Passive Autocatalytic Recombiners (PAR) for DBA events.
- Hydrogen igniters for severe accident events.
- Containment dome hydrogen sensors.

980 The PARs are designed to accommodate the rate and mass of hydrogen generated during a LOCA. PARs use catalytic material (Pd or Pt based) to oxidise hydrogen and, as the name suggests, are passive in nature requiring no external inputs to function (other than sufficient oxygen in the air). The AP1000 PAR design comprises a metal housing with a gas inlet at the bottom and a gas outlet at the top. The catalytic material is in the form of coated inert spheres or plates inside the housing through which the gas passes. The AP1000 has a total of two catalytic recombiners inside the containment, above the main operating floor. Westinghouse has arranged the PAR locations to account for the release locations during DBA events. Westinghouse claims that a single PAR is sufficient to meet the design requirements during DBA events.

981 The igniter assembly is a “*glow plug*” type which is designed to maintain a surface at over 900°C in the anticipated containment environment following a LOCA. The hot glow plug ignites hydrogen in the vicinity once the gas concentration reaches the flammability conditions. The igniters are mounted in an enclosure with a spray shield to protect the igniter from falling water drops from condensation of steam or operation of the containment spray. The hydrogen ignition subsystem consists of 64 hydrogen igniters distributed throughout the containment and rooms. Igniters are placed in the major regions of the containment where hydrogen may be released, through which it may flow, or where it may accumulate. The igniters are divided into two groups of 32, with each group claimed as sufficient to meet the plant needs. Power to each group can be provided by offsite power, on-site Class 2 stand-by diesels and 4 hours of igniter operation is provided by batteries. Assignment of igniters to each group is based on providing coverage for each compartment or area by at least one igniter from each group.

982 The VLS is an important system for the overall accident mitigation strategy for AP1000 due to claims made regarding:

- No containment failure from hydrogen if the hydrogen igniters are operational.
- The probability of containment failure due to diffusion flame is very small.
- No containment failure is predicted from deflagration.

983 Assessment of this system began during Step 3, but was very limited in nature, focussing on identifying the arguments and functionality for the AP1000 hydrogen control systems. I raised a number of TQs (522 to 527 and 1231, Ref. 8) and RO-AP1000-93 (Ref. 7) in conjunction with the severe accident inspector; the most relevant points from these responses are discussed in the assessment that follows. 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 my Reactor Chemistry assessment has been to determine that the rates of hydrogen production are reasonable and justified and that the chemical performance of the mitigation systems would meet the likely demands placed upon them.

984 My assessment has also been informed by a TSC contract which reviewed both relevant good practice (Ref. 124) and the AP1000 provisions (Ref. 125) for control of combustible gases.

4.6.3.2 Hydrogen Source Terms

985 When considering the generation of hydrogen during an accident scenario there are two principal aspects which relate directly to the design of any mitigation system; the mass and rate of hydrogen production, both 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 more challenging to the design.

986 For this reason it is common to classify the hydrogen source term in terms of ‘fast’ or ‘slow’ mechanisms. Fast hydrogen production mechanisms include zirconium oxidation, steel oxidation and 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. As is implicit, some of these mechanisms occur in-vessel with other ex-vessel. More than one mechanism could contribute to the production of hydrogen at any given time in a particular accident

sequence. Westinghouse considers all applicable mechanisms for DBA events but only the in-vessel phase mechanisms during severe accidents. The approach taken by Westinghouse for quantifying the source term in AP1000 is described below. Due to the nature of the AP1000 design these are discussed for DBA and severe accident events respectively.

4.6.3.2.1 Design Basis Events

987 The US approach to hydrogen generation during design basis accidents involves some limited core degradation. In this case there are two main factors which ultimately determine the amount of hydrogen produced during any accident. The amount (area) of hot zirconium and the availability of oxidant. 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 AP1000 Automatic Depressurisation System, if successful, will have already depressurised the RCS before this point thus clad ‘ballooning’ may cause local blockages and hence 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 may still include in-core surfaces. Slow sources may become more important in the long-term once the highly reactive zirconium is exhausted.

988 The DBA source term in AP1000 is calculated in ‘*AP1000 Containment Hydrogen Generation for DBA’s*’ (Ref. 76), referenced as part of the response to RO-AP1000-93.A1 (Ref. 123). This calculation evaluates the generation and build-up of hydrogen in the containment building following a DBA (LOCA) and confirms that the passive autocatalytic recombiners (PAR) limit the hydrogen concentration in the containment atmosphere to below allowable limits. Only the generation rate sections are discussed here with the PAR performance reviewed under Section 4.6.3.3. The calculation for the production of hydrogen inside containment following a loss of coolant accident (LOCA) is performed using the latest version of the GENNY computer code. This code is a Westinghouse derived code. The major sources of hydrogen considered in this analysis are given below, with the GENNY code only used to calculate the second, third and fourth of these with the others manually derived:

- Zirconium-water reaction.
- Corrosion of materials.
- Core solution radiolysis.
- Sump solution radiolysis.
- Initial hydrogen inventory in the RCS and containment.

989 The mass of hydrogen produced from the zirconium water reaction is calculated using a method that specifies a degree of zirconium oxidation as the higher of that calculated by the 10CFR50.46 (Ref. 78) Emergency Core Cooling System (ECCS) performance criteria assessment multiplied by a factor of 5 or a uniform depth of 0.0058 mm across the entire core. The 10CFR50.46 value is given in the EDCD as 0.2% (Ref. 1, Section 15.6.5), but is taken as 1% to bound future core designs and uncertainties. This analysis is assessed

in the Fault Studies report (Ref. 67). These two values are 5% and 0.54% respectively of the zirconium mass in the core, thus the 5% value is used. This results in a total zirconium hydrogen release of around 40 kg. This hydrogen is assumed to be released instantaneously. This method originates in a historic US regulatory requirement, see "*Regulatory Guide 1.7 Rev. 2, "Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident," November 1978*" (Ref. 77)), which may be out of date. I find that the Licensee should confirm that this method is still relevant and applicable to AP1000, and as such I consider this to be as Assessment Finding, **AF-AP1000-RC-59**.

990 The initial hydrogen inventory in the RCS is derived from the hydrogen added to the primary coolant during normal operation in order to control corrosion. This analysis assumes an initial RCS concentration of 50 cc kg^{-1}, which is the upper end of the EPRI operating range, plus the volume contained in the pressuriser steam space and an additional allowance for primary circuit leakage during normal operations (0.1% volume hydrogen in the containment free volume). This results in a hydrogen release, which is assumed to occur instantaneously, of around 8.5 kg.

991 The effects of radiolysis and corrosion produce similar amounts of hydrogen over the long term, with radiolysis dominating early in the analysis when decay power is higher. The radiolysis considers both the core and sump fluids, with assumptions on active materials in the two based upon US regulatory guide 1.7 (Ref. 77). This assumes 50% of the core inventory of halogens and 1% of other fission products are transferred to the sump, with significant absorption of beta and gamma energy by the intact core materials. Hydrogen generation rates decrease exponentially from above 10 g min^{-1} at 1 day after the accident to around 2.5 g min^{-1} after 30 days. A total inventory of around 160 kg is generated over the 30 days considered. Corrosion rates are determined by temperature, pH, surface areas and material. Temperature is derived from the EDCD analysis (Ref. 1) of MSLB (Main Steam Line Break), HL (Hot Leg) or CL (Cold Leg) LOCA with the worst case used at any given time step. Aluminium and zinc surfaces are considered to corrode according to rates derived at pH 9.5 and 11 respectively, across the entire available surface area. Hydrogen generation rates are generally over the range of 3 to 6 g min^{-1}, producing around 190 kg over the course of 30 days.

992 Organic materials such as cable insulation, epoxy paints, lubricating solutions, and gasket seals may produce combustible gases (primarily hydrogen or methane) due to radiolysis and corrosion. These are not considered in the AP1000 assessment. For most nuclear plants, the quantity of combustible gas that could be produced from organic materials inside containment is relatively small. This may add several 10s of kg of hydrogen over a 30 day period, but this is of the order of 5% compared to all the other sources.

993 These source terms appear to be conservative for use as a demonstration of the VLS performance under DBA events. It is notable that the assessment is based on US methodology. This will need to be revised for a UK Licensee and will need to be based on a more realistic assessment of the bounding accident sequence, although this will most likely reduce the source term. This is related to Assessment Finding, **AF-AP1000-RC-59**.

4.6.3.2.2 Severe Accident Events

994 For an accident to be considered "*severe*" significant fuel damage will have occurred, much beyond that seen in DBA events and eventually the core components, including the fuel, may 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 re-flooding will most likely result in a significant increase in the hydrogen generation due to an increase in steam availability.

995 Westinghouse claim that the VLS functions to limit the hydrogen concentration to less than 10% by volume inside containment following a severe accident event. The base assumption is that 100% of the fuel cladding reacts with water. This assumes that the most important parameter in the system design is the rate of hydrogen generation and it is recognised that certain accidents may actually generate more than this in totality. While this neglects longer term hydrogen production due to radiolysis and corrosion, as described for DBA events, the cladding reaction dominates the rate of hydrogen generation and it may not be possible to prevent the hydrogen concentration in the containment from exceeding the lower flammability limit of 4 percent volume, with the PARs having insufficient capacity to prevent this. The function of the VLS (or more specifically the igniters) in these cases is therefore to promote hydrogen burning as soon as possible after the lower flammability limit is reached thus minimising loads on the containment and the threat of Deflagration to Detonation Transition (DDT).

996 Hydrogen generation is described in the AP1000 Probabilistic Risk Assessment (PRA) (Ref. 79). The accident scenarios examined are based upon the results of the level 1 PRA analysis which indicated those scenarios with the highest probabilities of core damage and hence hydrogen generation. The main requirements for the in-vessel hydrogen analyses are to provide the sources of hydrogen, generation rates and release locations and associated steam for the assessment of the performance of the hydrogen management systems. A total of 25 accident scenarios are analysed for the PRA. These cases account for variations on the release rates, release locations and system availabilities. The scenarios examined include failure of gravity injection or recirculation, various LOCA states, vessel failure and variations in timings. Together these scenarios, and the variation of cases within them, cover the relevant parameters which will affect the hydrogen generation rate and release location and include cases with early and late re-flooding of the core, varying degrees of depressurisation and various release locations within containment. The analysis shows the importance of these parameters on the subsequent accident progression and gas mixing in containment. These aspects are assessed elsewhere (Ref. 80). The analysis does demonstrate the importance of the AP1000 Automatic Depressurisation System (ADS) to the design of the VLS, particularly the igniter locations, as the ADS stage 4 valves vent from the hot legs to the containment and provide a path of least resistance to release hydrogen as it is generated in the RCS.

997 In AP1000 the severe accident sources of hydrogen are calculated using the Modular Accident Analysis Programme (MAAP4). The use of MAAP4 is discussed further in Section 4.6.5.6. Westinghouse considers two sources of hydrogen during the in-vessel phase; zirconium and steel oxidation. 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 AP1000 MAAP4 analysis are believed to be the most consistent with knowledge in this area, so can be considered adequate.

998 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. Westinghouse use the Baker-Just model of oxidation to predict when the clad begins to collapse. This method predicts when the clad will collapse based on the temperature; a temperature of 2227°C will take several hours. Both of these factors would tend to produce conservative estimates for the VLS design basis.

999 Much greater uncertainties exist in the later stages of the MAAP4 predictions for AP1000. 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 AP1000 are broadly similar to other codes in this respect. Considering the limited contribution these aspects make to the overall hydrogen generation in the in-vessel phases these uncertainties appear tolerable, although a more robust case may be beneficial.

1000 During those scenarios which feature late reflooding the AP1000 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 Westinghouse optimises the time with an ordered core structure, thus maximising the hydrogen produced during any reflood. The best comparison for these effects comes from the Three Mile Island 2 (TMI-2) accident. MAAP4 predictions of the amount of hydrogen generated are generally understood to be reasonable, but the timings are subject to greater uncertainty.

1001 By way of illustration, Westinghouse predicts that the maximum in-vessel hydrogen produced varies from 279 to 588 kg with a peak instantaneous rate between 60 and 2,314 kg min^{-1} depending upon the particular accident scenario. It is expected that rates will be maximised closer to 100 kg min^{-1} for most sequences. The most penalising case presented in the PRA analysis is for a LB (Large Break) LOCA with accumulator failure (accident class 3BR) due to the rapid core uncovery and early re-flooding. Based upon the mass of cladding given in the EDCD (Ref. 22, Table 4.1-1) the total amount generable by all the zirconium in AP1000 is around 850 kg.

1002 As part of the overall Severe Accidents assessment of AP1000 (Ref. 80) ND commissioned independent TSC analysis of the most severe IVR (In-Vessel Retention) sequences using MELCOR (Ref. 228). While not specifically intended to determine the hydrogen generation they did produce results comparable to the Westinghouse MAAP analysis, and showed similar timings. Where differences exist these appeared to be related to artefacts in the codes or modelling.

1003 The cases considered for combustion analysis are assessed in Section 4.6.3.4.

1004 Overall the approach of basing the VLS design on the hydrogen generated by 100% cladding reaction is considered a reasonable methodology for demonstrating the suitability of the hydrogen control systems in AP1000. For the AP1000 design the rate and location of release are important determining parameters. The release rates predicted by MAAP4 can be considered conservative.

4.6.3.3 Chemistry of PARs

1005 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 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 an accident including steam, aerosols, fission products and sprays, as well as the containment temperatures and pressures, is a key claim in the AP1000 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.

1006 RO-AP1000-93 (Ref. 123) and TQ-AP1000-524 (Ref. 8) provided further details of the experimental validation of PARs. Westinghouse has confirmed that no testing has been undertaken on the specific AP1000 PARs. Information generated as part of EPRI research programmes are claimed to have provided design requirements for the AP1000 design. The most important reference is to tests conducted at the KALI-H_2 facility where NIS and AREVA PARs were tested under a range of test conditions (Ref. 81). It is not clear how the AP1000 PAR design relates to those tested as the Westinghouse design is not yet fixed, although the data for the "*NIS*" PARs appears to be used throughout. The performance of the AP1000 PARs needs to be confirmed to match that used in the modelling, once the design is finalised. I consider this to be an Assessment Finding, **AF-AP1000-RC-60**.

1007 I requested OEF for PARs in TQ-AP1000-526 and a comparison of the AP1000 PAR design to existing units (Ref. 8). As the AP1000 design is not yet fixed a comparison was not provided, although the main difference could potentially be the move away from catalytic plates and potential hydrophobic coatings as proposed for AP1000. Westinghouse stated that, as PARs are relatively new, OEF could not be provided although it was noted that the AP1000 approach of a PARs for DBA and Igniters for severe accident events is a new approach. More information was provided in the response to TQ-AP1000-488 (Ref. 8) and RO-AP1000-93 (Ref. 123). PARs have been installed in a number of US plants (for example, Indian Point) for hydrogen control in DBA events, although as the US NRC no longer mandates provisions for such hydrogen generation events only limited OEF is available. I know that many European plants use PARs, but Westinghouse have not cited any feedback from these plants. It appears Westinghouse have little experience in PAR performance in operational plants, instead reliant on experimental results which may not predict or consider effects seen in plants over many years, such as dust accumulation or corrosion of plates. This is a weakness in the case presented and is related to potential EMIT (Examination, Maintenance, Inspection and Testing) requirements, as discussed below. I consider this to be an Assessment Finding, **AF-AP1000-RC-61**.

1008 TQ-AP1000-525 (Ref. 8) requested information on the periodic testing of PARs to ensure that the functionality was retained. As the design is not yet fixed, the response provides little actual detailed information, such as performance criteria, testing method or replacement options. It does indicate that there is a requirement to test and maintain the PARs during each refuelling outage. Precautions must also be taken to prevent damage to the units during activities in containment, such as painting. This information should be reviewed once available and related to OEF from operational plants. This is related to Assessment Finding **AF-AP1000-RC-61**.

1009 As described in Section 4.6.3.2.1, the GENNY code is used to calculate the hydrogen generation and removal rate in containment for DBA events. The calculation uses a depletion rate equation for the PAR which calculates how much hydrogen is removed from the atmosphere based upon the temperature, pressure and gas concentrations. The basis for defining the hydrogen depletion rate is testing conducted by Battelle Frankfurt of both full-scale and segment model NIS passive autocatalytic recombiner units as described in the EPRI Report (Ref. 82).

1010 These tests included no significant levels of poisons. The original Westinghouse intent was to test the AP600 PARs in the presence of catalyst poisons which would be present following a DBA event that results in a source term as defined in NUREG 1465 (Ref. 83) up to the "*early in-vessel*" phase. Notably this would include 40% of the core halogen and 5% of the core tellurium inventory. Before this testing was undertaken the EPRI report "*Effects of Inhibitors and Poisons on the Performance of Passive Autocatalytic Recombiners PARs for Combustible Gas Control in ALWRs*" (Ref. 84) was published, reviewing literature and test data to estimate the effect of poisons in DBA events. This report concluded that even if the accident were to progress beyond a DBA to substantial in-vessel damage, PAR recombination capacity would be reduced by no more than 25%. Westinghouse incorporated this factor into the analysis conducted for AP1000, claiming that the 25% penalty remains conservative for the AP1000 DBA cases.

1011 Based upon the analysis presented in Ref. 76, the "*best estimate*" depletion rate (at 15 psi, 4 volume % hydrogen and 100°C) is around 10 kg hr^{-1} for each PAR. The analysis presents four cases which consider no PAR operation and "*best estimate*", "*lower boundary*", and "*worst case*" PAR performance. Best estimate and lower boundary are the uncertainty in the derived PAR depletion rate while the worst case includes degraded function at 75% efficiency with no operation until hydrogen reaches 3.5% volume (approximately 5 days after the event). Westinghouse recognises that the PARs will not operate at low hydrogen concentrations and have only a finite capacity; however for DBA events these considerations are not important. Similarly oxygen concentration will affect the PAR operation, with an oxygen starved gas resulting in a reduction in the PAR performance, but such conditions are not reached in DBA events. The analysis shows that it takes around 6 days to reach the lower 4% volume flammability limit and even with the worst case PAR performance this limit is not breached and the concentration is gradually reduced.

1012 While it is recognised that Westinghouse do not claim PARs during severe accident events, they will be present and may operate to some degree. For hydrogen removal this should be beneficial and they could also potentially act as igniters if the concentrations of hydrogen are high. For these reasons Westinghouse have not performed any analysis with PAR operation during severe accidents. I consider that this is an omission from the safety case and some limited analysis needs to be undertaken to provide confidence that the PARs have a benign effect in these cases. I consider this to be an Assessment Finding, **AF-AP1000-RC-62**.

1013 TQ-AP1000-1231 (Ref. 8) queried the potential for the PARs to affect fission product distribution in containment. During a severe accident iodine is the main concern and much effort is put into its management, including containment sprays and buffered sumps. The potential for PARs to interact with volatile iodine merits further scrutiny as this could influence the accident source term. Fission product control is described in more detail in Section 4.6.4. The response to TQ-AP1000-1231 states that this potential effect is not included in the AP1000 analysis, but can be considered negligible due to the predicted conditions during a severe accident. The low surface area of PARs in AP1000 combined with the conservative assumptions used in the analysis make the impact for AP1000 negligible. Westinghouse agree that the main parameters affecting this behaviour are CsI particle size and temperature; with igniter operation the MAAP4 analysis predicts little rise above 4% volume hydrogen in the containment meaning that the PAR temperatures remain relatively low. While some particles may be in the low range expected to be needed for this effect (<1 μm) it is expected that the distribution will be biased higher than this, further reducing the available population. I consider these to be reasonable arguments.

1014 I am content that an adequate case has been made for the PAR performance under DBA conditions. The design of the VLS, using PARs only during DBA events, means that the range of environments that the PARs operate under in AP1000 is relatively small. Only limited core degradation occurs and little fuel failure is expected, resulting in very little release of fission products to the containment. Steam has been demonstrated to inhibit the start-up rate of PARs and igniters, but to have little effect once they are operational. Thus the probability of device failure due to these reasons is low. The use of "*worst case*" assumptions, provision of effectively 100% redundancy and the availability of other hydrogen mitigation measure in the AP1000 design lends significant confidence that this aspect of the design is robust, provided adequate mixing of the containment is assured.

4.6.3.4 Combustion

1015 Unlike PARs there is no chemistry associated with operation of the igniters directly. They are merely a high temperature ignition source and the chemistry is associated with the combustion that occurs afterwards. Combustion in itself is not a problem provided the pressure and temperature loads this generates are within the capabilities of the design. While the ADS in AP1000 is primarily present to enable IVR and avoid high pressure phenomenon such as High-Pressure Melt Ejection (HPME), Direct Containment Heating (DCH) or basemat penetration, a secondary beneficial 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. Subsequent operation of the containment spray system may reduce the steam content making mixtures potentially combustible again.

1016 A number of the TQs (525, 526, Ref. 8) and the response to RO-AP1000-93 (Ref. 123) provide information on igniter OEF, design, performance and testing. Much of the information is related to containment mixing and flows and igniter locations, which is assessed elsewhere (Ref. 80).

1017 Igniters have been used in many operating plants in the US (for example, Catawba and DC Cook). It is notable that the OEF with "*glow plug*" type igniters, as proposed for AP1000, has been poor and has resulted in operational issues such as poor reliability and failures during testing. Westinghouse is investigating the use of a heating coil type igniter. From a chemistry point of view the type of device is somewhat irrelevant, however clearly if the latter is more reliable and overcomes the issues with glow plug devices its use should be considered. The alternative is to impose a more rigorous EMIT schedule on the devices. I consider that the safety case in this area should be reviewed when a design choice is finalised. This is related to Assessment Finding **AF-AP1000-RC-61**.

1018 The response to RO-AP1000-93 (Ref. 123) provides information on the igniter experimental programme which examined many aspects and phenomena of hydrogen combustion during severe accidents. Other test work is cited supported by Sandia

National Laboratories (SNL), US NRC and AREVA. The main reference is to NUREG/CR-5079 report, "*Experimental Results Pertaining to the Performance of Thermal Igniters*" (Ref. 85). This report provides insights to the AP1000 igniter locations and performance and combustion effects that could be expected. A comprehensive and large scale test programme was undertaken in the 1990's, including testing at ¼ scale. This provides confidence that igniters and their performance in PWR containments have been thoroughly investigated.

1019 Hydrogen-air-steam mixtures can burn in several ways dependant upon the conditions; diffusion flames, deflagrations and detonations. Diffusion flames (or stationary flames) result when hydrogen is released into an environment, creating a flammable plume. In AP1000 these are predicted at break locations or on the exit of the IRWST vents when the ADS valves operate. This is the least damaging combustion, provided the thermal loads do not result in harm. Deflagrations and detonations are rapid burning of pre-mixed gases above the flammability limits. The speed of the combustion is important in determining the consequences, with detonations often the quickest, most damaging and unpredictable. Thus, it is important that the transition from deflagration to detonation (DDT) is avoided.

1020 Westinghouse uses the MAAP4 code to model hydrogen behaviour in the containment, including its combustion, as described in the AP1000 PRA report (Ref. 79, Section 41) and Ref. 86. MAAP4 includes combustible gas burning models that examine the flammability, burn completeness and burning rates within each lumped parameter control volume in the containment. Hydrogen combustion is considered as diffusion flames when the igniters are operating. Overall, with the igniters operational the MAAP4 code predicts that hydrogen concentration is controlled and no global deflagration or conditions that will result in local or global DDT occur. The case presented in the PRA report is considered bounding by Westinghouse due to the rapid generation rate, 100% cladding oxidation and release into the lower compartments through the break location.

1021 The assessment of loads from a hydrogen burn (deflagration) is performed using the Adiabatic Isochoric Complete Combustion (AICC) approach, which is bounding for slow flames and involves only mass balances in its treatment of the burn chemistry. Quicker combustions can give higher transient pressures than those predicted by AICC. Westinghouse claim that the AICC pressure for a global deflagration of hydrogen from 100% cladding oxidation and 55% steam concentration does not exceed the structural limits of the containment pressure boundary.

1022 The probability of DDT is assessed, based upon the MAAP4 analysis, using the methodology developed by Sherman-Berman (Ref. 87). Essentially this method classifies the likelihood of DDT as a function of compartment geometry and conditions. Some of the more susceptible locations in AP1000 include the CMT room, valve vault and CVS room. The parameter used to define susceptibility to DDT is the "*detonation cell width*"; the larger this value, the less likely DDT. The analysis for AP1000 is actually that performed for AP600 (Ref. 88). The analysis presented in Ref. 86 provides some further, AP1000 specific, analysis of DDT. The sequences selected are based upon the level 1 PRA model for at-power and shutdown events assuming that all offsite power and standby diesel generators fail. The top 50 events for each state were determined and grouped into 7 and 5 representative cases respectively for at-power and shutdown. Detonation cell widths for the IRWST, PXS room, PXS and SG compartment are typically many orders of magnitude greater than the 1200 mm criteria, with only one case producing a value lower than this in the IRWST, but this still results in a low probability of DDT according to the methodology employed.

1023 In TQ-AP1000-1231 (Ref. 8), I queried the potential for the PARs or the igniters to increase the proportion of iodine in the gaseous form in containment. The effect of the PARs is discussed in para. 1013, while the potential effect of igniters is assessed in Section 4.6.4, as this is unlikely to affect operation of the igniters but may affect fission product control.

1024 The chemical treatment of combustion in AP1000 has a significant impact on flow distribution in the containment of AP1000. It is notable that the analysis presented for AP1000 is not very detailed in comparison with the OECD (Organisation for Economic Co-ordination and Development) report on fast combustion analyses (Ref. 126). To capture localised effects on combustion I consider that the Licensee should justify why more detailed analyses of flow and fast combustion in AP1000 is not required, and I consider this to be an Assessment Finding, **AF-AP1000-RC-63**. This action is also supported by the ND report on Severe Accidents and Containment (Ref. 80).

4.6.3.5 Summary

1025 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of hydrogen mitigation in accidents in AP1000 are:

- Westinghouse have justified the design of the AP1000 hydrogen control system, taking 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, location in relation to hydrogen releases and containment mixing behaviour and analysis of combustion hazards.
- The overall approach, using a mixture of PARs and igniters for design basis and severe accident events respectively, in addition to other features such as a manual containment vent and dedicated hydrogen sensors offer a suitable degree of confidence in the overall system design. The approach taken to calculate the system performance is conservative, using large source terms with significant margin over that expected in actual events.
- Westinghouse has made an adequate case to support use of PAR devices for design basis events. The impact of these during severe accidents and the operation and maintenance requirements require further development by a Licensee. I have raised Assessment Findings in these areas.
- The use of multiple, redundant igniters for larger hydrogen releases has been adequately demonstrated from a Reactor Chemistry perspective.
- The modelling approach regarding production and mixing of combustible gases in the containment is reasonable, using validated computer codes. The analysis regarding DDT and fast flames uses a dated methodology and the safety case would benefit from further work in this area using more advanced and modern analysis techniques. This would lend more confidence to the more penalising cases considered. I am satisfied this can be satisfactorily completed later in Licensing and is not a fundamental concern with the design.

1026 I judge that the claims, arguments and evidence as presented in this area appear reasonable and believe that Westinghouse have made an adequate case to support GDA.

4.6.3.6 Assessment Findings

1027 Based upon the assessment of hydrogen control in AP1000 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-AP1000-RC-59*** *– The Licensee shall review and document the hydrogen source term used in the design basis accident sequences which release hydrogen. The review should confirm that the methodology is relevant and applicable to AP1000. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*
>
> ***AF-AP1000-RC-60*** *– The Licensee shall confirm the performance of the as-installed Passive Autocatalytic Recombiners (PARs) is consistent with that used within the safety case analysis. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*
>
> ***AF-AP1000-RC-61*** *– The Licensee shall review and document the examination, maintenance, inspection and testing arrangements for the (Passive Autocatalytic Recombiners) PARs and hydrogen igniters. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*
>
> ***AF-AP1000-RC-62*** *– The Licensee shall consider any potential negative effects of Passive Autocatalytic Recombiners (PARs) in the analysis of accidents and update the Safety Case if necessary. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*
>
> ***AF-AP1000-RC-63*** *– The Licensee shall justify why more detailed analyses of flow and fast combustion in AP1000, in order to capture localised effects on combustion, is not required. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*

4.6.3.7 GDA Issues

1028 Based upon the assessment of hydrogen control in AP1000 described in Section 4.6.3 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.6.4 Assessment – Fission Product Control

1029 Public exposure to radiation in accidents is sensitive to the concentration and chemical form of the in-containment source term, which in turn depends on release fractions from the core, timings and the proportion of volatile components, such as iodine. The chemistry governing this process can be complex and affects the magnitude of the source term, which depends upon many factors including reaction rates, redox conditions, temperature and concentrations.

1030 Many of the SAPs (Ref. 3) provide guidance of relevance including EKP.2, ECV.3 and FA.15-17, 19 and 22 and the associated paragraphs. Of particular relevance is FA.19 on the assurance of validity of severe-accident analysis, which states;

1031 *“The data used in the analysis of safety-related aspects of plant performance should be shown to be valid for the circumstances by reference to established physical data, experiment or other appropriate means;*

> *558 Where uncertainty in the data exists, an appropriate safety margin should be provided.*
>
> *559 The limits of applicability of the available data should be identified and extrapolation beyond these limits should not be used unless justified."*

1032 ND (Ref. 97) provides more guidance relevant to severe accident analysis in general:

> *"This [risk assessment] will require quantitative understanding and modelling of the associated physical and chemical phenomena, and deterministic analyses of the progression of the faults chosen to represent each group. These analyses should be performed on a 'best-estimate' basis in order to provide an unbiased view of the associated risk, and to provide a realistic basis for the development of accident management strategies."*

1033 IAEA Safety Guide No. NS-G-1.10, Design of Reactor Containment Systems for Nuclear Power Plants (Ref. 12) contains many relevant sections related to the source terms, including:

> *"4.121. To assess the overall containment performance and in particular the measures for radionuclide management, the amount and isotopic composition of the radionuclides postulated to be released from the containment (the source term) should be assessed for the various accidents to be considered…"*
>
> *"4.122. The anticipated evolution of the physicochemical forms of the radionuclides in the containment should be assessed, with account taken of the latest knowledge (e.g. it is known that certain paints enhance the production of organic iodine).*
>
> *4.123. Once iodine is trapped in water pools inside the containment, it may revolatilize in the medium to long term if appropriate pH conditions are not maintained. It is therefore necessary to assess all conditions that could change the pH of the water pools during an accident and, if necessary, provide the necessary means to keep the water pools alkaline."*
>
> *"6.19. An assessment of possible radioactive releases from the containment should be made for selected severe accident sequences in order to identify any potential weaknesses with regard to the leaktightness of the containment and to determine ways to eliminate them. In this assessment, a best estimate approach should be used to evaluate possible leaks from the containment and the systems that may be unavailable for each specific sequence (such as the potential loss of containment isolation in the event of a plant power blackout)."*

1034 Overall, ND expects Westinghouse to justify the source terms used for AP1000 by demonstrating that they are appropriate and applicable to the specific design, its rated power and passive design features.

4.6.4.1 Overview of Fission Product Control in AP1000

1035 The AP1000 containment building structure is described in the PCSR (Ref. 1, Section 6.2). The reactor building comprises two concentric shells with the inner shell made of steel and the outer concrete. The shells are separated by a ventilated annular space. The inner containment building holds the Reactor Coolant System (RCS) and portions of associated structures, systems and components. AP1000 has a Passive Containment Cooling system (PCS), described in Section 4.2.8.

1036 Westinghouse claim the containment building of AP1000 can contain virtually all radioactive materials released in a severe accident, which involves the greatest release into the containment. This is principally because the containment has no vent and its leak rate would be less than 0.1% per day. Even at this rate, the release to the environment could be quite high without taking account of effects inside containment that collect and deposit materials to prevent their leakage. The factors of interest from a Reactor Chemistry perspective are:

- Mechanisms of fission-product removal inside the containment.
- Control of alkalinity of the IRWST and sumps.
- The in-containment Fire-Protection Spray system.

1037 During an accident which releases fission products into the containment atmosphere of AP1000 the PCS will operate. By keeping the metal containment shell cool, either by air flow alone or enhanced by evaporation of cooling water on the outside of the shell, Westinghouse have designed AP1000 to induce condensation on the inner surfaces. While this is primarily aimed at controlling the temperature and pressure in containment this also forms the main system for fission product control in AP1000. External cooling of the containment shell is intended to condense steam inside, causing aerosols to deposit passively and preventing their escape. The PCS operations can be seen below:

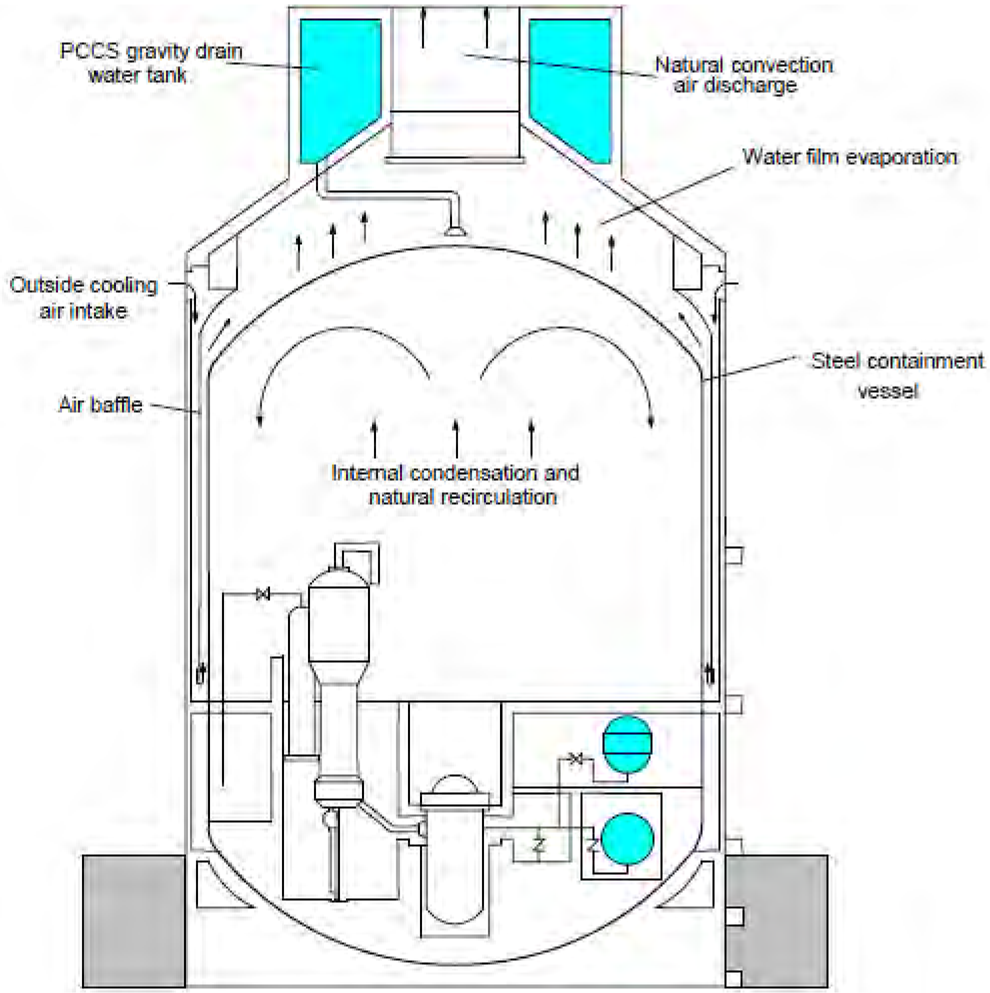

Figure 13: AP1000 Passive Containment Cooling System

1038 Fission products which are condensed onto the walls of the containment shell and internal structures are collected via a series of drains and sumps and returned to the IRWST. Under these circumstances the pH of the sumps and IRWST must be controlled in order to ensure that the pH remains slightly alkaline. The reasons for this are two-fold. Firstly iodine which is washed down with the condensate can undergo radiolytic reactions if the pH is not controlled and become re-volatilised into the containment atmosphere as a gaseous species. Secondly the returned water becomes contaminated with corrosive species, such as chloride, and the alkalisation of the sump ensures that subsequent corrosion, particularly SCC of stainless steels, is minimised preventing further failures or leaks in the long term. AP1000 features a system to buffer the sumps by dissolving granulated Tri-Sodium Phosphate (TSoP) in the water as part of the PXS.

1039 Unlike many PWRs, there is no dedicated recirculating spray system inside the AP1000 containment, although a Fire Protection System (FPS) spray may be used for up to 3 hours, if sufficient water is available. Like the PCS, the primary purpose of such a spray in other PWRs is to reduce the temperature and pressure in containment, by condensing steam, but this also has benefits in removing fission products to the sumps. Conversely, in AP1000 the spray is used only as an additional measure for fission product control. In many PWRs this spray is also buffered to a slightly alkaline pH and recirculated, but the FPS spray in AP1000 is not.

1040 The effectiveness of these systems depends on the extent and timing of the release into containment and the chemical and physical forms of the radioactive materials. Condensation is known to be an effective means of collecting solid and liquid aerosols but is much less effective for retaining nuclides which are volatile and in the gaseous form. Several radioactive materials like iodine, caesium, tellurium and silver can take gaseous forms depending on the chemistry. The most significant of these is iodine, principally ^{131}I due to its half-life and take-up by people. Other physical and chemical parameters of significance include the volumes and densities of aerosols and the ratio of hydrogen to steam. My assessment of fission product control in AP1000 concentrated on severe accident events as these release the largest amounts of fission products into the containment, but also considered events within the design basis such as LOCAs. An important factor in my assessment has been the potential production of gaseous radioiodine and the performance of the control systems in the longer term, potentially when the single use spray system had been used.

4.6.4.2 Source terms

1041 The safety submission by Westinghouse includes estimates for the quantities of fission products predicted to be released to the containment atmosphere from the core during accident scenarios. Ultimately, public exposure to radiation in accidents is sensitive to the concentration and chemical form of the in-containment source term, which in turn depends on release fractions from the core, timings and the proportion of volatile components, such as iodine. This chemistry can be complex and affects the magnitude of the source term depending upon many factors including reaction rates, redox conditions, temperature and concentrations.

1042 ND guidance (Refs 3 and 97) requires the assessment of the quantity of nuclear material that might be dispersed within the reactor and containment building, to ensure the design of mitigation systems and analysis of any off-site response are appropriate. The distribution of radioactive material also affects the quantities of radiation and heat, which the mitigation systems should withstand. The quantities of the fission-products, and other nuclides, their total radiation and heat dispersed in an accident are collectively known as the source-term.

1043 The main chemistry factors affecting the source-term are:

- The most important nuclides, in terms of doses from any PWR accident, are radioiodines. The chemistry of iodine is highly dependent on the alkalinity of the water in the coolant, sprays and sumps as well as the presence of organic material, such as paint. The control of radioiodine in accidents is made easier if it is converted to iodide form. This happens when elemental iodine comes into contact with alkalis like caesium or metallic vapours like silver. Molecular forms of iodine include elemental iodine itself and organic iodine, which are both volatile. Organic iodine is formed when iodine comes into contact with organic material, such a paints, oils or plastics, and is not convertible back to iodide form in an accident.
- The temperature reached in the accident affects the rates of release from the core of materials such as caesium, silver, molybdenum and tellurium. The release of gases such as krypton is quick and the release of materials like uranium is slow.
- The extent of reaction between the ZIRLO® cladding and the coolant and uranium dioxide fuel to produce uranium metal and hydrogen. This effect is known as the state of oxidation, or redox.

1044 The environmental releases in accidents which involve releases of fission products into the containment are basically predicted by integrating over time the activity remaining airborne in containment multiplied by the containment leak rate.

1045 My assessment of the source term was supported by TSC experts, reported in Ref. 172. Since no single Westinghouse report described all these phenomena, I raised actions 4 and 6 under RO-AP1000-55 (Ref. 7) asking Westinghouse to provide further justification and evidence for the design, and TQ-AP1000-877 (Ref. 8) to obtain further documentation. This section describes my assessment of the amount of nuclear material that may escape from damaged fuel and its chemistry within the containment building of AP1000.

4.6.4.2.1 Release Fractions and Timings

1046 The timing of events and the chemistry of radioactive products are highly dependent on the design of the plant and on the accident sequence itself. Therefore it is normal practice for the analysis of such events to define decoupling parameters that are recognized by industry and regulators, such as NUREG-1465 (Ref. 83) used by US NRC, for the source terms that may arise. These are usually defined as percentages for each of the radioactive elements in the core, with timings and variations for the type of reactor and degree of progression of the accident. It is common to group elements together where they have similar properties, such as volatility or solubility, which influence their behaviour in the containment environment. The amount of release of a particular species over time is known as the "*release fraction*".

1047 The release of iodine and caesium from the fuel-cladding gap is important at early times in a severe accident. Caesium iodide forms an aerosol but iodine also has more volatile forms and also may react with silver from the control-rods.

1048 I raised RO-AP1000-55.A6 (Ref. 7) to obtain justification for the adequacy of the fission product control systems in AP1000. The Westinghouse response (Ref. 149), received in September 2010, summarises the use made by Westinghouse of the release fractions defined in NUREG-1465, ‘Accident Source Terms for Light-Water Nuclear Power Plants’, as input to more detailed calculations in Refs 173, 174 and 180. NUREG-1465 provides “*realistic estimates of the "source term" release into containment, in terms of timing, nuclide types, quantities, and chemical form, given a severe core-melt accident”.* The NUREG-1465 recommended release into containment for a PWR can be summarised as below, which shows the percentage of total core inventory released for each nuclide grouping;

		Gap release	**Early In-vessel**	**Ex-vessel**	**Late In-vessel**	**Total**
Duration / hrs	-	0.5	1.3	2	10	13.8
Noble gases	Xe, Kr	5	95	0	0	100
Halogens	I, Br	5	35	25	10	75
Alkali metals	Cs, Rb	5	25	35	10	75
Tellurium group	Te, Sb, Se	0	5	25	0.5	30.5
Barium, strontium	Ba, Sr	0	2	10	0	12
Noble metals	Ru, Rh, Pd, Mo, Tc, Co	0	0.25	0.25	0	0.5
Cerium group	Ce, Pu, Np	0	0.05	0.5	0	0.55
Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	0	0.02	0.5	0	0.52

Table 13: NUREG-1465 Recommended Release Fractions

1049 The phases of the accident considered in NUREG-1465 can be defined as:

- Gap release – This phase involves the release of that radioactivity that has collected in the gap between the fuel pellet and cladding.
- Early In-vessel – During the early in-vessel release phase, the fuel as well as other structural materials in the core reach sufficiently high temperatures that the reactor core geometry is no longer maintained and fuel and other materials melt and relocate to the bottom of the reactor pressure vessel.
- Ex-vessel – The ex-vessel release phase begins when molten core debris exits the reactor pressure vessel and ends when the debris has cooled sufficiently that significant quantities of fission products are no longer being released.
- Late In-vessel – The late in-vessel release phase commences at vessel breach and proceeds simultaneously with the occurrence of the ex-vessel phase.

1050 At the time of preparation of NUREG-1465 In-vessel Retention (IVR) of molten core material during a severe accident, as intended in AP1000, was not applied in any US PWRs. However, the NUREG guide states; “*While the "passive" plants are generally similar to present LWRs, they are expected to have somewhat lower core power densities* *than those of current LWRs … despite the lack of specific accident sequence information for these designs, the in-containment accident source terms provided … may be considered generally applicable to the "passive" designs*." NUREG-1465 does also go on to state that; "*It is emphasized that the release fractions for the source terms presented in this report are intended to be representative or typical, rather than conservative or bounding values, of those associated with a low pressure core-melt accident, except for the initial appearance of fission products from failed fuel, which was chosen conservatively. The release fractions are not intended to envelope all potential severe accident sequences, nor to represent any single sequence*."

1051 In summary Westinghouse has chosen to apply some of the NUREG-1465 recommended release fractions, with differing timings, by assuming that all releases from the core stop after 1.8 - 2.0 hours when 40% of iodine and 30% of the alkalis have been released to the containment (i.e. Westinghouse have summed the 'Gap release' and 'Early In-vessel' phases of NUREG-1465). However, the NUREG guide also recommends a further 35 and 45% release for the halogens and alkalis respectively after this period, including a 10% release fraction from the 'Late In-vessel' phase, which was not used by Westinghouse, despite the relatively high core power.

1052 A recent published study using the MELCOR code concluded that the release-rates and fractions recommended by NUREG-1465 may be pessimistic by a factor of around two (Refs 153 and 227). Westinghouse has used around 50% of the total NUREG-1465 source term in their calculations.

1053 The source-term used by Westinghouse begins after 25 minutes and finishes within 2 hours. The ten-hour in-vessel release of a further 10% for iodine, recommended by NUREG-1465, was not used for AP1000 and the release fractions used by Westinghouse seem to apply to solid fuel material.

1054 The Westinghouse response to RO-AP1000-55.A6 (Ref. 149) appeared to claim that filtration of fission product aerosol by the leakage paths from the containment as a means of controlling the release, in preference to the use of sprays. Their case is described in more detail below, but I wrote to Westinghouse (Ref. 177) and queried this approach, partly because it double-counted the containment structure (once for pressure-retention and again for filtration). My letter also queried why internal spray recirculation was not reasonably practicable. On 27 September 2011, I also raised TQ-AP1000-1047, 1048, 1049, 1052, 1053 and 1054 (Ref. 8), covering various aspects of fission-product control in a severe accident. TQ-AP1000-1049 specifically asks Westinghouse to justify the 1.8 hour limit and absence of a late vessel release.

1055 Westinghouse responded to TQ-AP1000-1052 and 1054 shortly afterwards and provided supporting references (listed below) early in 2011, in addition to revising the response to RO-AP1000-55.A6.

1056 Westinghouse updated their response to include my comments in Ref. 150. This updated response does not address any of the queries described above, mainly updating the description of the AP1000 spray system and the ALARP justification.

1057 The updated Westinghouse response to RO-AP1000-55.A6 (Ref. 150) provides a relatively high level description of fission product control in AP1000, stating that "*the responses to these TQs* [TQ-AP1000-1047 to 1049 and 1052 to 1054] *will provide additional information and clarification to support the discussion".* Overall, the evidence to support the appropriate derivation and application of the source term in AP1000 is incomplete and a number of questions remain. TQ-AP1000-1047 questions the aerosol size distribution used in Ref. 174. TQ-AP1000-1048 queries the effect of acid gases on the alkalinity of water in containment and iodine retention. TQ-AP1000-1053 queries the efficiency of processes for iodine removal. TQ-AP1000-1053 seeks a comparison of the US and European treatment of organic iodine. All of these TQs are discussed further below. To date, Westinghouse has not presented a consistent and structured safety case containing sufficient evidence to support the AP1000 accident analysis, specifically:

- Evidence to support the overall fractions of released nuclides.
- Evidence to support the timings of nuclide releases.
- Evidence to support the long-term behaviour of released nuclides under the containment conditions.

1058 In summary, the AP1000 safety submission for the control of fission-product releases in accidents is outlined in Refs 21, 174, 180 and 159. Westinghouse have not adequately justified the source terms for fission product release in AP1000 and, on the basis of the evidence I have seen to date, appear to be underestimating the releases of the important radioiodines. As this is a fundamental requirement for the safety case, I consider this to be a GDA Issue **GI-AP1000-RC-01**.

4.6.4.2.2 Speciation of Releases

1059 What form the releases take is also important in assessing how they behave in the containment environment, particularly for iodine which exhibits complex behaviour. Details were provided in the response (Ref. 149) to RO-AP1000-55.A6 (Ref. 7); for their analysis Westinghouse has also chosen to use the recommendations given in NUREG-1465 (Ref. 83). The forms of iodine released are recommended by NUREG-1465 as 95% aerosol, 4.85% gaseous elemental and 0.15% gaseous organic. The last remains airborne but the aerosol and elemental forms are flushed and deposited from the air at a fixed rate until 0.5% is left, otherwise the calculation would proceed until the aerosol iodine was unrealistically small.

1060 The other complication with the behaviour of iodine is the changes in chemical form that occurs following its release into containment. This can be influenced by the mitigation systems described later in Sections 4.6.4.4 and 4.6.4.5.

1061 I raised TQ-AP1000-485 and 1053 (Ref. 7) querying the fate of deposited iodine and the fraction converted to organic form by contact with paints and other reactions. In response to TQ-AP1000-485 Westinghouse said that the proportion of organic iodine assumed in their calculations is pessimistic by comparison with the equivalent European guide (Ref. 223). This reply assumes that the initial release of elemental iodine has been estimated correctly.

1062 As part of TQ-AP1000-1049 (Ref. 8) I asked Westinghouse to justify the proportion of organic iodine.

1063 These TQs were raised on 27 September 2011 and responses to TQ-AP1000-1049 and 1053 were not received until 12 April 2011, too late for assessment during Step 4. The GDA Issue, **GI-AP1000-RC-01**, requests more realistic analyses of this chemistry to cover these TQs.

1064 I raised TQ-AP1000-1231 (Ref. 8) to query the conversion of caesium iodide to volatile molecular iodine in recombiners and PARs. The Westinghouse reply provided adequate assurance that the effect would be small for the PARs, on the basis that a very small proportion of the iodides would pass through the PARs in a severe accident. The igniters could cause temperatures in most of the containment atmosphere to spike to cause this reaction, but Westinghouse gave no evidence for igniters. The effect of igniters on the chemistry of iodine has been considered in the past and I consider this a gap in the safety case that the licensee should review and fill. I consider this to be an Assessment Finding, **AF-AP1000-RC-64**.

1065 As with the release fractions and source terms, Westinghouse have not made an adequate case to justify that the speciation of the released species, particularly iodines, is appropriate to AP1000. This is part of the GDA Issue relating to the source terms, **GI-AP1000-RC-01**.

4.6.4.2.3 Thermal Source Term

1066 The source term also determines the nuclear heating caused by radioactive decay. This is the most important factor driving most of the effects in an accident. There are well-established and validated methods (such as Ref. 158) for predicting heat output, short of running the ORIGEN (US) or FISPIN (UK) codes for every nuclide. All these methods have a number of input selections that a user can make, TQ-AP1000-1188. For the same nominal power, burn up and cooling, selecting different options can vary the result by around ±10%. As shall be seen in Section 4.6.5 on core melt chemistry, this could make a significant difference to results. A pessimistic source term for the containment analysis will be an optimistic term for the reactor core.

4.6.4.3 Passive Fission Product Control Mechanisms

1067 The response to RO-AP1000-55.A6 (Ref. 150) clarifies what passive processes Westinghouse claim are contributing to fission product control in AP1000. Further details are provided in the EDCD (Ref. 22, Appendix 15B). Westinghouse claims that these processes, enhanced by operation of the PCS, are sufficient to remove particulates and elemental iodine from the containment atmosphere. Noble gases and organic iodine are assumed to be unaffected and remain in the containment atmosphere until decayed or released by leakage. The effect of these mechanisms on aerosol and elemental iodine removal are described below.

4.6.4.3.1 Aerosol Removal

1068 Westinghouse claim that aerosols are removed by gravity (sedimentation) and heat transfer driven natural processes (diffusiophoresis and thermophoresis). Sedimentation accounts for around 30% of the overall aerosol removal, with the rest by the phoretic processes, which vary in their contribution as the accident progresses but are somewhat complementary such that the effect of one increases as the other decreases.

1069 The flow of vapours and aerosols between rooms and leakage from the containment was calculated by hand and by software, using TITAN5. Westinghouse claims the natural mechanisms of sedimentation by which radioactive material falls and is swept downwards by condensing steam to decrease the release term. These effects are calculated by the STARNAUA code (Ref. 174) using pressures and temperatures calculated by MAAP4 analysis (Ref. 173 and TQ-AP1000-1047 (Ref. 8)).

1070 The TITAN5 code was verified against hand-calculations and comparison with a code called RADTRAD. It is a simple dilution and transfer model which doesn’t include any chemistry. I asked Westinghouse for further information on releases to the containment in TQ-AP1000-1049 (Ref. 8).

1071 The calculation of deposition rates by STARNAUA models several effects, Ref. 175:

- Gravitational sedimentation does not take account of agglomeration of particles, which is a conservatism noted by Westinghouse.
- The sedimentation rate is directly proportional to the density of aerosol calculated for a mixture. I found the calculation was wrong, but agree with Westinghouse that the error is small for components of similar density.
- The diffusiophoretic term depends on atmospheric properties calculated by MAAP and is independent of properties of the aerosol.
- The thermophoretic term is also independent of aerosol properties other than the particle diameter.

1072 Westinghouse divide the source term into three aerosol populations; a) the gap release b) fission-products released early from the core and c) a larger early release of other high-density material (i.e. uranium) from the core.

1073 The Westinghouse method appears to calculate a single deposition rate (or "*lambda*") for application to all three aerosol populations (Ref. 174). As a result, the denser particles dominate the sedimentation rate and may over-estimate sedimentation by more radioactive aerosol populations. Since agglomeration is ignored and sedimentation is a small fraction of the deposition, the magnitude of the error due to these effects is thought to be small. I have asked Westinghouse to clarify details of the aerosol models used and state how STARNAUA was validated in TQ-AP1000-1047 (Ref. 8). The response to this TQ has not been assessed as it was received on 10 March 2011 and is therefore included in the GDA Issue **GI-AP1000-RC-01**.

1074 Overall, the physical processes that govern the removal of aerosols in AP1000 are reasonable. In fact, these processes will occur in most PWR containments to some degree during an accident; in AP1000 the effects of these are enhanced by the PCS and are not supplemented by other 'active' means. As Westinghouse did not respond to many of my questions in time for assessment during Step 4, my assessment in this area is incomplete and this is part of the GDA Issue on source terms **GI-AP1000-RC-01**.

4.6.4.3.2 Elemental Iodine

1075 Elemental iodine is removed by deposition on the surfaces inside containment (shell, walls, vessels etc.) where it is 'washed' back to the sumps via condensation. An important chemical point with this approach is that the condensation is not pH buffered, unlike the sumps, to prevent the formation of volatile forms of iodine; there is an implicit assumption in the Westinghouse case that the process of 'washing' to the sumps is quick enough to prevent re-volatilisation in appreciable quantities.

1076 The figure of 0.15% gaseous iodine used in the Westinghouse analysis is derived from experiments in the USA in the early 1970s, which measured the conversion of elemental iodine to organic forms. Aerosol was not included in these experiments, and if the aerosol was included a much greater organic fraction would be formed. I raised TQ-AP1000-877 and 1052 (Ref. 8) seeking further justification of the fraction of organic iodine and explanation of TITAN5. In response, Westinghouse claim that deposited aerosol iodine could be retained and washed away, instead of converted to organic iodine and the US method results in higher organic iodine than is commonly assumed in Europe. As this is an important assumption, evidence for the washing effect was requested in TQ-AP1000-1053 (Ref. 8), the response to which was not received until 29 April 2011, too late for assessment during Step 4. As Westinghouse did not respond to a number of my queries in time for assessment during GDA, this is part of the GDA Issue on source terms, **GI-AP1000-RC-01**.

1077 The behaviour of released nuclides in the long-term is also important in determining the consequences of any accident. For example, this is known to occur when iodine comes into contact with paints or possible pyrolysis products. TQ-AP1000-1048, 1052 and 1231 (Ref. 8) covered various effects within containment that might result in re-suspension of the caesium and iodine. The response to TQ-AP1000-1052 did not address questions about iodine converting to organic form adequately and the response to TQ-AP1000-1231 ignored the effect of igniters. More realistic iodine chemistry would take account of the conversion of non-volatile forms of iodine to more volatile forms through the course of the accident. Westinghouse has responded by stating that release fractions employed were more pessimistic than used in Europe and bound expected mechanisms for re-suspension. As Westinghouse did not respond to a number of my queries in time for assessment during GDA, this is part of the GDA Issue on source terms, **GI-AP1000-RC-01**.

4.6.4.4 Control of Alkalinity

1078 In accidents, the alkalinity (pH) of water volumes and films within containment that become contaminated with iodine directly affects the retention of iodine and the amount of volatile iodine available for release. As is common for PWRs, the AP1000 sumps contain sacks of granular Tri-Sodium Phosphate (TSoP) for this purpose. The sacks are held on the walls about 30 cm above the floor, out of reach of accidental spillages, in racks which allow water to enter when these areas are flooded during an accident. TQ-AP1000-668 (Ref. 8) was raised to query this aspect of the design.

1079 For the smaller releases of iodine to the containment arising from a LOCA, Westinghouse assumes there is no additional volatile iodine produced after the initial release. This defines the minimum level of buffering needed. Additional TSoP would be needed for more severe accidents where there would be a larger iodine source term and to counteract any acidic vapours from combustion and the effect of radiation on nitrogen in the containment. Westinghouse outlined their specification for the TSoP addition in their responses to TQ-AP1000-668 and 877 (Ref. 8) and supporting references. Their calculation of the extra TSoP needed to compensate for burning cables and nitric oxides was based on the AP600 design. Westinghouse updated this calculation for AP1000 and I queried several points on this update in TQ-AP1000-1048 (Ref. 8). Westinghouse appears to have included the main considerations I would expect in such a calculation. I have not been able to completely assess this calculation because of uncertainties that remain elsewhere (for example on the source terms) but note a number of conservatisms such as, maximising the boric acid content, assuming conservative dissolution rates for the TSoP and adding margin over the calculated minimum mass of TSoP required.

1080 Westinghouse have calculated the minimum dissolution time of the TSoP as under 3 hours, with the intent to ensure the pH is above 7 before 8 hours. These timings are based upon SCC tests of stainless steels, not iodine retention requirements, but do appear reasonable.

1081 In the response to RO-AP1000-55.A6 (Ref. 150) Westinghouse described the control of pH in the AP1000 water volumes. They distinguish between the sump and the IRWST. The sump is assumed to be pH buffered with sufficient TSoP such that "*iodine activity that enters the containment sump is assumed to stay in the water solution and does not* *re-evolve*". This is based upon test conducted at Oak ridge laboratory in NUREG/CR-5950 (Ref. 239).

1082 For the IRWST, Westinghouse assumes that the pH is not buffered. In a severe accident the IRWST drains into the sump, but some boric acid solution remains in the IRWST. Westinghouse expect there to be sufficient flow to mix these volumes in such an accident, but do not assume so in the LOCA dose analysis. In such circumstances, taking account of other factors such as dilution flow and acid production, the calculated pH of the IRWST drops to around 5 which ultimately results in around 20% of the iodine being in the elemental form, with 3% of this assumed to convert to the organic form. The volatilisation of this to the gaseous phase depends on the partition coefficient, which using the assumed coefficient results in around 8% of all the IRWST elemental iodine being in a volatile form in the IRWST headspace. Westinghouse claim that even if this is released to the containment the passive removal mechanisms collect this and the release remains dominated by the organic fraction.

1083 It has been shown in the European PHEBUS tests (Ref. 178) that iodine deposited on unbuffered surfaces can become volatile again, due to the formation of organic and elemental iodine. The quantity of iodine airborne will be determined by the balance of the production rates and limiting values of removal mechanisms. Responding to TQ-AP1000-1052, Westinghouse claimed the US approach (Ref. 83) is more pessimistic than the European approach (Ref. 223). The RO-AP1000-55.A6 response (Ref. 150) does not consider the film retention mechanism. I raised TQ-AP1000-1053 (Ref. 8) requesting further details on the chemistry of other water bodies in the reactor. The response to this TQ was not received in time for assessment and this is part of the GDA Issue relating to the source terms, **GI-AP1000-RC-01**.

4.6.4.5 AP1000 Spray System

1084 AP1000 does not have a buffered spray because Westinghouse do not believe that sprays are needed, see TQ-AP1000-484 (Ref. 8), with the passive mechanisms available. Westinghouse was asked to justify the absence of a recirculating buffered spray as part of RO-AP1000-55.A6 (Ref. 7). The updated response to this action (Ref. 150) contains a much clearer description of the Westinghouse case in this area, and is discussed below.

1085 Westinghouse claim that, in addition to the passive mechanisms promoted by the PCS, two additional features of AP1000 promote fission product removal:

- An active Containment Spray System (CSS), described in the EDCD, Section 6.5.2. (Ref. 22). The CSS is fed with demineralised water and is not recirculated or buffered before use for fission product control. Capacity is limited to 3 hours flow.
- Aerosol impaction. This is the process whereby aerosols are deposited in the containment leak due to impaction on surfaces. Westinghouse does not include this mechanism in the analysis for AP1000 but claim that this is a significant conservatism. As this is not used I have not assessed it further.

1086 Westinghouse does not use the CSS in any radiological release analysis for AP1000. The primary function of the CSS is as part of the Fire Protection System (FPS). Westinghouse state that the CSS *is available* to the operator as part of severe accident mitigation. Westinghouse does not impose any duty on the CSS during design basis accidents. The decision on whether or not to activate the CSS should be made by the operator according to the SAMG (Severe Accident Management Guidelines) and taking account of the precise state of the plant weighing many other factors, such as flooding caused by introducing additional water or de-inerting of the containment atmosphere leading to increased potential for hydrogen deflagration.

1087 In AP1000 operation of the CSS would increase the rate of aerosol removal to the sumps. In addition it would increase the rate of washing of elemental iodine to the sumps however, as it is not pH controlled, it would not affect the potential for iodine re-volatilisation from un-buffered films, other than it leaves the iodine less time to do this before it is washed to the sumps. It would not affect organic iodine or noble gas releases. Therefore the main benefit in activating the CSS in AP1000 appears to be to minimise iodine releases. It is in this area where many of the outstanding questions relating to the AP1000 source term reside, hence it is difficult to come to conclusions at this stage.

1088 TQ-AP1000-1243 (Ref. 8) was raised asking Westinghouse to list connections of the FPS and to clarify their intentions for their use. If multiple other backup cooling water supplies fail, in addition to fighting fires the FPS can supply water to cool the following; the reactor core, the spent fuel pool and the outer containment shell. Whilst very unlikely, such demands on the FPS would be no less likely than a demand for fission-product control if fuel is damaged. Therefore there may be circumstances in which it was preferable to not use the FPS spray for fission–product control. Sprays for fire-protection usually have a high flowrate. It may be ALARP to increase FPS water storage capacity or decrease the flowrate to make FPS last longer than 3 hours when used in the CSS. As currently designed, other uses of the FPS could draw down on its capacity to support severe accident management. I consider this to be an Assessment Finding, **AF-AP1000-RC-65**.

1089 Responding to RO-AP1000-55.A6 (Ref. 150) Westinghouse said the incremental benefit of a spray to public dose would be around 20 mSv. Westinghouse said the additional equipment for a recirculating system would have to be outside containment for space reasons and to allow maintenance, which would create a new leakage path. The costs and inconvenience of reducing this dose would therefore exceed guidance values from the UK Health-Protection Agency for justifying the improvement.

1090 The extra benefit of a spray was small because Westinghouse included filtration by the containment structure (aerosol impaction) as additional means of mitigating a release. Filtration of aerosol in containment leakage paths is not claimed but is used by Westinghouse to justify their ALARP position on sprays. Were the effect of the spray credited before the passive filter, then its benefit would be greater than 200 mSv. I pointed this out to Westinghouse by letter, Ref. 177.

1091 Because of the CSS, the additional benefit of a recirculating system would only be realised after the 3 hour operation of the spray, after which time Westinghouse believes any release would have fallen to 50% of the early release peak in most accidents. I raised TQ-AP1000-1054 (Ref. 8) to obtain clarification of various spray performance factors. In reply Westinghouse claims that after 3 hours, the proportions of iodine in the tail of a release will be controlled more by the limiting values of cleanup factors and less by passive deposition, Ref. 174, or a spray. Westinghouse agreed that FPS spray would accelerate the removal of iodine, and extensions to the spray capacity / efficiency should further accelerate removal, but in every case the total amount of iodine removed would be unaltered. I concluded that the additional benefit of a recirculating spray would be small if the amount of iodine evolved late in the accident was small. However, I have raised a GDA Issue concerning the source term in AP1000, including for iodine later in an accident, and further assessment of this topic is dependent on the outcome of the GDA Issue, **GI-AP1000-RC-01**.

1092 In addition to using MAAP to predict conditions inside containment, Westinghouse has had MAAP used to provide input to the level 2 PRA. The level 2 PRA was developed principally to consider and evaluate alternatives in the management of severe accidents (known as Severe Accident Management Design Alternatives (SAMDA)). The analyses in Ref. 173 covered a range of hypothetical early and late failure releases. Since the AP1000 shares several accident mitigation features with older PWR and its core-damage frequency is lower, the PRA results in no recommendation for improvement.

1093 MAAP models the release of radioactive material from the core during the early phases of an accident and whilst the core collapses. The MAAP code does not model vaporisation from a pool of molten corium in the bottom of the vessel, but picks up the release from corium-concrete interactions if the vessel fails. Westinghouse does not make any claims for this latter phase, other than its extreme unlikelihood, TQ-AP1000-1056 (Ref. 8). The absence of late-phase source term is discussed in Section 4.6.4.2.1 of my report.

1094 The FPS spray was not simulated in any of the MAAP calculations for the PRA. Unlike STARNAUA, MAAP does not model diffusive deposition but it does model agglomeration, so provides a reasonable representation of passive deposition for PRA purposes. Sensitivity tests by Westinghouse showed the detailed iodine chemistry models in MAAP made little difference, so they were switched off. The chemical iodine models in MAAP would be expected to underestimate iodine release since the MAAP version predates the PHEBUS tests and other recent experimental data by several years. However, this sort of approximation is reasonable in a system-level code. Westinghouse use of the MAAP code to analyse these phenomena is justified. It does not model the chemistry of all the radioactive species released but works by grouping nuclides with the behaviour of the most significant species. The timings it predicts for the source-term is likely to be as reliable as many other existing codes. MAAP is well-established. However, I find that there is no comprehensive statement of its validation for use with AP1000 specifically. This is part of Assessment Finding **AF-AP1000-RC-69**, described in Section 4.6.5.6.

1095 Overall, I am not able to conclude on the adequacy or otherwise of the AP1000 spray system until the source term queries are resolved as part of **GI-AP1000-RC-01**, but believe that an adequate case could be made.

4.6.4.6 Summary

1096 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of accident source terms in AP1000 are:

- For AP1000, Westinghouse has analysed the release from the core using early in-vessel release factors from NUREG-1465 and ignoring potential late releases and the conversion of iodine to more volatile forms as an accident progresses. Both of these assumptions will tend to reduce the source term. Knowledge of the fundamental chemistry of radioiodine and other nuclides under accident conditions has improved greatly over recent decades, but recent European work has added the new complexity of volatile organic iodine being formed on surfaces in the containment building. This effect may be small, but it could have a greater impact on AP1000 because there is no dedicated spray system. This effect has not been quantified by Westinghouse. I expect Westinghouse to justify the application of appropriate source terms to AP1000 specifically, in representative accident sequences.
- Overall, the evidence to support the appropriate derivation and application of the source term in AP1000 is incomplete and a number of concerns remain. To date,

Westinghouse has not presented a consistent and structured safety case containing sufficient evidence to support the AP1000 accident analysis, specifically:

i) Evidence to support the overall fractions of released nuclides.

ii) Evidence to support the timings of nuclide releases.

iii) Evidence to support the long-term behaviour of released nuclides under the containment conditions.

- Because this is fundamental to the assessment of the mitigation systems and plant design I have raised this as a GDA Issue. In order to update the safety case for AP1000, it is necessary to identify what is released, how it is released and when.
- The definition of a source term also includes the decay heat remaining in the core. Calculations by Westinghouse assume almost 20MW of decay heat remains in the core after losses to containment are taken into account. The sensitivity of IVR to this figure is discussed in Section 4.6.5 of my report on core damage, from which it is clear that parameters defining the maximum thermal load are important to the IVR concept.
- Many of my questions in Step 4 related to the performance of the mitigation system:

  i) For design-basis accidents, I am satisfied that the natural deposition rate combined with a robust containment shell provides adequate protection for controlling iodine release from containment and that an in-containment spray is not justified.

  ii) The dynamic equilibrium between production and removal rates for iodine compounds will be very different in a reactor without a recirculating spray. Instead, the proportion of organic and elemental iodine may be dominated by surface effects and not the alkalinity of the IRWST or the FPS spray. Nevertheless, I am content that, provided the source term is correct, the design of AP1000 is broadly adequate.

  iii) I have queried a number of the assumptions used by Westinghouse to predict releases and obtained clarification for several. There are several questions outstanding on assumptions made for physical aerosol behaviour, production rates for several key species, justification for assumptions made in the LOCA dose analysis and further details on calculations for pH. These are part of the GDA Issue on source terms.
- If the CSS were actuated manually, the airborne concentration of fission products including iodine within containment would be significantly reduced in the 3 hours after actuation. The incremental benefit of a dedicated spray may then be quite small if the FPS could be used at the right time. Stocks of water reserved for the FPS can also be used as a back-up to other safety functions. This creates a requirement to assess severe accident guidelines to enable an operator to choose how best to use FPS supply. It may also be ALARP to increase stocks of water or provide a low-flow spray option.

1097 Overall, Westinghouse has provided much improved clarity on the fission product control mechanisms in AP1000, which are based upon passive processes and backed by an ‘optional’ spray system for use during severe accidents. Westinghouse responded to many of my queries (namely TQ-AP1000-1047 to 1049 and 1052 to 1054) late in Step 4. Since I have not assessed a number of these responses, they will be assessed as part of

GDA Issue **GI-AP1000-RC-01**. I believe that an adequate safety case could be made for AP1000, but this has yet to be completed.

4.6.4.7 Assessment Findings

1098 Based upon the assessment of fission product control in AP1000 described in Section 4.6.4 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-AP1000-RC-64*** *– The licensee shall review the potential for the high temperature spike caused by igniters to convert iodides to volatile forms of iodine and update the safety case and analysis if necessary. This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.*
>
> ***AF-AP1000-RC-65*** *– The licensee shall review severe accident management guidelines for the provision of spray water for fission product control and consider whether any improvements to the Containment Spray System (CSS) design or performance would be reasonably practicable. This Assessment Finding should be completed before initial nuclear operations of the reactor; Target milestone – Initial criticality.*

4.6.4.8 GDA Issues

1099 Based upon the assessment of fission product control in AP1000 described in Section 4.6.4 above, I have identified the following GDA Issue which requires resolution:

> ***GI-AP1000-RC-01*** *– Accident Source Terms – Westinghouse should provide justification to demonstrate that the source term released into the containment during accidents is appropriate for AP1000*.

4.6.5 Assessment – Chemical Aspects of Core Damage and In-Vessel Retention

1100 It is important to note that Westinghouse claims that severe accidents (i.e. those resulting in core damage) are “*virtually excluded*” by the AP1000 design and the design of AP1000 has been optimised to minimise the risk of accidents. The core damage frequency claimed by Westinghouse in the PCSR for AP1000 is 2.4 x 10^{-7} per year. The large release frequency for these events is of the order of 2 x 10^{-8} per year. My assessment of core damage has been proportionate to this. The assessment below 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.

4.6.5.1 Overview of AP1000 Approach to Core Damage Accidents

1101 Even in a shutdown state, the core of a PWR has a decay heat output amounting to several MW. This heat must be removed to stop the temperature of the core rising enough to cause damage to the structure of the core. Core damage would make cooling more difficult through loss of coolable geometry and ND expects designers to consider how a degraded core could be cooled and stabilised. Severe Accident Management Guidelines (SAMG) would guide the operators in such an event and the principal recovery action needed would be to reflood the core.

1102 If the operator can supply enough water to the core to keep the fuel mostly intact the main safety challenges would be from hydrogen and a release of radioactive material within containment, as assessed earlier in this report in Section 4.6.3 and 4.6.4.

1103 If the operator failed to reflood the core or cooling was insufficient, there could be a loss of cladding material and melting of the control rods, followed by degradation of the fuel itself. The more damage that occurred, the higher the temperature that would be reached. In the event that no recovery action was successful, within several hours at design decay power, the core would eventually degrade to a molten mixture of uranium dioxide, zirconium cladding, waste products and various structural materials such as steel; a mixture often called ‘corium’.

1104 The chemistry that occurs during such changes is complex and can affect core melting in a number of ways. The combinations of dry-out, partial dry-out, early and late reflood are the main external parameters affecting the chemical form of the corium and possible releases to containment. During such events the chemistry can influence:

- What fission products, and their heat, are located in different phases of the debris.
- Whether one or more molten layers form.
- Heat flow through the formation of crusts (barriers) or metallic layers.

1105 AP1000 would take a different approach to UK and US PWRs in such extreme cases, by flooding the area surrounding the RPV, the reactor pit, with water so that most of the fuel could be retained within the vessel even if it did melt inside the RPV. This strategy relies on an enhancement of the AP600 design and is known as In-Vessel-Retention (IVR) (Ref. 210). This approach has been used at a number of reactors, such as Loviisa, but these generally have low power cores (less than 1000 MW_e). In principle, this strategy brings advantages in terms of simplicity. For IVR to be successful, the flow of heat per unit area of the reactor vessel wall must not exceed certain values, known as the Critical Heat Flux (CHF). Above the CHF the vessel can no longer retain the weight of the molten material it holds. The effectiveness of heat-removal systems is considered in the ND report on Containment and Severe Accidents (Ref. 80), along with the potential for steam explosion. Some specific chemistry aspects of these phenomena are assessed below.

1106 Overall, Westinghouse claims that IVR is sufficiently reliable to ensure that AP1000 exceeds UK regulatory expectations and pessimistically assumes that if IVR fails, then containment has also failed. As a consequence, Westinghouse does not claim specific features of AP1000 to mitigate ex-vessel phenomena as distinct from in-vessel phenomena. I did not assess ex-vessel phenomena and these were assessed by ND in the context of PSA level 2. This section of my assessment concentrates on whether or not IVR would succeed and whether IVR could make AP1000 less safe than other PWR design concepts. My assessment was supported by TSC contractors who reviewed the AP1000 approach, Ref. 172.

1107 To justify IVR, Westinghouse relies on a combination of experimental tests and computer simulations, mainly using MAAP4, with support from other codes. In RO-AP1000-55.A4 (Ref. 7) and TQ-AP1000-1055 (Ref. 8), I asked how the tests and models linked into an overall safety case. In response Westinghouse provided a useful roadmap document (Ref. 225) which linked the safety case together and contained many relevant reference documents (particularly Refs 173, 182, 204, 205, 208 and 209). My assessment that follows is based mainly on these responses, plus additional TQs as noted.

4.6.5.2 Chemistry Aspects of the AP1000 Core Damage Safety Case

1108 MAAP was used by Westinghouse to model the sequences, timings of events and to predict reactions of the cladding with steam or the fuel and the release of volatile fission products. The conditions in containment predicted by MAAP were also used to determine whether or not key equipment would survive a severe accident (Refs 202 and 206). I obtained documentation on MAAP and its validation via TQ-AP1000-1050, 1055 and 1188, which was also reviewed by my TSC and my assessment of MAAP is outlined in Section 4.6.5.6 below.

1109 A significant factor determining chemistry in the core during such an event is the availability of cooling water supplied to the core. Westinghouse considers three main scenarios; boil-off in which no extra water is added, early reflood in which water is added before major fuel damage and late reflood after a significant relocation of the core to the lower plenum. The availability of cooling water determines the quantities of metallic zirconium and uranium in the corium. See Section 4.6.5.5 on cladding oxidation.

1110 If the fuel damage reaches a stage where there is a sufficient quantity of molten corium this will eventually relocate to the bottom of the RPV, the lower plenum. There are two possible routes for this:

- Sideways through the shroud and barrel, then down to the lower plenum.
- Directly downwards, melting through the lower debris and core-support structures.

1111 Since the core shroud in AP1000 is thinner than the reflector it replaced (from AP600), Westinghouse concludes that sideways relocation is more likely and occurs sooner than direct relocation. However Westinghouse can only quote MAAP as supporting this hypothesis since the analysis of Ref. 208 did not model the relocation part of the process. Sideways relocation was the behaviour observed in the accident at Three Mile Island Unit 2. While considered more unlikely, the direct melting route could potentially be significant because it affects the potential for layering of the corium and the potential superheat carried by the corium. The implications of this are assessed in Section 4.6.5.8 below.

1112 The interaction between hot molten corium and water could be important during this relocation, whichever path is taken. A rapid boiling or flashing of water into steam, occurring when water is either superheated, rapidly heated by fine hot debris produced within it or via interaction with molten metals could result in a “steam explosion”. This is not actually a chemical explosion, although chemical reactions can result, but is a very rapid production and expansion of steam. The resultant pressure this generates could damage the RPV and jeopardise the success of IVR. My assessment of the chemical aspects of these events is given in Section 4.6.5.4 below.

1113 One area where the IVR concept has been criticised is known as the “*focusing effect*”. This is where the critical heat flux could be exceeded if phase segregation in the corium led to the formation of a thin metallic layer that might focus heat on a narrow segment of the vessel wall (Ref. 184). The original case for IVR in AP1000 did not consider this aspect but in response to this criticism and ND questions on related matters, Westinghouse refined their assessment during Step 4 (Ref. 183) and updated their roadmap document, Ref. 225, to take account of uncertainties in the debris chemistry. Westinghouse concluded that the overall large release frequency increases from 1.95 x 10^{-8} to 2.42 x 10^{-8} per reactor year from the combination of IVR failure due to debris chemistry uncertainty and hydrogen combustion (Ref. 183). The conditional containment failure probability increases from 8.1% to 10.0%. Westinghouse claim that melting of the core shroud and core support plate in AP1000 provides much more steel to the corium, producing a much thicker top metal layer which tends to prevent focussing and generally slows down the relocation. These phenomena are assessed in Sections 4.6.5.7 and 4.6.5.8 below.

1114 During such events if the temperature is allowed to increase enough, volatile components in the core and fuel will be driven off. As well as providing the source term in containment assessed in Section 4.5, the fission-products provide the bulk of the decay heat source. As such, the decay power in the core will decrease as FPs are lost to other parts of the reactor and the containment. The success or otherwise of IVR will therefore be related to both the amounts and location of fission products in the corium. Control rods usually contain silver, indium and cadmium, which are also volatile. The silver may react with iodine and reduce its volatility.

1115 The mechanism for external vessel cooling may also be influenced by chemistry effects and I consider these in Section 4.6.5.3 below.

1116 TSC contractors working for the PSA Inspectors in ND repeated some of the Westinghouse PRA for AP1000 (Ref. 185). I specified a number of chemical parameters to be considered in this sensitivity analyses. The results concluded the two most significant chemical factors affecting the success of IVR were:

- the loss of volatile fission products; and
- the depth of the metal layers.

1117 The sensitivity of IVR to assumptions regarding the loss of volatile fission products is assessed further below and my assessment of focussing appears in Section 4.6.5.7.

1118 In order to establish a boundary condition for the RPV wall, Westinghouse assumed that the vessel wall was thinned by partial melting, and the chemical properties of the steel were modelled quite simply. Creep data for American RPV steels under severe accident conditions have been developed under the framework of the European SARNET programmes REVISA and OHLF, Ref. 207, but were not used. Westinghouse justifies this approach because the RPV would be depressurized, and their analysis concluded that softening of the RPV wall would not cause failure due to stress, so-called creep failure. Creep rupture failure of the vessel was considered and evaluated analytically for AP600 in “In-Vessel Coolability and Retention of a Core Melt” (Ref. 234). In this analysis Westinghouse state that the portion of the wall carrying the load is relatively cold and under low stress and the wall is supported by the buoyant force of the water and therefore not subjected to significant creep. Westinghouse predicts that any failure of IVR in AP1000, if it occurred, would be due to melting of the RPV wall.

4.6.5.3 Coolant in the Reactor Pit

1119 If the strategy is to flood the pit, then borated water should be used to avoid a risk of re-criticality. The borated water would be provided from the IRWST in AP1000.

1120 The reliability, design and efficiency of the systems used to remove heat from the RPV in AP1000 is the single aspect of the design for IVR which dominates all others, including the chemistry. There is a critical heat flux (of 1,800 kW m^{-2} at the RPV waistline) above which vessel failure should be expected. Below this value, IVR is successful. Values of the critical heat flux at different points on the AP600/1000 vessel wall were determined in the ULPU experiments (Ref. 209). AP1000 has a higher decay power than AP600, so the circulation of the water in the pit was enhanced by permitting circulation over the skin of the pressure vessel inside the heat shield (Ref. 203).

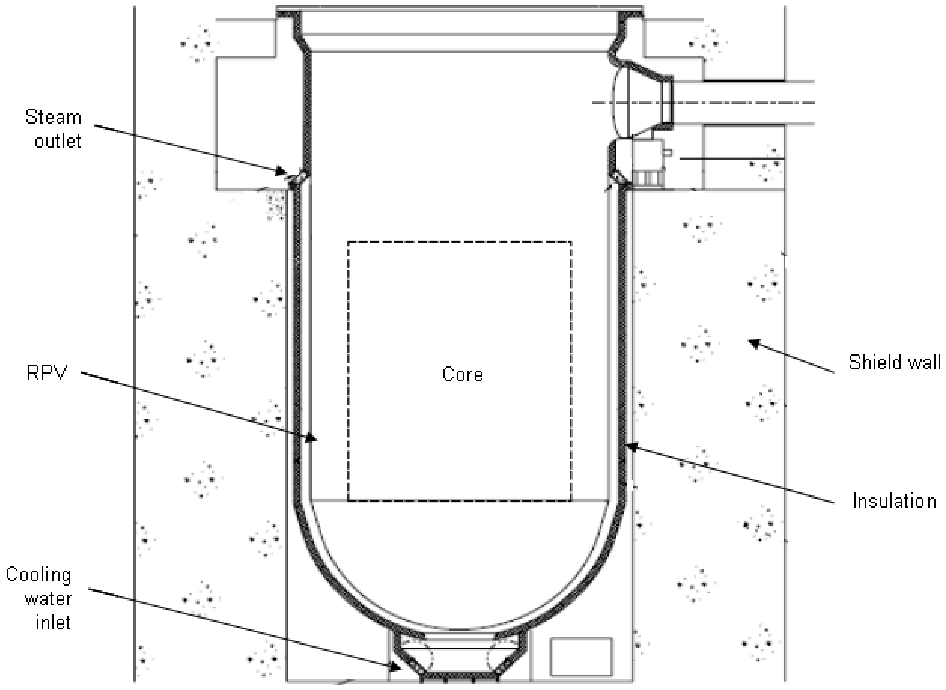

Figure 14: AP1000 Reactor Pressure Vessel Insulation

1121 Westinghouse has considered factors that might decrease the efficiency of external cooling. The effects of pure water and water with tri-sodium phosphate (TSoP) and with boric acid were compared in the ULPU tests. External cooling was least effective with pure water and most effective with TSoP dissolved. The effects of boric acid and TSoP tended to cancel but the mixture was still better than pure water (Refs 204 and 209). Two-phase flow in the cooling channel would flush any precipitated boron or TSoP out from under the heat shield.

1122 Depending on the cause of the accident, debris may enter the pit, but the flow rates are low so Westinghouse claimed debris should not be carried into cooling channel, which in any case has a total cross-sectional area of 1 m^2 (TQ-AP1000-1051 (Ref. 8)). I found that a debris inlet filter was not specified for the reactor cooling annulus in Ref. 203 and the drawing leaves this detail for the supplier to define. The licensee should justify this detail of the design. I consider this to be an Assessment Finding, **AF-AP1000-RC-66**.

1123 Otherwise, Westinghouse has considered the chemistry of the pit coolant carefully and I am content that the chemistry in the pit could be controlled well enough for accidents of this type.

4.6.5.4 Steam Explosion

1124 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, and regulators must rely instead on expert judgement, such as the NRC Steam Explosion Review Group (SERG). The risk of steam explosion in AP1000 was assessed by Westinghouse in Chapter 34.2.2.1 of the AP1000 PRA (Ref. 79).

1125 The assessment of the in-vessel steam explosion for AP1000 essentially uses approaches endorsed by the US NRC's steam explosion review group, which are similar to the approach used in the UK. There is no chemistry in the assessment, although it is thought that chemical processes do contribute to the likelihood of a steam explosion and, possibly, its efficiency. From its studies, Westinghouse concludes that in-vessel steam explosion is both unlikely to occur and unlikely to fail the lower head.

1126 Westinghouse uses the sideways relocation mechanism to justify its conclusion that in-vessel steam explosion is unlikely. The early barrel failure predicted by MAAP limits the amount of melt that can be mixed with water at any one instant, compared with the possibility of substantial downward relocation through the lower core support plate. It also improves the possibility that the core support plate will drop even lower into the plenum. Westinghouse cites the more detailed thermal modelling performed by Fortum, Ref. 208, but Fortum did not model the relocation process itself.

1127 Westinghouse also analysed the consequences of explosion to demonstrate that lower head failure was unlikely. In common with other analyses of the consequences of steam explosions, the methods used by Westinghouse do not include much melt chemistry because there was insufficient known at the time when these codes were developed. However the energy of melt oxidation could and should be considered. Understanding of steam explosions, including the effects of melt chemistry is gradually developing, e.g. through the Test for Real cOrium Interaction with water (TROI) experiments in Korea and the OECD SERENA activity. It has become possible to model the effect of chemical reactions between the corium and the water more recently and the Licensee should review these activities and ensure that assessments for AP1000 are updated if there is a significant improvement in understanding or modelling. This should also be the case where expert opinion has a negative impact on the AP1000 case, as exemplified by the ‘focusing effect’. I consider this to be an Assessment Finding, **AF-AP1000-RC-67**.

1128 Westinghouse conservatively assumes that failure of IVR would result in a large release, but has nevertheless analysed the consequences of IVR failure. The Westinghouse analysis of the ex-vessel event (Ref. 205) involves no chemistry and the ND assessment of it appears in the report on containment and severe accidents (Ref. 80), together with further ND assessment of the in-vessel case, including other factors outside chemistry.

1129 Overall, the approach taken by Westinghouse for both in-vessel and ex-vessel steam explosions broadly incorporates the current state of knowledge from a chemistry perspective.

4.6.5.5 Oxidation of the Cladding

1130 Early re-flooding of a damaged core produces a corium consisting of oxides which tend to be less reactive. These are called ‘high-oxidation’ scenarios

1131 Dry out and late reflood tend to be ‘low-oxidation’ scenarios, in which there would be more melting and more zirconium metal to react with the fuel. Late re-flood may be less effective and lead to water lying on a crust on top of re-melting corium, as is thought to have occurred at TMI-2 (Ref. 210). This would produce a more reactive corium of lower viscosity which could separate into two or more layers.

1132 The extent of zirconium oxidation is a critical factor. Section 5.4.2 of the Westinghouse IVR analysis (Ref. 183) concludes that IVR is successful when Zr oxidation exceeds 34%

and fails when Zr oxidation is 22% so I asked Westinghouse what distribution of Zr oxidation fractions was expected. The response in TQ-AP1000-1051 (Ref. 8) quoted expert opinions including a NUREG study, which indicated 30% oxidation would be the minimum in scenarios without re-flood and 60% the best estimate for scenarios with successful re-flood.

1133 As the MAAP code predicts the amount of hydrogen produced by the reaction of steam with ZIRLO®, it also predicts the heat produced by their reaction, which can be quite significant. Oxidation of zirconium alloys by air generates twice as much heat than oxidation by steam. Compared to Zircaloy-4, ZIRLO® is less resilient to oxidation by air but it is normal in analyses of this type to assume air ingress is prevented by steam and hydrogen production. As the surface area of zirconium decreases by orders of magnitude as the core melts, MAAP predicts the production of hydrogen and heat from this reaction effectively to cease once relocation of corium to the lower plenum has completed.

1134 The loss of FP (Fission Product) heat is not usually credited in analyses of this type and Westinghouse has performed relatively few studies of IVR sensitivity to this parameter. Analysis undertaken for ND PSA inspectors (Ref. 185) identified that the success of IVR is sensitive to small changes in the decay heat lost and I believe that the future Licensee should undertake further studies to assure there are no "*cliff-edge*" effects, also taking account of the results of the TSC assessment. I consider this to be an Assessment Finding, **AF-AP1000-RC-68**, as described more fully below.

4.6.5.6 Use of Chemistry in the MAAP4 Code

1135 The MAAP code was used by Westinghouse to model entire accident sequences from their initiating faults through successive protection failures to increasingly unlikely scenarios including extensive core damage. However, Westinghouse did not use MAAP itself to analyse the success criterion for IVR, which were beyond its capabilities.

1136 The reaction between zirconium and steam is the 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. The production of hydrogen in severe accidents is assessed in Section 4.6.3.

1137 Whilst this is happening, nuclear material with a low melting point is vaporised. This results in the source term assessed in section 4.6.4 of my report. It also reduces the heat loading in the vessel by around 25%. Some reactor designers ignore this reduction in heat-loading as a conservatism, but Westinghouse find it necessary to take account of it for AP1000, demonstrating the relatively low margins in the calculations. The method used within MAAP4 to determine the balance of thermal energy (decay heat, vaporisation and heats of reaction between phases) is the subject of TQ-AP1000-1050 and 1051 (Ref. 8). Overall, the partitioning of decay power between the corium phases present and the containment is reasonably well established, so the decay heats predicted by MAAP are about as accurate as should be expected. However, the analysis of IVR for ND (Ref. 183) concluded that IVR was quite sensitive to the percentage heat lost to vaporisation. For instance, if the percentage heat lost by vaporisation was only 18%, IVR would not be as successful in roughly one out of ten scenarios.

1138 Many of the physical and chemical properties of the materials used by the MAAP4 code to model the core are based on algorithms in MATPRO (MATerial PROperties database), the properties system developed by INEEL for the RELAP5 and SCDAP severe accident codes (Ref. 181). When MATPRO was developed, there were data for (U, Zr, O) mixtures and melts up to 2273K, as could be used in detailed models for fuel, but no data for mixtures of these three elements with iron. TQ-AP1000-1055 (Ref. 8) was raised to clarify the approach used in MAAP to modelling these effects.

1139 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 MAAP4 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 can model key features of the U-Zr-O system including the eutectic and extended mutual solubilities at higher temperature. However, it appears these may not be the criterion used to initiate slumping and relocation of the core in MAAP, see below.

1140 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 in MAAP4. In TQ-AP1000-1055 (Ref. 8), I asked Westinghouse how significant the thermal conductivity of the melt would be in analysing accidents. Westinghouse presented calculations showing that thermal conductivity had only a small effect on the timings of events and the dominating factor appears to be the total heat. Unlike MATPRO, MAAP4 does include the heats of melting, as mass and energy are conserved in MAAP4, Ref. 172. This gives better agreement with experiments than achieved by MATPRO alone.

1141 For modelling heat transfer in the molten pool, MAAP4 relies on the Nusselt correlation which overestimates heat transfer in the molten pool at low superheat, the Rayleigh correlation may be better, Refs 172 and 226. See the section on heating of the lower plenum, 4.6.5.8.

1142 Overall I conclude that MAAP4 will provide reasonable approximations to the redox, temperature and liquid fractions for the fuel at a given composition and heat in AP1000. These are used (Ref. 182) to provide estimates of hydrogen / steam (Section 4.6.3.2), check the source term (Section 4.6.4) and provide parameters for subsequent analyses of IVR undertaken outside the MAAP code.

1143 Once a severe accident is assumed to start, MAAP4 generally predicts times for the core to transfer to the lower head greater than one hour. For a small number of transients, including the total loss of feedwater, relocation of the melt may not occur for more than a day. Once the core reaches the lower head, any remaining water boils off in 30 minutes.

1144 My TSC compared fifteen of the severe-accident scenarios modelled by Westinghouse in MAAP, using the MELCOR code. MELCOR should be capable of modelling core geometry and dynamics in more detail than MAAP. MAAP does not model the core barrel explicitly whereas MELCOR does.

1145 Results of the MELCOR analyses agreed with a large number of the MAAP results, specifically the timings of events predicted by the two codes were quite similar. However, MELCOR and MAAP disagreed on one significant detail, concerning the temperature at which core slumping and relocation was initiated. In MAAP this started at 3,100K, the melting point of pure UO_2 and that failure of the core support plate occurred at a similarly high temperature. The equivalent figure in MELCOR is 2,800K. This means that the corium that transfers to the lower head in MELCOR is a superheated liquid whereas in

MAAP, it is an equilibrated slurry containing a large solid fraction. Reports by two of our TSC agree on the different approaches needed to predict the thermal effects in superheat and equilibrium. The implications of this are assessed in Section 4.6.5.8. If the melting temperature is artificially raised in MELCOR to match the value used in MAAP, the two codes generate equivalent results.

1146 In general the modelling of melt chemistry in the MAAP4 code is as detailed as in MELCOR (Ref. 154) and the difference in the temperature at which relocation begins reflects genuine uncertainty in this parameter. The results of the VERCORS test programme (Ref. 229) suggest a fuel collapse temperature nearer 2,300K, even lower than MELCOR. Neither MELCOR nor MAAP claims to predict this key parameter, which is simply an assumption in both codes. I consider temperatures above 3,000K unrealistically high and data based upon chemical analysis and experiment for the most realistic mixed system should be used, where available.

1147 MAAP4 does not model layering or focussing of the melt, whereas MELCOR does. In order to analyse the focussing phenomenon, Westinghouse used a steady-state approximation, starting from the equilibrated slurry predicted by MAAP. MELCOR can predict dynamic effects such as transient superheat on chemistry in the lower plenum.

1148 Overall, I conclude that the chemical approximations used by MAAP4 are generally as good as can be found in other codes available today. However, there should be a validation statement for the applicability of MAAP4 to AP1000 which should cover the points raised by my assessment and the assumptions employed for AP1000 for the whole of the analysis beyond design basis. I consider this to be an Assessment Finding, **AF-AP1000-RC-69**.

4.6.5.7 Melt Focussing

1149 Chemistry determines the phases formed; whether there could be layering of the melt and where crusts may form. The formation of a crust at an interface strongly influences the flow of heat and temperatures at the interface. If a thin metal layer forms over an oxide melt, the low thermal conductivity of the melt combined with the higher conductivity of the metal may direct a significant proportion of the heat through the metal layer. The edge of the metal layer would then concentrate heat on a small area of the vessel wall and threaten its integrity, Ref. 183. The MASCA tests (Ref. 184) and subsequent analyses (Ref. 211) revealed the potential for such an effect that could challenge IVR, resulting from the separation of corium into liquid layers based on a miscibility gap. Such layering may lead to a focussing effect, whereby heat could be channelled through the metallic layer and attack the reactor vessel wall over a narrow area. Westinghouse accepts this effect is theoretically possible if the layer thicknesses are constrained to particular ratios and the heat is high enough. In response, Westinghouse presented the following qualitative arguments that such conditions are highly unlikely because:

- The melt may not segregate into layers but stay as a single phase or an agglomeration of several phases.
- There must be sufficient steel in a metallic layer for the density to be low enough to float on the oxide.
- If there is too much steel, the metal layer would be too thick for focussing to occur.
- If the metallic layer is too thin, focussing cannot occur.

1150 Analyses of the system (Zr + U + O) have been undertaken using the SGTE database by my TSC. They concluded that only one liquid phase would exist below 2763 K, together with various solid phases. With steel present, there must be more than one liquid phase. However, the exact temperature and ranges of composition for the phases cannot presently be predicted accurately. At higher temperatures there could be more than two layers, with the metallic layer either heavier or lighter than the oxide layer, depending on how much steel had melted.

1151 Westinghouse wanted to address the potential for focussing presented by Seiler (Ref. 184), even if it was a very high-temperature “worst case” phenomenon. In order to reproduce this effect in AP1000, Westinghouse initially modelled a layered corium melt formed by the direct relocation pathway, in APP-PRA-GSC-305 (Ref. 182). The molten debris bed was assumed to separate into two layers, a lower density metal layer over a higher density layer of uranium dioxide and zirconium dioxide. In this analysis, the decay power is assumed to be entirely contained within the oxide layer. In this case, the predicted metal layer was too thin for a focussing effect.

1152 To get a top metal layer that was thick enough for focussing, Westinghouse repeated their calculations with extra molten steel from the core shroud and barrel, which melts with zirconium and uranium to form a corium with three liquid layers that are not in isothermal chemical equilibrium, as observed in the MASCA tests:

- A top layer comprising mainly steel and zirconium with some uranium.
- A middle layer of molten oxides containing most of the decay heat.
- A bottom layer comprising mostly uranium and zirconium plus a small amount of steel.

1153 The focussing effect is a relatively new concept and Westinghouse calculated this part of the scenario outside of the MAAP code, in EPS-PRA-GSC-306 (Ref. 183). Calculating decay powers and layer thicknesses for various faults and reflooding scenarios, Westinghouse found that layering generally did not cause vessel failure by focussing and that IVR was successful in more than 90% of the cases studied.

1154 Westinghouse claim that these two sets of analyses, when taken together, bound the potential IVR states for AP1000:

- The analysis in APP-PRA-GSC-305 (Ref. 182) represents a lower bound mass of iron that could participate in the formation of the bottom metal layer (including only the steel structures below the lower core support plate) and a bounding estimate of the resulting top metal layer thickness crediting only the mass of the lower support plate and core shroud.
- The analysis in EPS-PRA-GSC-306 (Ref. 183) presents an upper bound of the mass of iron that could participate in the formation of a bottom heavy metal layer (maximizing the mass of iron in the bottom layer based on the zirconium oxidation fraction according to Seiler).

Westinghouse consider that these analyses theoretically bound the potential maximum and minimum masses of iron that could be included in the bottom layer.

1155 By maximising the mass of iron in the bottom layer in EPR-PRA-GSC-306 (Ref. 183) Westinghouse claim to have minimised the depth of the top layer. The depths of the top-layers in the scenarios examined were generally greater than 75 cm and I asked Westinghouse and my TSCs what the effect of layer depths of 50 and 30 cm would be. Westinghouse replied that vessel failure would result, but that such depths were very unlikely. The depth of the top layer is dependent of the mass of molten steel and the proportion of steel in the bottom layer. This echoes an informal external review of IVR undertaken for Westinghouse prior to their production of EPR-PRA-GSC-306, see TQ-AP1000-1271 (Ref. 8). My TSC confirmed by calculation that it was possible for a top layer between 30 and 50 cm deep to cause focussing and noted that Westinghouse had not varied the proportion of steel in the bottom layer during some sensitivity analyses (Ref. 185). I believe that the Licensee will need to strengthen the sensitivity studies performed in this area to provide further confidence that such states are indeed very unlikely and there are no “cliff-edge” type effects. This is part of Assessment Finding **AF-AP1000-RC-68**.

1156 The top layer must have a density low enough to float without being so thick that focussing cannot occur. There are a number of geometric parameters to note when considering layering:

- The critical heat flux varies around the walls of the reactor vessel. It is highest at the equator of the plenum and lowest at the pole.
- With a fixed amount of metal in a layered corium melt, the depth of the top layer depends on the depth of the bottom layer as the plenum is wider nearer the top.
- A lower total depth would also mean a lower heat due to partial melting.

1157 This means a precise combination of temperatures, masses and other independent parameters is necessary to cause IVR failure by the focussing effect through the top metal layer. The PRA conducted by Westinghouse concludes these only coincide in 10% of scenarios. It is noteworthy that the simulations conducted for ND by my TSC (Ref. 228) did not reveal any failures due to focussing.

4.6.5.8 Direct Relocation and Heating of the Lower Plenum

1158 The critical heat flux for IVR is lowest at the bottom pole of the lower head. In my assessment, I considered chemistry that could lead to a high heat loading in this zone.

1159 If all the metal transfers to a bottom layer, Westinghouse believe that most of the decay heat will transfer from the top oxide layer upwards and the lower critical heat flux at the pole will not be exceeded. In APP-PRA-GSC-305 (Ref. 182) Westinghouse addresses this scenario by assuming the heat in the lower layer is directly proportional to its uranium content which in turn is limited to 40% by mass. In these calculations, Westinghouse assumed that some of the steel reacted with the fuel to release uranium metal. As they do not react, and it is improbable that steel and fuel should mix in this way, I asked Westinghouse what the effect for IVR would be if the volume of the lower metal layer was smaller. Westinghouse replied the inclusion of extra uranium in the bottom metal layer was pessimistic because it increased the heat to the bottom of the vessel, TQ-AP1000-1050 (Ref. 8).

1160 If there was a direct relocation of corium to the lower head, such a condition could be geometrically unfavourable for IVR because a) critical heat fluxes are lower close to the bottom pole and b) focussing may be more likely. Westinghouse claim that sideways relocation is more likely and occurs sooner than direct relocation, due to the thickness of the core shroud in AP1000.

1161 As part of our assessment, ND commissioned TSC support to repeat fifteen of the Westinghouse sequences using the MELCOR code. The application of this code specifically to AP1000 was still being developed during Step 4. Specific sequences studied included:

- 3BE-0, which goes to early demand for IVR, comparison of oxidation predicted by MAAP4 with MELCOR.
- 3BE-5, which goes to late IVR demand, with high Zr oxidation (claimed success).
- 3BL-0, which although there is melt relocation to the lower plenum and attack on the core plate, debris remains water-covered and so is also a success state.

1162 The report from this work arrived in June 2011. While it is difficult to compare results directly, preliminary results from MELCOR show generally good agreement with MAAP4 simulations for several of the sequences studied. Neither focussing nor failure at the pole was predicted by MELCOR.

1163 As described in Section 4.6.5.6, MELCOR and MAAP do disagreed on the temperature at which core slumping and relocation was initiated. In MAAP this started at 3,100 K, the melting point of pure UO_2 and failure of the core support plate occurred at a similarly high temperature. The equivalent figure in MELCOR is 2,800 K. This means that the corium that transfers to the lower head in MELCOR is a superheated liquid whereas in MAAP, it is an equilibrated slurry containing a large solid fraction. The superheated liquid corium may fail the reactor vessel in a third of the scenarios examined. The results of the VERCORS test programme (Ref. 229) suggest a fuel collapse temperature nearer 2,300 K, even lower than MELCOR. Neither MELCOR nor MAAP claims to predict this key parameter, which is simply an assumption in both codes. I consider temperatures above 3,000 K unrealistically high and data based upon chemical analysis and experiment for the most realistic mixed system should be used, where available.

1164 If the corium that transfers to the lower plenum is fully liquified, MELCOR predicts that it carries sufficient heat with it to cause a temporary thermal transient that could melt the RPV wall in one out of the four scenarios examined. Note that my TSC do not report that IVR will fail, just that the modelling predicts an effect that may cause failure. An important difference between the MAAP and MELCOR analysis here is that MELCOR is not capable of modelling the lower core support plate inside the lower plenum, as is physically the case in the AP1000 design. MAAP does have this capability. Westinghouse argue that if MELCOR could model this feature more accurately, even fully liquified corium would not fail the RPV as the core support plate would initially act as a heat sink for any superheat and ultimately add more metal to the debris to mitigate any potential focussing. While this appears a reasonable argument, it is difficult to compare across different codes in this way and it remains unclear to me if this is an actual predicted consequence or a modelling artefact brought about by the differences in modelling between MELCOR and MAAP.

1165 The correlations used by Westinghouse employ the Nusselt correlation which overestimates heat transfer in the molten pool when there is little or no superheat. This may be another reason why MAAP4 and MELCOR predict different results for SBLOCA. It is good practice to conduct sensitivity analyses, and this has only been undertaken to a limited extent for AP1000, see para 43 in Ref 172.

1166 The amount of heat, steel and fuel are topics that should be reviewed when the complete MELCOR benchmarks are available. I find that the Westinghouse analysis of failure of the bottom part of the lower head that concluded there was no risk was based on a set of assumptions that are invalid. Whether because of higher thermal ratings of the bottom metal layer or because of direct relocation and superheating, local heat fluxes close to the pole of the vessel base may be higher than Westinghouse expects, potentially reducing margins for bottom failure. These calculations should be repeated by more thorough analyses taking more realistic chemistry into account and including metallic fission-products in the heat output for the bottom layer, in a wider sensitivity study. This is part of Assessment Finding **AF-AP1000-RC-68**.

4.6.5.9 Summary

1167 Based upon the evidence presented during GDA, the main conclusions I draw for the assessment of core damage events in AP1000 are:

- It is important to note that Westinghouse claims that severe accidents (i.e. those resulting on core damage) are “virtually excluded” by the AP1000 design and the design of AP1000 has been optimised to minimise the risk of accidents. The core damage frequency claimed by Westinghouse in the PCSR for AP1000 is 2.4 x 10^{-7} per year. The large release frequency for these events is on the order of 2 x 10^{-8} per year. My assessment of core damage has been proportionate to this. The assessment above 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.
- Westinghouse have presented the relevant chemistry related parameters which influence the success or otherwise of IVR. Westinghouse have been developing their analysis in these areas throughout Step 4, and argues that IVR is successful in the majority of accidents where it might be called upon.
- Westinghouse accepts that it cannot demonstrate IVR will be successful in every circumstance, even when the cavity has been flooded. They justify this position by claiming that accident management reduces the likelihood of a demand for IVR and also modifies the chemistry of the melt, making successful IVR much more likely.
- Westinghouse models generally predict melting of the core barrel and sideways relocation. This controls the timing of the sequence and helps to reduce the likelihood of focussing or steam-explosion by reducing the rate of delivery of hot material to the lower plenum.
- The Westinghouse demonstration for IVR includes much pessimism but some of the assumptions used have the ability to obscure phenomena actually taking place. Successful IVR seems to depend on phenomenology including sideways relocation, the significant melting of steel and some fission-product loss. All of these are potentially variable and I do not yet believe that Westinghouse has as yet given adequate consideration to demonstrating these effects. While I consider that an adequate case has been made to support GDA, I consider that the Licensee will need to provide further evidence in these areas and I have raised a number of Assessment Findings to support this.
- I conclude that Westinghouse analyses of failure of the bottom part of the lower head that concluded there was no risk were based on assumptions that were invalid. There remains uncertainty over the likelihood of transferring corium directly to the lower head and the modelling of chemistry within the lower head. While the assumption may be invalid, this does not mean the conclusions are incorrect, however.
- The timings and decay heat predicted by MAAP4 are likely to be sufficiently reliable for assessing IVR. However, some key conclusions in the analysis of AP1000 depend on MAAP4 alone. Such reliance on a single code is not secure, without validation of

its applicability to features of importance to AP1000 such as the core shroud and key melting points.

- The number of sensitivity analyses to key chemical parameters conducted by Westinghouse appears to be limited. I find that the Licensee should undertake independent sensitivity studies using more realistic chemistry to support the Westinghouse analysis. More realistic calculations varying amounts of steel and uranium in the lower head, and the loss of FP heating should be undertaken by the Licensee. These may remove some of the Westinghouse pessimisms, whilst introducing others, but will improve the overall confidence in the safety case.
- As there are no immediate prospects for significant improvements to the understanding of the chemical behaviour of the melt, it is accepted that Westinghouse has taken a conservative approach to other thermodynamic properties of the melt.
- Given that the most recent analyses for IVR include a wider range of actions to add water to a degrading core, there is a need to demonstrate that uncertainties in the late phase melt progression, particularly when there is some re-flooding, have been considered adequately in developing severe accident management guidelines.
- ND accepts the Westinghouse position not to assess corium – basemat interaction which they assume leads to containment failure. This is pessimistic and there are no additional uncertainties for this stage of an accident compared to other PWR designs.
- The Licensee will be expected to keep the safety case up to date with improvements in the knowledge of severe accident phenomena, their consequences and their mitigation.

1168 Overall, I conclude that Westinghouse have made an adequate case to support the claim that the core in AP1000 should remain within the vessel during a severe accident, but parts of the Westinghouse analysis need further testing and refinement. I have raised a number of Assessment Findings in these areas.

4.6.5.10 Assessment Findings

1169 Based upon the assessment of core damage chemistry in AP1000 described in Section 4.6.5 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-AP1000-RC-66 – *The Licensee shall generate evidence for the debris content of the coolant entering the annulus and whether this could adversely affect the performance of vessel cooling in a severe accident. This Assessment Finding should be completed before RPV installation because the inlet to the heat shield fits under the RPV; Target milestone – Install RPV.*

AF-AP1000-RC-67 – *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-AP1000-RC-68 – *The Licensee shall perform a wider sensitivity study on the bottom and top layers of corium taking account of more realistic chemistry of metals and fission-products. This should include sensitivity analyses for the amount of* *fission-product heat loss during core melting for In-Vessel Retention (IVR) success. This Assessment Finding should be completed before first nuclear operations with the reactor; Target milestone – Initial criticality.*

AF-AP1000-RC-69 – *The Licensee shall generate analyses of the accident progression and supporting chemistry data, as used to analyse sequences beyond the design basis. Evidence to support the specific chemistry related assumptions, as referred to in this report, should be clearly and unambiguously presented. This methodology should include evidence that MAAP4 has been validated for the range of calculations presented in the safety case. This Assessment Finding should be completed before first nuclear operations with the reactor; Target milestone – Initial criticality.*

4.6.5.11 GDA Issues

1170 Based upon the assessment of core melt chemistry in AP1000 described in Section 4.6.5 above, I have identified no Reactor Chemistry GDA Issues in this area.

4.7 Overseas Regulatory Interface

1171 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 (US NRC).
- the French Autorité de sûreté nucléaire (ASN).
- the Finnish Säteilyturvakeskus (Radiation and Nuclear Safety Authority, Finland) STUK.

1172 While neither ASN nor STUK are undertaking assessments of the AP1000, I have had some discussions with the US NRC as part of my GDA assessment process, since they are undertaking a similar exercise in respect of the AP1000 for licensing in the United States of America. 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

1173 I have worked with the Environment Agency as an integral part of the GDA assessment process; although for the Westinghouse AP1000 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

1174 I have considered conventional safety legislation in a general sense as part of my GDA assessment, primarily to ensure that the AP1000 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 AP1000.

1175 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 AP1000.

5 CONCLUSIONS

5.1 Conclusions from the Assessment

1176 This report presents the findings of the Step 4 Reactor Chemistry assessment of the Westinghouse AP1000 reactor. I have assessed:

- The Westinghouse 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.

1177 Before summarising the main conclusions for each of the main areas of my assessment two generic points are notable:

- Westinghouse has been continuously developing the design of AP1000 throughout the GDA assessment. While this has caused questions to be raised regarding design definition and the cohesiveness of the safety case, a number of positive design changes have been incorporated which have allayed some of my concerns in the original design.
- As a result of the GDA assessments, the consolidated PCSR for AP1000 has been updated and now includes a chapter dedicated to Reactor Chemistry. This will be a valuable addition to the safety case and should provide a basis for the Licensee to further develop the plant chemistry. As the Step 4 PCSR contained no chemistry chapter, and this chapter was issued during March 2011, I have not yet fully assessed this document. This has been raised as a cross-cutting GDA Issue; **GI-AP1000-CC-02**.

5.1.1 Chemistry Standards, Limits and Conditions

1178 As a plant vendor, Westinghouse do not specify the operational chemistry regimes for AP1000, referring instead to industry guidelines which, in some cases, allow the operator a certain degree of freedom. Westinghouse has greatly improved its chemistry documentation for AP1000 during Step 4 and I am pleased that Westinghouse has produced a *"chemistry manual"* specific to AP1000 to help support the construction, commissioning and operation of AP1000 by the Licensee. This documentation still allows the Licensee to define the precise operating chemistry to be applied in any UK AP1000, therefore the Licensee will need to devise, justify and document the operating chemistry. Additionally, despite these improvements Westinghouse is not able to make ALARP claims for the plant chemistry and this will be required as the safety case for UK AP1000 develops. Westinghouse also does not propose limits and conditions related to the vast majority of chemical or radiochemical parameters. This is a significant deficiency in our expectations, where I expect the plant designer to identify all limits and conditions which are important to safety and derived from the safety case, even if the precise values and timings are unknown at present. These aspects are reflected in my assessment. This is a significant shortfall and will need to be addressed before nuclear safety-related construction and is the subject of a cross-cutting GDA Issue, **GI-AP1000-CC-01**.

5.1.2 Primary Circuit

1179 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. Westinghouse has designed AP1000 to use natural boric acid, without the capability to recycle the effluent, and have incorporated a system of 'grey rods' to minimise the requirements for coolant control during the operating cycle. This simplifies the boron management of the plant, removes many components and simplifies concerns regarding accumulation of radioactivity and contamination. I assessed the systems for managing boron in the primary circuit, including the potential for inadvertent dilution and found a reasonable case had been presented, but further work was needed to document the whole case. With these exceptions, I am content with the proposed design for boron control in AP1000.

1180 As described above, Westinghouse have chosen not to specify the precise operating chemistry for AP1000, leaving such decisions to the Licensee. This is a significant aspect that will need further work as the safety case for AP1000 is developed. I am content that AP1000 can be operated safely within the broad guidance suggested by Westinghouse, but expect that the Licensee will need to define robust and tight controls to achieve an ALARP operating strategy.

1181 I have assessed the major chemistry systems which allow the operator to control, monitor and change the primary chemistry, including those that are used during accidents. The AP1000 has a number of systems for these aspects which have been simplified and made passive, in line with the overall plant design philosophy, but are functionally very similar to existing PWRs in a number of regards.

1182 I have assessed the Chemical and Volume Control System (CVS) in some detail as part of my assessment. This system is novel in a number of aspects due to its operation at full RCS pressure, inside containment and with direct injection of hydrogen for corrosion control. I am content that an adequate case has been made from a Reactor Chemistry perspective for most of this system, with the exception of the hydrogen dosing control.

Hydrogen dosing impacts on other considerations such as ORE and radwaste dependant upon how the Licensee chooses to use the capabilities. The hydrogen dosing arrangement was subject to a late design change during GDA and I have not yet been provided with adequate evidence to demonstrate that this system will operate as expected. Due to the importance of maintaining tight control of hydrogen, I have raised this as GDA Issue **GI-AP1000-RC-03**, requiring Westinghouse to demonstrate that the hydrogen dosing system in AP1000 has the capacity and capability to provide suitable control over the primary coolant hydrogen concentration during all operating modes and potential faults.

1183 Sampling of the primary coolant is an important chemistry function allowing the operator to maintain control. The nuclear sampling system is another feature which has been simplified in the AP1000 design. Based partly upon our assessment, Westinghouse incorporated a design change late in GDA. While significantly improving the design, and resolving some of our concerns, I am still not content that the design is adequate and have a number of concerns regarding sampling adequacy, waste generation, design features and overall sampling capability. Westinghouse has not shown the design to be equivalent to relevant good practice in this area. I believe that these concerns must be resolved before nuclear safety-related construction and consider that further design changes may well prove to be necessary. I have raised this as a GDA Issue for Westinghouse to demonstrate that the sampling arrangements for the primary circuit and connected auxiliary systems of AP1000 are adequate to support safe operations; **GI-AP1000-RC-02**.

1184 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 AP1000 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 heavy levels of wear. Their use has declined over the years but they can only be eliminated if the alternative is proven to be suitable. Westinghouse presented a reasoned case in this regard, although Stellite^{TM} reduction should be kept under review for each AP1000 unit as this is a developing area. I also asked Westinghouse to assure me that the trace cobalt content of alloys in AP1000 has been reduced significantly, which they have done. Westinghouse also provided details on other impurities and alloys likely to cause radioactivity. Westinghouse has proposed to electropolish the steam-generator channel heads as a means to further reduce activity build-up in these areas. The overall approach demonstrated by Westinghouse to materials related issues was encouraging and well reasoned and presented.

1185 One technique being applied by many operators worldwide is the addition of zinc to primary coolant. Traces of zinc are claimed to control radiation fields within reactors. It was less clear if there were any detrimental effects of zinc addition and I asked Westinghouse for extensive evidence, which they provided. On the balance of evidence presented, it appears that zinc addition is justified and the use of zinc during commissioning appears to be a welcome addition.

1186 Estimates of the radioactive materials such as tritium and cobalt isotopes that would be produced by AP1000, have been provided by Westinghouse based on a standard US method. These estimates took no account of different management schemes for AP1000, nor in some instances the specifics of the design. Based on the evidence Westinghouse have provided, plus our independent reviews, I believe that AP1000 may be prone to the development of fuel crud and production of cobalt isotopes unless robust controls are put in place by the Licensee. This will be an area where further work is required by the Licensee to develop the AP1000 safety case for the UK.

5.1.3 Spent Fuel Pool

1187 The AP1000 SFP safety case related to criticality and loss of cooling events relates to Reactor Chemistry in a number of areas including boron control and the potential for radioactive releases. This has been a cross-cutting area during GDA. In response to our assessment, Westinghouse has proposed a number of design improvements to the Spent Fuel Pool and has revised the safety case in a number of areas. Whilst broadly in line with my expectations, these were received late in GDA and will need further assessment. A GDA Issue has been raised in this area, which will require a satisfactory resolution before an adequate safety case can be made; **GI-AP1000-FS-01**.

5.1.4 Secondary Circuit

1188 Despite Westinghouse identifying all aspects of the secondary circuit as being in the scope of the GDA assessment, a number of the important chemistry systems are not yet fully designed. Despite these gaps I have assessed a number of aspects of the design including principal material choices, corrosion threats, chemistry control and tolerance of abnormal chemistry. At a high level it is apparent that Westinghouse has incorporated operating experience and feedback into the design and main material choices for AP1000. A number of detailed material choices, and the operating chemistry, are not yet decided and will only be defined by the eventual Licensee. Thus while reasonable arguments have been made by Westinghouse in these areas, the principal deficiency is that a holistic assessment of 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. I have identified a number of Assessment Findings where further work will be required. 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.

1189 A novel design choice for the AP1000 secondary circuit is the use of Electrodeionisation (EDI) for purification of the steam generator blowdown. All other PWRs, with the exception of one, use conventional ion-exchange based treatment systems. I have assessed a number of features of this design and have been satisfied with the responses from Westinghouse for the most part, with some areas requiring further work. In response to my questioning during GDA, Westinghouse have initiated a test programme for the EDI with alternative secondary chemistry treatments, but results are not yet available. On the basis that these tests do not find any problems, I am content that an adequate case has been made for this system for GDA, although would encourage further testing under actual plant conditions.

5.1.5 Ancillary Systems

1190 AP1000 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 ion exchange systems for liquid wastes. These are based on mature and proven technology. I have raised findings for the Licensee to further define the design and controls for these systems in operation.

1191 The design of the ancillary component heat removal system, the CCS, incorporates many features of existing power plants. While Westinghouse has not defined the operating chemistry for this system I can see no reason why one cannot be specified by the Licensee.

5.1.6 Accident Chemistry

1192 The AP1000 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.

1193 As a result of ND assessment, Westinghouse amended their calculations for SGTR events during Step 4. The revised case included a revised chemistry model. Overall the case presented by Westinghouse includes the majority of the fundamental chemistry that I would expect to see in the safety case for SGTRs, although in some cases it has been simplified. The assumptions used appear to be very conservative for the most part, with the exception of not considering releases post break equalisation. In addition to SGTR Westinghouse amended the analysis of a number of design basis events, such as LOCA, and I have not assessed the chemistry of these.

1194 AP1000 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 (PAR) for design basis events and igniters for severe accidents. From a chemistry perspective the claims, arguments and evidence in this area are reasonable.

1195 For the extremely unlikely event that the core is damaged and the effects of decay heat and reduced cooling combine so that that the core becomes hot enough to melt fuel, AP1000 provides an in-vessel melt retention system. This involves flooding the pit and the vessel with water from the IRWST, the chemical performance of which I assessed. I concluded that some aspects of the Westinghouse analysis of IVR were very pessimistic but certain chemical assumptions were not supported by several independent analyses. However, I am satisfied that a reasonable argument has been presented and that the overall containment goal is more often than not achievable.

1196 The containment of AP1000 has been designed to retain radioactive material in an accident which simplifies the management of radioiodine. AP1000 does not include a recirculating, pH buffered spray system for fission product control as in many PWRs, instead relying on a passive deposition mechanism driven by external cooling supplemented by a spray if necessary. The chemistry aspects of this case were presented to ND very late in GDA and I have asked Westinghouse to demonstrate that the source term released into the containment during accidents is appropriate for AP1000 in GDA Issue **GI-AP1000-RC-01**. Until my queries over the source term are satisfactorily resolved, I cannot conclude on the adequacy of the design in this area.

5.1.7 Overall Reactor Chemistry Safety Case for AP1000

1197 To conclude, I am broadly satisfied with the claims, arguments and evidence laid down within the PCSR (Ref. 1) and supporting documentation for the AP1000 (Ref 240). I note that the PCSR I assessed for Step 4 did not contain much chemistry information, but Westinghouse have provided responses to my queries in supporting documents and have undertaken a revision to the PCSR to include the chemistry related aspects of the safety case, albeit too late for assessment during Step 4 (**GI-AP1000-CC-02**).

1198 I consider that from a Reactor Chemistry view point, the Westinghouse AP1000 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

1199 As a consequence of my assessment of the AP1000 reactor design for GDA, I have identified 69 Assessment Findings and 3 specific and 3 cross-cutting Reactor Chemistry GDA Issues that need to be resolved, as appropriate.

5.2.1 Assessment Findings

1200 I conclude that the Assessment Findings listed in Annex 1 should be addressed during the forward programme of this reactor as normal regulatory business.

5.2.2 GDA Issues

1201 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.

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Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 3)

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. 3)

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. 3)

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.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 3)

SAP No.	SAP Title	Description
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.
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.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 3)

SAP No.	SAP Title	Description
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.
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.

Table 1

Relevant Safety Assessment Principles for Reactor Chemistry Considered During Step 4 (Ref. 3)

SAP No.	SAP Title	Description
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.
FA.18	Calculation methods	Calculational 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	96
T/AST/007	01	Severe accident analysis	97
T/AST/037	01	Heat transport systems	98
T/AST/005	04	ND guidance on the demonstration of ALARP (as low as reasonably practicable)	99
T/AST/014	01	Internal hazards	100
T/AST/023	01	Control of processes involving nuclear matter	101
T/AST/016	02	Integrity of metal components and structures	102
T/AST/021	01	Containment: chemical plants	103
T/AST/022	01	Ventilation	104

Table 3

Step 4 Reactor Chemistry Assessment Topics (Ref. 5)

	Area	**Topic**	**Assessment Objective**	**Relevant section(s) in this report**
01	Standards	Application	Identify detailed application of EPRI material and its development into a standard	4.2.10
02	Start-up and Shutdown	Primary	Identify current approach and expectations for start-up and shutdown, 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	Demonstration that the system performance and reliability requirements of the CVS are substantiated by the detailed engineering design. Dosing equipment.	4.2.2
05		Radioactivity	Demonstration that 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 formed	4.2.5
08		Zinc	Demonstration that zinc addition is beneficial and waste is reduced SFAIRP	4.2.6
09		Hydrogen	Demonstration that hydrogen levels are adequate for safe plant operation	4.2.7
10		Safety Systems	Demonstration that chemical conditions are maintained in safety circuits	4.2.8
11		Sampling	Demonstrate system provides adequate control and sampling activities safe	4.2.9
12		Holistic View	Demonstrate chemistry needs of ORE, circuit and fuel integrity are balanced	4.2.10
13	Secondary Circuit	Chemistry and Materials	Demonstration that chemistry needs of circuit materials, fouling and impurity control are adequately balanced	4.4.2
14		Integrity	Demonstration that the chemistry maintains integrity of the pressure boundary and key components	4.4.3
15		Sampling	Demonstrate system provides adequate control for safety	4.4.4
16	Fuel Pool Systems	Spent Fuel Pool	Demonstration that requirements for normal operations, SFP faults and extended lifetime are adequate	4.3
17	Accident Chemistry	Source Terms	Demonstration that chemistry factors are adequately accounted for	4.6.2.3, 4.6.3.2, 4.6.4.2 and 4.6.5

Table 3

Step 4 Reactor Chemistry Assessment Topics (Ref. 5)

	Area	Topic	Assessment Objective	Relevant section(s) in this report
18		SGTR	Demonstrate underlying chemistry in fault is appropriately identified and applied	4.6.2
19		Hydrogen Control	Demonstration that performance of hydrogen control system would meet the demands placed upon it	4.6.3
20		FP Control	Demonstration that filters and sprays adequate to control Fission Product releases	4.6.4
21		Core Melt	Demonstrate key parameters included and are 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	Demonstration of 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 AP1000 (Ref. 19)

No.	Text
1	Not all areas have been fully assessed within the current AP1000 PCSR due to difficulties in separating out claims and arguments (Step 3) as Westinghouse is still developing arguments and evidence in a number of areas for Reactor Chemistry.
2	Detailed commentary on the AP1000 safety case has been provided. As stated the PCSR makes extensive use of the DCD in providing the bulk of the safety case information. However, even in combination these two documents do not provide a complete ‘claims – arguments - evidence’ submission; specifically some of the ‘evidence’ that would be required for Reactor Chemistry assessment, especially in GDA Step 4 and subsequent licensing, is lacking. Even with these shortcomings the submission provided for Step 3 was just satisfactory as a starting point for the Reactor Chemistry assessment conducted.
3	Westinghouse will need to address these shortcomings in safety documentation during Step 4. We will agree a way forward with Westinghouse for the next issue of the PCSR.
4	The AP1000 design includes a number of novel and/or technically complex systems. These interact directly with the Reactor Chemistry assessment. Westinghouse will need to supply evidence and justification for these systems (from a Reactor Chemistry perspective) during Step 4.
5	Westinghouse believes that Reactor Chemistry has been used as an input during the development of the AP1000 design. However, based on the balance of the assessment conducted so far, we believe that contrary to this belief the chemistry is on occasion being used as a remediation rather than mitigation and some systems may not have benefitted from a significant chemistry input. This is exemplified by the necessity (as opposed to an aim) of zinc addition in AP1000.
6	The overall view formed during this assessment is that ALARP justifications are an area where further work will be needed by Westinghouse.
7	Analysis and substantiation of Reactor Chemistry is ongoing at Westinghouse which is aimed at demonstrating the design proposal will meet the safety objectives before construction or installation commences.
8	Westinghouse has taken account of EPRI guidelines, but not the latest versions and has not accounted for the draft IAEA chemistry standard.
9	In common with other regulators, ND does not have direct access to current EPRI documentation applicable to AP1000. We will require Westinghouse to provide an appropriate means of accessing this information during Step 4, especially where it is cited as evidence.
10	For the regulator, further interaction with NRC and input from standard bodies for Reactor Chemistry (e.g. EPRI, VGB etc.) may be necessary.
11	We believe that the standards applied to the chemistry of AP1000 are becoming increasingly important. In the chemistry context a ‘standard’ relates to the ability of the designer or operator to compare chemical predictions and procedures with current practice of other designers, operators or even industries. Westinghouse may improve areas where design and operating safety assumptions for AP1000 can be verified against external evidence and present these in safety documentation.
12	Due to the design of AP1000, we expect containment access to be restricted when the RCS is at pressure. Direct operator access to containment to clear faults therefore cannot be assumed.
13	We believe significant safety aspects of secondary circuit corrosion and integrity should be included in the scope of GDA for Step 4.
14	We are encouraged that Westinghouse appears to have put a significant effort into the chemistry effects of severe accidents, although some of the assessment may be dated.

Table 4

Conclusions from Step 3 Reactor Chemistry Assessment of AP1000 (Ref. 19)

No.	Text
15	To meet the GDA deadlines and provide ND with information for use in our assessment of chemistry in AP1000, 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 and EDCD Reactor Chemistry Content (Refs 1 and 22)

Chapter	Title	Section(s)	Examples of relevant Reactor Chemistry content
Pre-Construction Safety Report			
1	Introduction	all	Safety case structure and overview
2	General plant description	all	General description of plant
4	Safety aspects of design	2, 3, 4, 5	Classification of SSCs, hazard identification
5	Safety assessment approach	2, 3, 5	Fault schedule, DBA, Severe accident analysis
6	Description of plant systems and their conformance with design requirements	2, 3, 4, 5, 6	Primary circuit, reactor design, engineered safety features, auxiliary systems (CVS, H_2 control, RNS, CCS etc.), radwaste systems, sampling systems, secondary systems (BDS, condenser etc.)
8	ALARP assessment of the design of the AP1000	2, 3, 4	Relevant good practice, PRA approach, major design decisions
9	Safety management throughout the plant lifecycle	3	Commissioning, operations
10	Commissioning	5, 13	Procedures, HFT
11	Operational management	all	Limits and conditions, EMIT, operational management
12	Radiological protection	2, 4	Source terms, ALARP
14	Environmental aspects	2	Discharges
15	Radioactive waste management	4	Liquid waste systems, gaseous waste systems
European Design Control Document			
1	Introduction and general plant description	1 to 9	General description of plant
3	Design of structures, components, equipment and systems	1, 8, Appendix 3B, Appendix 3D	Conformance with NRC criteria, leak-before-break evaluation, design of structures and components, containment design
4	Reactor	2, 3, 5	Fuel design, reactivity control, reactor materials
5	Reactor cooling system and connected systems	2, 3, 4	Reactor coolant system design, connected systems, RPV material specifications, primary water chemistry specifications, corrosion, CMTs, ADS, SG design

Table 5

Step 4 PCSR and EDCD Reactor Chemistry Content (Refs 1 and 22)

Chapter	Title	Section(s)	Examples of relevant Reactor Chemistry content
6	Engineered safety features	2, 3	Containment systems and emergency tanks, passive core cooling system, containment cooling, hydrogen control systems, sump pH control, IRWST and spargers, fission product control
9	Auxiliary systems	1, 2, 3, 4	SFP cooling and clean-up systems, CCS design, demin water treatment system, primary and secondary sampling systems, CVS, ventilation including HEPA filters
10	Steam and power conversion	1, 3, 4	Secondary circuit overview including steam and power conversion systems, secondary side chemistry, condensate polishing system, FW system, BDS design, chemical dosing
11	Radioactive waste management	1, 2, 5	Source terms, radwaste , monitoring
12	Radiation protection	1, 2, 4	Source terms, radiation protection and ALARP – zinc, dose assessment
14	Initial test program	2	Test program
15	Accident analyses	0, 1, 4, 5, 6, 7	Accident analyses, inadvertent boron dilution, inadvertent water addition, LOCA including source terms, releases from other subsystems, SGTR
16	Technical specifications	Bases parts 1 and 2, Tech specs	Reactor core safety limits, reactor coolant limits, tech specs including boron, lithium etc.
18	Human factors engineering	2, 6	Human factors – staffing
19	Probabilistic risk assessment	0, 15, 34, 36, 39, 41, Appendix 19B, Appendix 19E	CVS, IVR, H_2 generation, PRA including boron dilution

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-01	The Licensee shall specify the normal operating chemistry regimes for the primary, secondary and auxiliary circuits of UK AP1000. The specifications should be comprehensive and incorporate evidence for all modes of operation.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence; Target milestone – Cold Ops.
AF-AP1000-RC-02	The Licensee shall specify the chemistry-related action level boundaries that are appropriate for AP1000. The documentation shall include evidence that the boundaries are appropriate and a demonstration that Operational Experience Feedback (OEF) has been used in their development.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence; Target milestone – Cold Ops.
AF-AP1000-RC-03	The Licensee shall generate evidence that operating chemistry regimes, including limits/conditions and action levels/corrective actions, do reflect the design of UK AP1000 given its difference to existing PWRs.	This Assessment Finding should be completed before plant operations using the intended operating chemistry commence; Target milestone – Cold Ops.
AF-AP1000-RC-04	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.

Annex 1

Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-05	The licensee shall update the safety case to include a more detailed consideration of homogeneous boron dilution events, including sources, mitigation and consequences and review operating procedures for dilution control in the Chemical and Volume (control) System (CVS).	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-AP1000-RC-06	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 controls 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-AP1000-RC-07	The Licensee shall review which valves could be subject to Stellite^{TM} replacement, especially those which are "*optional*" according to procurement specifications. The review shall include environmental conditions of the valve in service and likely wear rates with evidence supporting the final selection made.	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-AP1000-RC-08	The Licensee shall review and consider alternative materials to Stellite^{TM} for applications within AP1000, 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.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-09	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-AP1000-RC-10	The licensee shall define a surveillance programme for control rods, flywheels 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-AP1000-RC-11	The Licensee shall conduct sensitivity analysis for fuel crud formation in AP1000. This should be used to demonstrate that levels of crud can be controlled and reduced So Far As Is Reasonably Practicable (SFAIRP) in AP1000 and should be based upon the detailed operating chemistry and core design for the UK AP1000 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 AF-AP1000-RC-01; Target milestone – Initial criticality.
AF-AP1000-RC-12	The Licensee shall review how the thresholds for power-shift due to crud (CIPS) or crud induced localised corrosion (CILC) are justified, and the methods of measurement to which they apply. The Westinghouse threshold appears to be based purely on plant Operational Experience Feedback (OEF).	This Assessment Finding should be completed before nuclear operations, as this is when fuel crud is formed; Target milestone – Initial criticality.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-13	The licensee shall review and justify the controls that are in place throughout the fabrication, installation and commissioning of metal surfaces that will be in contact with primary coolant to ensure that releases will be ALARP. This may involve a review of fabrication and site controls that influence corrosion release.	This Assessment Finding should be completed before relevant metal surfaces are delivered to site; Target milestone – Mechanical. Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-AP1000-RC-14	The Licensee shall ensure that the safety case related to zinc addition in AP1000 is consistent regarding concentrations, limits, zinc form and claims, arguments and evidence.	This Assessment Finding should be completed before zinc is first used in the reactor systems; Target milestone – Hot Ops.
AF-AP1000-RC-15	The licensee shall specify limits for silica, iron and nickel in the primary circuit of AP1000 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.
AF-AP1000-RC-16	The Licensee shall ensure that the form of zinc used and the amounts added will result in a net reduction of radioactivity across the plant and in wastes.	This Assessment Finding should be completed before zinc is applied to the reactor with nuclear fuel present; Target milestone – Initial criticality.
AF-AP1000-RC-17	The Licensee shall review the latest evidence for the effectiveness of low levels of zinc at controlling corrosion in alloy 690 and stainless steels before deciding on a regime for its addition. The review should consider both the Inconel 690 and stainless steel components.	This Assessment Finding should be completed before zinc is first used in the reactor systems; Target milestone – Hot Ops.
AF-AP1000-RC-18	The Licensee shall decide on the optimum band for hydrogen concentration in AP1000, once Westinghouse has demonstrated that the design of the dosing system fulfils its required function (in GDA Issue GI-AP1000-RC-03). The specification should include justification for the limits chosen and the actions to be taken when limits are exceeded.	This Assessment Finding should be completed before hydrogen is first applied to the reactor; Target milestone – Hot Ops.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-19	The licensee shall specify operating procedures for monitoring safety systems chemistry, detecting and removing out of specification fluids, and reviewing any unusual behaviour.	This Assessment Finding should be completed before any safety stocks of coolant are needed and filled for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-20	The Licensee shall define restrictive specifications for cobalt in the primary sampling system lines.	This Assessment Finding should be completed before procurement of the sampling system lines; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-AP1000-RC-21	The Licensee shall review the need for manual operation of isolating valves on the primary sampling system manifold, including consideration of operator radiation exposure and operability with the plant at power. Consideration should be given to operating rules to limit the time spent with the sampling system in a degraded functional state.	This Assessment Finding should be completed before active operations commence; Target milestone – Initial criticality.
AF-AP1000-RC-22	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.
AF-AP1000-RC-23	The Licensee shall specify values for radiochemistry parameters prior to head-lift during a shutdown, including evidence of their suitability and links to the safety case.	This Assessment Finding should be completed before the plant is first operated with nuclear power, as this is when activity is first generated; Target milestone – Initial criticality.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-24	The Licensee shall specify timings and criteria for stopping the main reactor coolant pumps, including swapping to residual heat removal flow control. The criteria should be linked to the claims for chemistry in the safety case.	This Assessment Finding should be completed before the plant is first operated with nuclear power, as this is when activity is first generated; Target milestone – Initial criticality.
AF-AP1000-RC-25	The Licensee shall ensure that oxygen levels are controlled in the residual heat removal system during shutdowns. Documented controls should include appropriate limits and conditions related to allowable concentrations and temperatures before connection to the reactor coolant system.	This Assessment Finding should be completed before inactive commissioning activities commence; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-26	The Licensee shall define arrangements that are specific to the design of AP1000, for the management of ion exchange resins and filters in the Chemical and Volume control System (CVS). The effect of the timing of changes on operator radiation exposure, wastes and plant chemistry should be considered, as well as operational transients and un-planned operations.	This Assessment Finding should be completed before nuclear operations, as this is when the ion exchange and filters will trap radioactive materials; Target milestone – Initial Criticality.
AF-AP1000-RC-27	The Licensee shall specify chemistry requirements for start-up and shutdown following anticipated operational transients such as fuel failure.	This Assessment Finding should be completed before fuel is first loaded into the reactor core; Target milestone – Initial Criticality.
AF-AP1000-RC-28	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 AP1000 units commissioned prior to any UK new build. The documentation should justify the controls during HFT of AP1000, 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.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-29	The Licensee shall define the chemistry requirements associated with testing of the Passive Core Cooling System (PXS) during commissioning.	This Assessment Finding should be completed before the PXS is first exercised and corrosive or flammable conditions may be created; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-30	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-AP1000-RC-31	The Licensee shall review the adequacy of the sampling arrangements for boron in the spent fuel pool, including justification for the choice of continuous on-line instrumentation versus grab sampling.	This Assessment Finding should be completed before fuel is brought on to site and boron is required for reactivity control purposes; Target milestone – Fuel on-site.
AF-AP1000-RC-32	The Licensee shall review and document the justification for the corrosion monitoring scheme for the Metamic^{TM} material in the spent fuel pool racks.	This Assessment Finding should be completed before plant fuel is delivered to site, to permit the location of coupons or measurements; Target milestone – Fuel on-site.
AF-AP1000-RC-33	The Licensee shall review and document the justification for the surface treatment to be applied to the Metamic^{TM} material in the spent fuel pool racks.	This Assessment Finding should be completed before fuel is brought on to site and the pools are filled, but should be considered during manufacture; Target milestone – Fuel on-site.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-34	The Licensee shall consider the surface finish to be applied to areas of the spent fuel pool subject to level oscillations and produce a justification for the finish specified.	This Assessment Finding should be completed before fuel is brought on to site and the pools are filled, but should be considered during manufacture; Target milestone – Fuel on-site.
AF-AP1000-RC-35	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.
AF-AP1000-RC-36	The Licensee shall generate evidence that controls over radioactivity (excluding tritium) in the spent fuel pool and connected systems, including the IRWST, are adequate for UK AP1000. This should include consideration of those factors out of scope for the GDA assessment, such as detailed operating and shutdown chemistry regimes, limits and conditions and operational procedures. This should include consideration of both operator radiation exposure and discharge considerations.	This Assessment Finding should be completed before nuclear operations, as this is when activity will be first generated; Target milestone – Initial Criticality.
AF-AP1000-RC-37	The Licensee shall produce evidence that the secondary cooling water source chemistry is within the design basis for the AP1000 'standard plant' assessed as part of GDA.	This Assessment Finding should be completed before operation of the plant; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-38	The licensee shall update the safety case documentation to reflect the defined secondary chemistry regime. The Licensee shall ensure that chemistry parameters are consistent, wherever mentioned in safety documentation.	This Assessment Finding should be completed before operation of the plant; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-39	The Licensee shall conduct a design review for post-electrodeionisation (EDI) treatment in the steam generator blowdown system, based upon the site operating chemistry.	This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-40	The Licensee shall generate evidence for testing of the AP1000 electrodeionisation (EDI) system with the intended operating chemistry.	This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-41	The Licensee shall generate evidence for the performance of the steam generator blowdown electrodeionisation (EDI) system under representative site operating conditions, including chemistry regime and at representative temperatures, or shall document the justification for why such evidence is not required to support the safety case.	This Assessment Finding should be completed before operation of the plant, but should be considered before installation of the plant can be completed and the system is used for the first time; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-42	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.	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-AP1000-RC-43	The Licensee shall review the condensate polishing system (CPS) performance requirements once an operating chemistry regime, cooling water source and limits and conditions are defined. Documentation for the review should include justification for the final performance specification.	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-AP1000-RC-44	The Licensee shall review the requirements for automatic actions in case of significant ingress of impurities that could damage Steam Generator (SG) 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, but should be considered during the design finalisation stage for the secondary circuit, as this may indicate design changes are necessary; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.
AF-AP1000-RC-45	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 operation of the plant but with sufficient time to allow design modifications if necessary; Target milestone – Hot Ops.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-46	The Licensee shall review requirements for a minimum chromium specification for carbon steel pipework in the secondary circuit and ensure the relevant pipework and fittings are procured to the specifications made.	This Assessment Finding should be completed before relevant metal surfaces are delivered to site; Target milestone – Mechanical. Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-AP1000-RC-47	The Licensee shall specify arrangements for sampling of the secondary side of the steam generators in the case of a tube rupture, including evidence that the specifications are appropriate.	This Assessment Finding should be completed before nuclear operations, but should be considered during design finalisation to allow for any changes as necessary; Target milestone – Initial criticality.
AF-AP1000-RC-48	The Licensee shall review the implications of 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-AP1000-RC-49	The Licensee shall review the design of the secondary sampling systems and consider reasonably practicable measures that could be taken to improve the sampling capabilities, especially for those samples which are used for automatic control of the plant chemistry.	This Assessment Finding should be completed before hot operation of the secondary side of the plant, but should be considered during design finalisation to allow for any changes as necessary; Target milestone – Hot Ops.
AF-AP1000-RC-50	The Licensee shall review the tolerance of the gaseous radwaste systems (WGS) to explosive hazards and generate evidence that the specified flammable gas limits are appropriate.	This Assessment Finding should be completed before the system is commissioned so that its performance can be verified; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – inactive commissioning.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-51	The Licensee shall undertake a rigorous assessment of the gaseous radwaste system (WGS) performance when a fully developed outage schedule is prepared.	This Assessment Finding should be completed before the system is commissioned so that its performance can be verified, but should be considered earlier; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-AP1000-RC-52	The Licensee shall conduct a review of the types of liquid waste ion exchange and absorbent media to be used in the liquid radwaste system (WLS). This will be based on developments in ion-exchange technology, estimated volumes and specific characteristics of the liquid radwaste to be processed. The review should also taking account of ALARP considerations and provide evidence for the suitability of the chosen design.	This Assessment Finding should be completed before radioactive waste is produced in the reactor; Target milestone – Initial criticality.
AF-AP1000-RC-53	The Licensee shall generate evidence that the liquid radwaste system (WLS) sampling system is adequate.	This Assessment Finding should be completed before the equipment monitoring radioactive waste is commissioned; Target milestone – Mechanical, Electrical and C&I Safety Systems, Structures and Components – delivery to Site.
AF-AP1000-RC-54	The Licensee shall generate evidence to demonstrate the adequacy of the arrangements for monitoring filter and ion exchange vessel pressure drops and dose rates.	This Assessment Finding should be completed before radioactive waste is produced in the reactor, but should be considered beforehand to minimise any changes as necessary; Target milestone – Initial criticality.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-55	The Licensee shall include the safety aspects of the component cooling water system (CCS) 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-AP1000-RC-56	The Licensee shall analyse the chemistry of SGTR faults completely, to a safe shutdown state when all releases have effectively ceased. The analysis should consider all release paths using the most up to date knowledge of iodine chemistry, where appropriate.	This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated, but should be considered prior to this to ensure SAP Target 4 limits can be met; Target milestone – Initial criticality.
AF-AP1000-RC-57	The Licensee shall review use of the ‘backfill’ method for depressurisation in steam generator events, if this continues to be credited in the safety case. The review shall present evidence that safety implications of the backfill method, if used, have been considered.	This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated; Target milestone – Initial criticality.
AF-AP1000-RC-58	The Licensee shall consider a more appropriate source term for the analysis of steam generator tube rupture events and generate evidence that the source term is appropriate. Arbitrary reductions in source terms to meet limits are not appropriate without justification.	This Assessment Finding should be completed before nuclear operations, when radioactivity is first generated; Target milestone – Initial criticality.
AF-AP1000-RC-59	The Licensee shall review and document the hydrogen source term used in the design basis accident sequences which release hydrogen. The review should confirm that the methodology is relevant and applicable to AP1000.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-60	The Licensee shall confirm the performance of the as-installed Passive Autocatalytic Recombiners (PARs) is consistent with that used within the safety case analysis.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.
AF-AP1000-RC-61	The Licensee shall review and document the examination, maintenance, inspection and testing arrangements for the (Passive Autocatalytic Recombiners) PARs and hydrogen igniters.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.
AF-AP1000-RC-62	The Licensee shall consider any potential negative effects of Passive Autocatalytic Recombiners (PARs) in the analysis of accidents and update the Safety Case if necessary.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.
AF-AP1000-RC-63	The Licensee shall justify why more detailed analyses of flow and fast combustion in AP1000, in order to capture localised effects on combustion, is not required.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.
AF-AP1000-RC-64	The licensee shall review the potential for the high temperature spikes caused by igniters to convert iodides to volatile forms of iodine and update the safety case and analysis if necessary.	This Assessment Finding should be completed before fuel is loaded into the reactor, as this is the hydrogen source; Target milestone – Fuel load.
AF-AP1000-RC-65	The licensee shall review severe accident management guidelines for the provision of spray water for fission product control and consider whether any improvements to the Containment Spray System (CSS) design or performance would be reasonably practicable.	This Assessment Finding should be completed before initial nuclear operations of the reactor; Target milestone – Initial criticality.

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Assessment Findings to Be Addressed During the Forward Programme as Normal Regulatory Business

Reactor Chemistry – AP1000

Finding No.	Assessment Finding	MILESTONE (by which this item should be addressed)
AF-AP1000-RC-66	The Licensee shall generate evidence for the debris content of the coolant entering the annulus and whether this could adversely affect the performance of vessel cooling in a severe accident.	This Assessment Finding should be completed before RPV installation because the inlet to the heat shield fits under the RPV; Target milestone – Install RPV.
AF-AP1000-RC-67	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-AP1000-RC-68	The Licensee shall perform a wider sensitivity study on the bottom and top layers of corium taking account of more realistic chemistry of metals and fission-products. This should include sensitivity analyses for the amount of fission-product heat loss during core melting for In-Vessel Retention (IVR) success.	This Assessment Finding should be completed before first nuclear operations with the reactor; Target milestone – Initial criticality.
AF-AP1000-RC-69	The Licensee shall generate analyses of the accident progression and supporting chemistry data, as used to analyse sequences beyond the design basis. Evidence to support the specific chemistry related assumptions, as referred to in this report, should be clearly and unambiguously presented. This methodology should include evidence that MAAP4 has been validated for the range of calculations presented in the safety case.	This Assessment Finding should be completed before first nuclear operations with the reactor; Target milestone – Initial criticality.

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

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

Annex 2

GDA Issues – Reactor Chemistry – AP1000

WESTINGHOUSE AP1000® GENERIC DESIGN ASSESSMENT

GDA ISSUE

ACCIDENT SOURCE TERMS

GI-AP1000-RC-01 REVISION 0

Technical Area	**REACTOR CHEMISTRY**		
Related Technical Areas	Fault Studies Probabilistic Safety Assessment Radiation Protection		
GDA Issue Reference	**GI-AP1000-RC-01**	**GDA Issue Action Reference**	**GI-AP1000-RC-01.A1**
GDA Issue	Westinghouse should provide justification to demonstrate that the source term released into the containment during accidents is appropriate for AP1000.		
GDA Issue Action	Westinghouse to demonstrate that the accident source term is applicable to the passive design features of AP1000, and justify the sensitivity of the analyses to more realistic radionuclide behaviour in the containment. Westinghouse should provide analyses, or alternative means agreed by the regulator, to justify the duration and quantity of the release including both the short and long term behaviour. With agreement from the Regulator this action may be completed by alternative means.		

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WESTINGHOUSE AP1000® GENERIC DESIGN ASSESSMENT

GDA ISSUE

PRIMARY SAMPLING SYSTEMS

GI-AP1000-RC-02 REVISION 0

Technical Area		**REACTOR CHEMISTRY**	
Related Technical Areas		Mechanical Engineering Radiation Protection	
GDA Issue Reference	**GI-AP1000-RC-02**	**GDA Issue Action Reference**	**GI-AP1000-RC-02.A1**
GDA Issue	Demonstrate that the sampling arrangements for the primary circuit and connected auxiliary systems of AP1000 are adequate to support safe operation of the plant.		
GDA Issue Action	Westinghouse to provide a detailed schedule of sampling required to support operation of AP1000. This schedule should include consideration of all modes of operation and should consider: • Parameters to be measured from which location and the frequency of sampling. • The schedule should be clearly linked back to the safety case. • Where the sample is expected to be collected (i.e. using the Grab Sample Panel (GSP), radiochemical laboratory or local provisions). • Primary circuit and auxiliaries, including but not limited to the Spent Fuel Pool and Waste Liquid System (WLS). The details should be specific to AP1000 and any differences in plant design; reference to industry guidelines is not a sufficient response in itself. With agreement from the Regulator this action may be completed by alternative means.		

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WESTINGHOUSE AP1000® GENERIC DESIGN ASSESSMENT
GDA ISSUE
PRIMARY SAMPLING SYSTEMS
GI-AP1000-RC-02 REVISION 0

Technical Area	**REACTOR CHEMISTRY**		
Related Technical Areas	Mechanical Engineering Radiation Protection		
GDA Issue Reference	**GI-AP1000-RC-02**	**GDA Issue Action Reference**	**GI-AP1000-RC-02.A2**
GDA Issue Action	Westinghouse to provide a justification and evidence that the primary sampling systems (PSS) in AP1000 will support the sampling schedule delivered under A1. The response by Westinghouse should consider: • Specific features of the AP1000 design, such as the location of cooling provisions and the maintenance of high pressure lines. • The effect of recent design changes on system performance should be considered, for example the reduction in line diameter. • Specific consideration should be given to representative sampling of zinc, corrosion products and hydrogen. • A justification should be given to which sample lines are or are not included in the PSS, specifically why backup cooling systems are not sampled through the PSS and why the design of AP1000 does not include an inlet sample from the Chemical Volume control System (CVS). • Justification and evidence should be given on the use of a GSP, as opposed to a ventilated enclosure (as expected in the SAPs ECV 1 - ECV1 – 10 and associated paragraphs), and sampling provisions outside of the GSP (i.e. as currently for some systems and not others). • Justification should be provided for not including a boron meter as a means of continuously monitoring the coolant boron concentration now that a design change to flowing samples has been included. • The impact of the design change on the served and dependant systems should be clearly reviewed and documented (for example, the impact of increased PSS flow on the WLS input or CVS make-up requirements). • Evidence should be provided to demonstrate that waste generation of the system is within the safety case and that the design has sufficient redundancy to accommodate operational transients. With agreement from the Regulator this action may be completed by alternative means.			

Annex 2

WESTINGHOUSE AP1000® GENERIC DESIGN ASSESSMENT

GDA ISSUE

HYDROGEN DOSING SYSTEM

GI-AP1000-RC-03 REVISION 0

Technical Area		**REACTOR CHEMISTRY**	
Related Technical Areas		Mechanical Engineering	
GDA Issue Reference	**GI-AP1000-RC-03**	**GDA Issue Action Reference**	**GI-AP1000-RC-03.A1**
GDA Issue	Demonstrate that the hydrogen dosing system in AP1000 has the capacity and capability to provide suitable control over the primary coolant hydrogen concentration during all operating modes and potential faults.		
GDA Issue Action	Westinghouse to present a consistent and structured safety case containing suitable and sufficient evidence to support the AP1000 hydrogen addition system, or other means agreed with the regulator. This evidence should provide confidence that the system will meet the functional requirements of the plant under all modes of operation and anticipated transient conditions. Westinghouse should consider physical testing of the design if sufficient evidence cannot be provided by calculations. The case should include an analysis of the likely faults with the hydrogen addition system. This should include consideration of both under and over dosing of hydrogen. The arrangements, either engineered or administrative, to control these faults should be clearly highlighted. The faults should consider all modes of operation where the hydrogen addition system is required to function. With agreement from the Regulator this action may be completed by alternative means.		