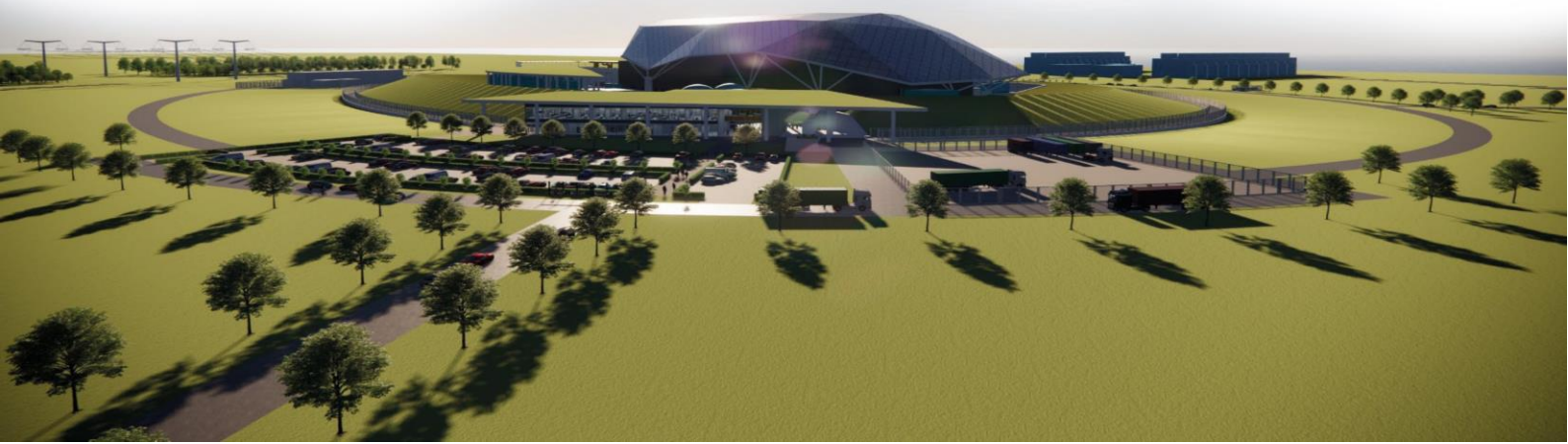




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Environment, Safety, Security and Safeguards Case Version 2, Tier 1, Chapter 20: Chemistry



Record of Change

Date	Revision Number	Status	Reason for Change
March 2023	1	Issue	First version of Chapter 20 of E3S Case
March 2024	2	Issue	This version incorporates developments of the Chemistry based on Reference Design 7, aligned to Design Reference Point 1, including: <ul style="list-style-type: none">• New and refined claims and arguments.• A section on Component Cooling Water (CCW) systems chemistry.• A section on accident chemistry.• Updates to other sections to reflect current design and chemistry position.
May 2024	3	Issue	Updated to correct revision history status at Version 2. Also minor template/editorial updates for overall E3S Case consistency

Executive Summary

This chapter of the Environment, Safety, Security, and Safeguards (E3S) Case presents the overarching summary and information for the Chemistry of the Rolls-Royce Small Modular Reactor (RR SMR). The chapter outlines the claims, arguments, evidence (CAE) available to underpin the top-level claim that the RR SMR chemistry regime and development of the chemistry systems design, reduces risks as low as reasonably practicable (ALARP) during all normal operating modes and accident conditions for all phases of the lifecycle.

Issue 1 of this chapter was delivered in March 2023 at the start of generic design assessment (GDA) Step 2 and was aligned to reference design 5 (RD5), baselined at the preliminary concept definition (PCD) design stage. Its purpose was to provide the starting point for regulatory assessment at the beginning of GDA Step 2. Since then, the design of the RR SMR has progressed, and a suite of Tier 2 chemistry documents have been produced across several topic areas. This is the final version (i.e. Version 2) of E3S Case Tier 1, Chapter 20: Chemistry delivered towards the end of GDA Step 2. It is developed in support of the reference design 7 (RD7) design, corresponding to the design reference point 1 (DRP1) for the GDA. It incorporates information from Tier 2 documents, including updated CAE. The overall aims of the chemistry programme are summarised, which are to reduce, ALARP:

1. Corrosion of structural materials, maintaining structural integrity and ensuing availability and reliability of structures, systems and components (SSCs).
2. Fuel cladding corrosion, maintaining fuel cladding integrity.
3. Out-of-core radiation fields and generation of radioactive waste.

A further aim is to ensure that SSCs are provided so that monitoring and control of the chemistry of RR SMR systems can be achieved to maintain compliance with water chemistry specifications. Alarms and warnings will be utilised where possible to provide additional information regarding when an action level (AL) is reached and when system chemistry might require correction.

For the systems within the scope of this revision of E3S Case Version 2, Tier 1, Chapter 20: Chemistry, the chemistry regime at the current stage of development is summarised, discussion of how the chemistry regime has been developed to reduce risks to ALARP is presented, and future development and verification activities that are required to substantiate the chemistry aspects of the RR SMR design are introduced. At this stage of design development, there is confidence that the claims can be met when the full suite of evidence is developed.

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20.0 Introduction

20.0.1 Introduction

Chapter 20 of the Rolls-Royce Small Modular Reactor (RR SMR) Environment, Safety, Security and Safeguards (E3S) Case presents the overarching summary and entry point to the chemistry information for the RR SMR.

From early concept design, an initial set of chemistry specifications were put in place to aid the RR SMR plant design. These chemistry specifications were based on relevant good practice (RGP) and developed to meet the RR SMR design objectives. As the design and operating philosophy has matured, the chemistry specifications have been refined to reflect the changes and maintain an optimised approach to chemistry control. The most recent chemistry specifications, which support E3S Case Version 2, Tier 1, Chapter 20: Chemistry, are provided in References [1] and [2] for Reactor Island [R01] and Turbine Island [T01] respectively.

E3S Case Version 2, Tier 1, Chapter 20: Chemistry is the ‘Tier 1’ document (i.e. the top tier submission) for chemistry and presents the overarching summary and entry point to evidence located in lower tier documents. Version 1 of E3S Case Tier 1, Chapter 20: Chemistry (Reference [3]) was delivered in March 2023 at the start of generic design assessment (GDA) Step 2 and was aligned to reference design 5 (RD5) and baselined at the preliminary concept definition (PCD) design stage. Its purpose was to provide the starting point for regulatory assessment at the start of GDA Step 2 and it was predominantly based on RGP and operational experience (OpEx) such as that taken from References [4], [5], [6], [7], [8] and [9].

This document is the final version (i.e. Version 2) of E3S Case Tier 1, Chapter 20: Chemistry delivered towards the end of GDA Step 2. It is developed in support of the reference design 7 (RD7) design, corresponding to the design reference point 1 (DRP1) for the GDA. In addition to the RGP and OpEx used to produce Version 1 of E3S Case Tier 1, Chapter 20: Chemistry, it incorporates information from Tier 2 chemistry documents written during GDA Step 2. It also refers to other documents that have been produced such as system design descriptions (SDDs), decision records and materials degradation technical justifications (TJs). The Tier 2 chemistry documents present refined claims, additional sub-claims, arguments and the first level summary of underpinning evidence.

20.0.2 Scope and Maturity

20.0.2.1 Chapter 20 Scope

E3S Case Version 2, Tier 1, Chapter 20: Chemistry provides a summary of the chemistry of the RR SMR design and presents the associated safety claims and arguments. The structure of the chapter is aligned to much of the Tier 2 documentation that has been produced and includes the following sections and content:

1. Role of Chemistry in Reducing Doses and Risks ALARP (section 20.1): the holistic approach being taken to provide confidence that all chemistry objectives are met, and the risk of material degradation is reduced as low as reasonably practicable (ALARP) is described. An overview of the factors considered when determining RR SMR chemistry regimes are discussed. Reference is made to E3S Case Version 2, Tier 1, Chapter 24: ALARP Summary (Reference [10]) and the top-level ALARP claim.

2. Chemistry Specifications (section 20.2): an overview of how chemistry specifications are being developed for systems within Reactor Island [R01] and Turbine Island [T01] is provided.
3. Monitoring and Control (section 20.3): an overview of how monitoring and control is achieved to maintain compliance with RR SMR chemistry specifications is provided.
4. Primary Coolant Chemistry (section 20.4): an overview of the RR SMR primary coolant system is provided. Topics such as material degradation, fuel cladding integrity, radioactivity, chemistry control parameters, start-up and shutdown chemistry are all discussed.
5. Primary Auxiliary System Chemistry (section 20.5): an overview of RR SMR primary auxiliary systems and the technical basis for chemistry control is provided.
6. Secondary Coolant Chemistry (section 20.6): an overview of the RR SMR secondary coolant system is provided. Topics such as corrosion and sludge deposition are all discussed.
7. Component Cooling Water System Chemistry (section 20.7): an overview of RR SMR component cooling water (CCW) systems and the technical basis for chemistry control is provided.
8. Turbine Island Auxiliary System Chemistry (section 20.8): an overview of Turbine Island [T01] auxiliary systems and the technical basis for chemistry control is provided.
9. Normal Operation Source Term (section 20.9): the purpose of generating the RR SMR normal operation source term (i.e. to underpin various technical assessments) is described. Radionuclide groups and the source term derivation methodology are all described.
10. Accident Chemistry (section 20.10): an overview of how accident chemistry effects are considered in design and the assessment of radiological consequences for the RR SMR are provided.

Commissioning chemistry is also within the scope of E3S Case Version 2, Tier 1, Chapter 20: Chemistry. Future issues will include objectives and available options for commissioning the primary coolant systems, including hot functional testing (HFT), which will be summarised from a Tier 3 document 'Commissioning Chemistry' which will be submitted during Step 3. E3S Case Version 2, Tier 1, Chapter 20: Chemistry will not define the commissioning chemistry regime and procedures during GDA but will present RGP for commissioning pressurised water reactors (PWRs) and demonstrate that the RR SMR plant design does not foreclose options for future licensees.

Based on the above, the following is captured as an assumption on the future dutyholder/licensee:

Assumption on Future Dutyholder/Licensee A20.1: *The final decision on the optimum commissioning chemistry regime for the RR SMR plant will be deferred until the site-specific licensing period.*

The chemistry aspects of the following systems are currently included in the scope of E3S Case Version 2, Tier 1, Chapter 20: Chemistry, with reference designation system for power plants (RDS-PP) coding given in square brackets:

1. Primary Coolant Systems:
 - a. Reactor Coolant System (RCS) [JE], including:
 - i. Reactor Coolant Pump (RCP) System [JEB],

- ii. Reactor Coolant Pressuring System (RCPS) [JEF],
 - b. Reactor Pressure Vessel (RPV) [JAA],
 - c. Chemistry and Volume Control System (CVCS) [KB], including:
 - i. Level and Volume Control System (LVCS) [KBA],
 - ii. Chemistry Control System [KBD],
 - iii. Coolant Purification System (CPS) [KBE],
 - d. Cold Shutdown Cooling System (CSCS) [JNA],
 - e. Component Cooling System (CCS) [KAA],
 - f. Chilled Water System (CWS) [KJ],
 - g. Emergency Boron Injection System (EBIS) [JDK],
 - h. Low Pressure Injection System (LPIS) [JNG],
 - i. High Pressure Injection System (HPIS) [JND],
 - j. Internal Fuel Storage [FA], including:
 - i. Spent Fuel Storage and Cask Loading [FAB],
 - ii. Spent Fuel Pool (SFP) [FAB10],
 - iii. Refuelling Cavity [FAE],
 - iv. Refuelling Pool [FAF],
 - v. Fuel Pool Cooling System (FPCS) [FAK],
 - vi. Fuel Pool Purification System (FPPS) [FAL],
 - vii. Fuel Pool Supply System (FPSS) [FAT],
 - k. Reactor Island Sampling System (RISS) [KU], including:
 - i. Nuclear Sampling System (NSS) [KUA],
 - ii. Auxiliary Sampling System (AxSS) [KUB], and
 - iii. Process & Emissions Radiation Monitoring System (PERMS) [KUK].
- 2. Secondary Coolant, Turbine Island [T01] and Balance of Plant (BoP) [B01] systems:
 - a. Steam Generators (SGs) [JEA],
 - b. Passive Steam Condensing System (PSCS) [JNB],

- c. Local Ultimate Heat Sink (LUHS) [JNK],
- d. Feedwater System [LA], including:
 - i. Deaerator System [LAA],
- e. Steam System [LB], including:
 - i. Auxiliary Steam Piping System [LBG],
- f. Condensate System [LC], including:
 - i. Condensate Storage Tank (CST) [LCP],
 - ii. Steam Generator Purification System (SGPS) [LCQ],
- g. Condensate Polishing System [LD],
- h. Auxiliary Feedwater System [LJ],
- i. Chemical Supply System [QC],
- j. Chemical Gas Supply System [QJ],
- k. Auxiliary Non-Nuclear Sampling System (ANSS) [QU],
- l. Auxiliary Steam Generating and Supply System [QH], including:
 - i. Permanent Boiler System [QHA],
 - ii. Temporary Boiler System [QHR],
 - iii. Steam Distribution System [QHS],
- m. Steam Turbine System [MA],
- n. Hydrogen Cooling System [MKG], and
- o. Turbine Island Closed Cooling Water System (TI-CCWS) [PG].

The chemistry aspects of the systems listed below are excluded from the scope of E3S Case Version 2, Tier 1, Chapter 20: Chemistry however, these systems are included within the overall scope of the E3S Case. Information relating to these systems is presented in E3S Case Version 2, Tier 1, Chapter 11: Management of Radioactive Waste (Reference [11]).

- 1. Waste Treatment Systems:
 - a. Liquid Waste Treatment System [KN], including:
 - i. Liquid Radioactive Effluent Treatment System (LRETS) [KNF],
 - b. Gaseous Radioactive Waste Treatment System [KP], including:

- i. Gaseous Radioactive Effluent Treatment System (GRETS) [KPL], and
- c. Solid Radioactive Waste Processing System [KM].

Chemistry is a cross-cutting topic and is closely related to other topic areas. The scope of this chapter covers the chemistry aspects of the RR SMR, with:

1. Materials selection and justification of the integrity of structures, systems and components (SSCs) covered primarily in E3S Case Version 2, Tier 1, Chapter 23: Structural Integrity (Reference [12]).
2. Accident chemistry also covered in E3S Case Version 2, Tier 1, Chapter 15: Safety Analysis (Reference [13]).
3. Normal operation source term also covered in E3S Case Version 2, Tier 1, Chapter 12: Radiation Protection (Reference [14]).

20.0.2.2 Design/Programme Maturity

RR SMR design information presented in Version 2 of E3S Case Tier 1, Chapter 20: Chemistry is largely based on the design definition towards the end of GDA Step 2. Version 2 is developed in support of the RD7 design, corresponding to DRP1 for the GDA. Development of the chemistry specifications and associated justifications are being progressed in line with the design programme to inform the design development and the demonstration that exposures to workers and the public are reduced to ALARP.

20.0.2.3 Further Development and Underpinning

To achieve the aims and objectives of the RR SMR project (Reference [15]), the design includes relatively novel aspects of the primary coolant chemistry regime for a PWR, summarised as:

1. The adoption of a boron-free chemistry regime, with duty reactivity control being achieved via the control rods.
2. Use of potassium hydroxide (KOH) as the alkali agent.

At this stage of the design programme, preliminary assessments have been undertaken to provide confidence in the baseline chemistry regime. Arguments and evidence for the choice of KOH as the alkali agent and the adoption of a boron-free chemistry regime are recorded in decision records, such as References [16] and [17]. A verification and validation (V&V) programme is also being implemented to provide the underpinning justification for the RR SMR design, which includes several development activities related to chemistry. The strategic approach to V&V being taken by RR SMR is set out in the 'Rolls-Royce SMR Approach to Verification and Validation' document (Reference [18]).

The general aim of the materials and chemistry V&V programme is to demonstrate that the RR SMR primary coolant chemistry regime (boron-free KOH) is at least 'no worse' than the widely adopted PWR primary coolant chemistry regime of lithium hydroxide (LiOH)/boric acid. A large amount of OpEx and test data exists to underpin the LiOH/boric acid chemistry regime which will be used as part of the underpinning for the RR SMR primary coolant chemistry regime alongside results from the V&V programme. Examples of types of testing that will be carried out on materials representative

of those used in the RCS [JE] in both boron-free KOH and LiOH/boric acid environments are as follows:

1. General corrosion testing (Reference [19]),
2. Stress corrosion cracking (SCC) testing (Reference [20]),
3. Environmentally assisted fatigue (EAF) testing (Reference [21]),
4. Irradiation assisted SCC (IASCC) testing (Reference [22]), and
5. Fuel clad corrosion testing.

Further details on the V&V programme are provided in Tier 3 materials degradation TJ documents, some of which are referenced in the points above. Following completion of the testing, the TJs will be updated with results from the testing programmes reported. The results will also be considered in future Tier 3 chemistry documents, future reissued Tier 2 chemistry documents and the future reissued Tier 1 chemistry document. Chapter 20 is based on the key assumption that the V&V activities will provide the required evidence to support development of the chemistry safety case and successfully demonstrate that a boron-free KOH regime is 'no worse' than a LiOH/boric acid regime with regards to materials degradation. The production of the Chemistry E3S Case has been developed considering the testing programme schedules (Reference [23]).

The materials degradation TJs also support the Tier 2 RR SMR ageing management plan (AMP) document (Reference [24]) defines the generic approach to justifying that the RR SMR design is robust against ageing effects influenced by the design environment. It is noted that a fuel clad corrosion TJ is currently outside the scope of the AMP; however, the results from the fuel clad testing programme will still be reported within Tier 3 chemistry documents.

20.0.3 Claims, Arguments, Evidence Route Map

The top-level claim for E3S Case Version 2, Tier 1, Chapter 20: Chemistry is as follows:

Claim 20: The RR SMR chemistry regime and development of the chemistry systems design, reduces risks as low as reasonably practicable (ALARP) during all normal operating modes and accident conditions for all phases of the lifecycle.

The complete suite of evidence to underpin the claims in the E3S Case is generated through the RR SMR design process and E3S Case programme and is documented in the claims, arguments, evidence (CAE) Route Map (Reference [25]), and described further in E3S Case Version 2, Tier 1, Chapter 1: Introduction (Reference [26]).

The overall purpose of the Tier 1 chemistry document is to summarise how the chemistry design (chemistry specification) contributes to achieving the fundamental E3S objective (*protect people and the environment from harm*) and delivery of the fundamental functions (*control of reactivity; cooling of radioactive material; confinement of radioactive material*).

An initial set of chemistry claims and arguments were developed for Version 1 of E3S Case Tier 1, Chapter 20: Chemistry in March 2023. An updated list of all chemistry claims is provided in Appendix A (section 20.13), with links to show where arguments and evidence are summarised in this document.

Claims and arguments have been developed based on the decomposition of the top-level claim for chemistry, aligned with the overarching E3S Design Principles (Reference [27]). The chemistry CAE structure provides traceability from the top-level claim all the way down to the resulting chemistry specifications adopted for different systems. During the production of the Tier 2 chemistry documents, new claims / sub-claims were developed, and some refinements were made to the phrasing and identifications (IDs) of the previous claims provided in Version 1 of E3S Case Tier 1 Chapter 20: Chemistry. [Redacted]. It is noted that chemistry is a broad subject that influences, and is influenced by, the wider RR SMR design. The top-level claim and the five arguments that it is decomposed into are presented in Figure 20.0-1.

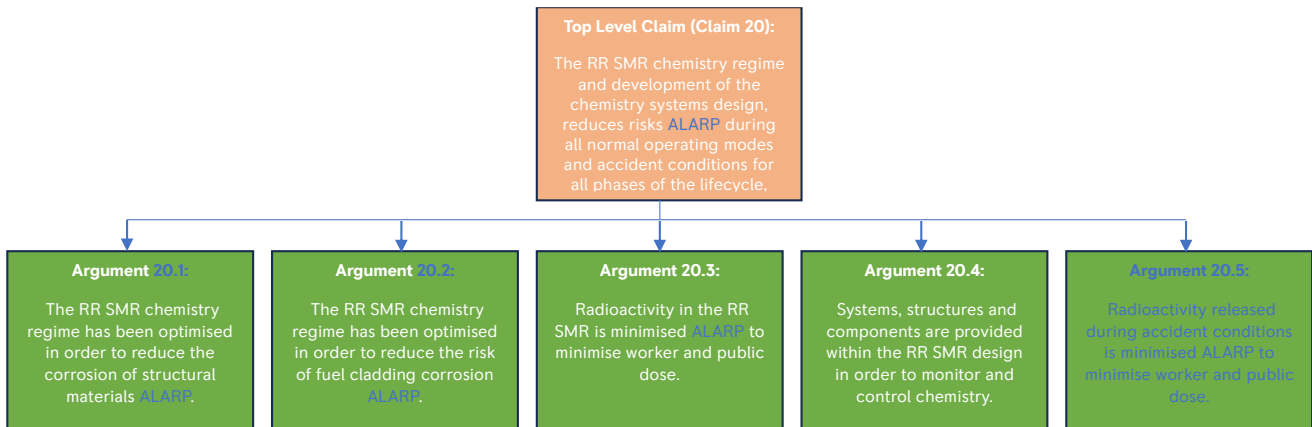


Figure 20.0-1: Chemistry Top-Level Claim and Decomposition to Arguments.

It is noted that the term ‘so far as is reasonably practicable (SFAIRP)’ has typically been used in claims in the issued chemistry Tier 2 documents, rather than the term ‘ALARP’. Each are discussed in more detail in the E3S Case Version 2, Tier 1, Chapter 24: ALARP Summary document (Reference [10]). They essentially mean the same thing and at their core is the concept of ‘reasonably practicable’. However, the term ‘ALARP’ is used more commonly than ‘SFAIRP’ throughout the wider E3S Case and in the United Kingdom (UK) nuclear industry. On this basis, ‘ALARP’ rather than ‘SFAIRP’ is used throughout this Tier 1 document.

20.0.4 E3S Case Chemistry Document Structure

The Tier 1 chapter is supported by underpinning Tier 2 and Tier 3 documents, which are being developed to provide the underpinning evidence to support the chemistry safety claims.

The Tier 2 reports have been grouped by topic area. They consist of six reports specifically in relation to Reactor Island [R01], four reports specifically in relation to Turbine Island [T01], and a further report covers chemistry controls used to minimise corrosion within CCW systems.

Each Tier 2 report presents the claims and arguments being made for each topic and summarise the detailed evidence presented in the Tier 3 reports. The overall, holistic, justification for the RR SMR chemistry regime is provided within the Tier 1 chapter. The Tier 3 reports will provide the detailed technical underpinning (evidence) and will typically be structured by chemistry parameter.

Tier 3 reports will cover all modes of operation and all the topic areas summarised within the Tier 2 documents. Revision 1 of the Tier 2 reports have been written before the Tier 3s, as some information is not yet available to produce the Tier 3 reports.

An iterative approach is being taken regarding development of the chemistry documentation:

1. The Tier 1 chapter was produced first and set the overall structure of chemistry case and defines the preliminary claims. Interim versions of the Tier 1 chapter are being produced during the GDA process.
2. The Tier 2 reports have been produced and review and refine the preliminary claims as required, as well as provide more detailed evidence to support the claims. The Tier 2 reports identify any knowledge gaps and further work that is required to fully underpin the claims. These documents are largely based on generic PWR information, with a commentary of the applicability to the RR SMR design provided. The Tier 2 reports have been produced during GDA Step 2.
3. During GDA Step 3, the Tier 3 reports will be produced, incorporating the matured design information and data from the materials testing programme. This evidence presented will be specific to the RR SMR design.
4. Following issue of the Tier 3 reports, the Tier 2 reports will be updated, incorporating information from the Tier 3 reports (and streamlining the level of evidence presented). This will be undertaken during GDA Step 3.
5. Finally, at the end of GDA Step 3, the Tier 1 chapter will be updated in order to incorporate the Tier 2 and 3 information.

The proposed structure for the chemistry documents is shown in Figure 20.0-2, Figure 20.0-3 and Figure 20.0-4 for Reactor Island [R01] systems, Turbine Island [T01] systems and CCW systems respectively.

Normal operation source term and accident chemistry are further topics associated with E3S Case Version 2, Tier 1, Chapter 20: Chemistry (sections 20.9 and 20.10). Details on the strategy for deriving the normal operation source term is provided in the 'Normal Operation Source Term Strategy Report' (Reference [28]) and the radionuclide list and associated methodology is outlined in the 'Normal Operation Source Term Radionuclide Selection Report' (Reference [29]). The 'Accident Chemistry Strategy Report' (Reference [30]) describes the strategy and approach for the inclusion of chemical phenomena in the radiological consequence analysis for design faults and offsite dose analysis for severe accidents, as well as how chemistry feeds into system design in the RR SMR.

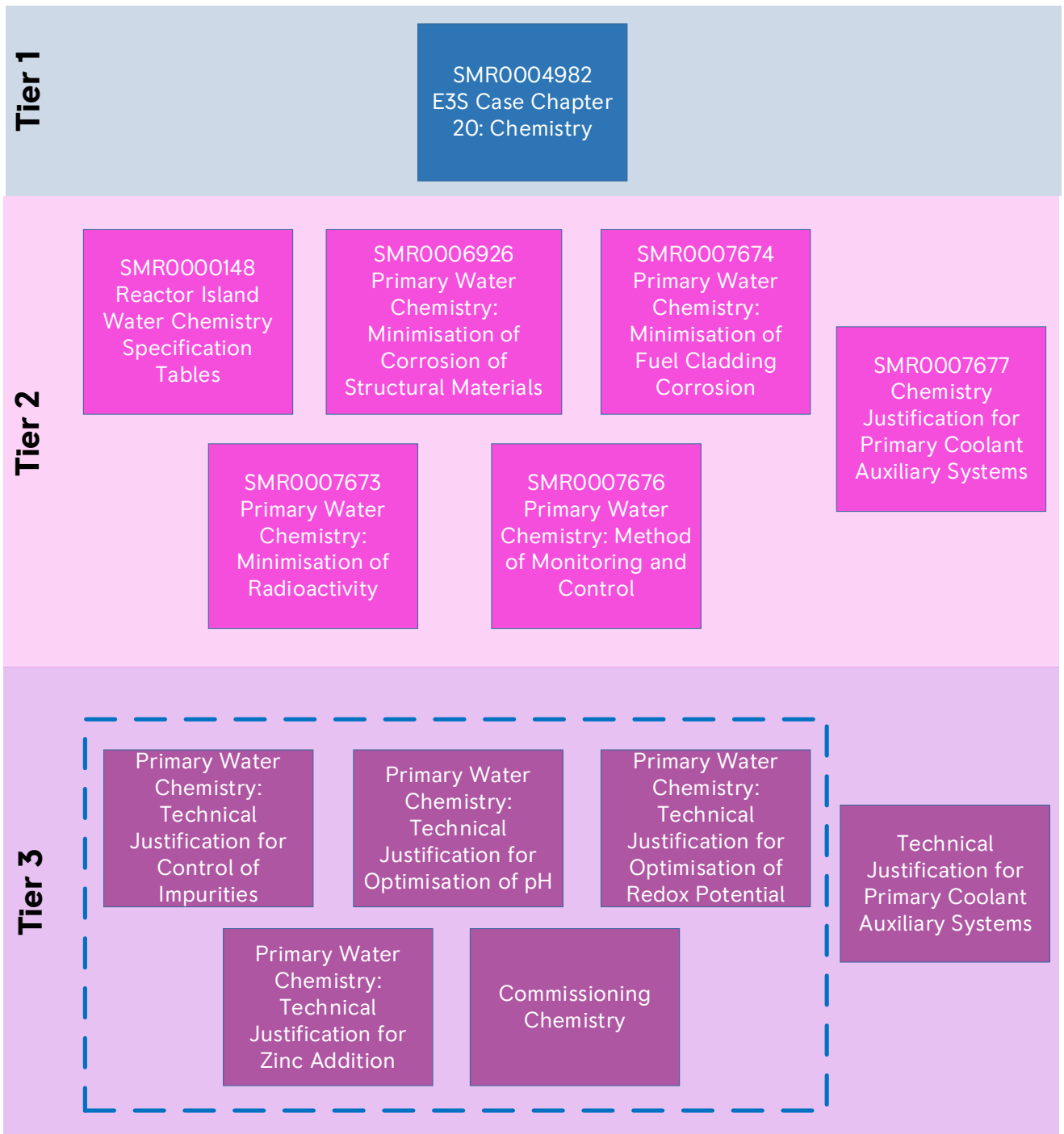


Figure 20.0-2: Chemistry document structure relating to Reactor Island [R01] systems.

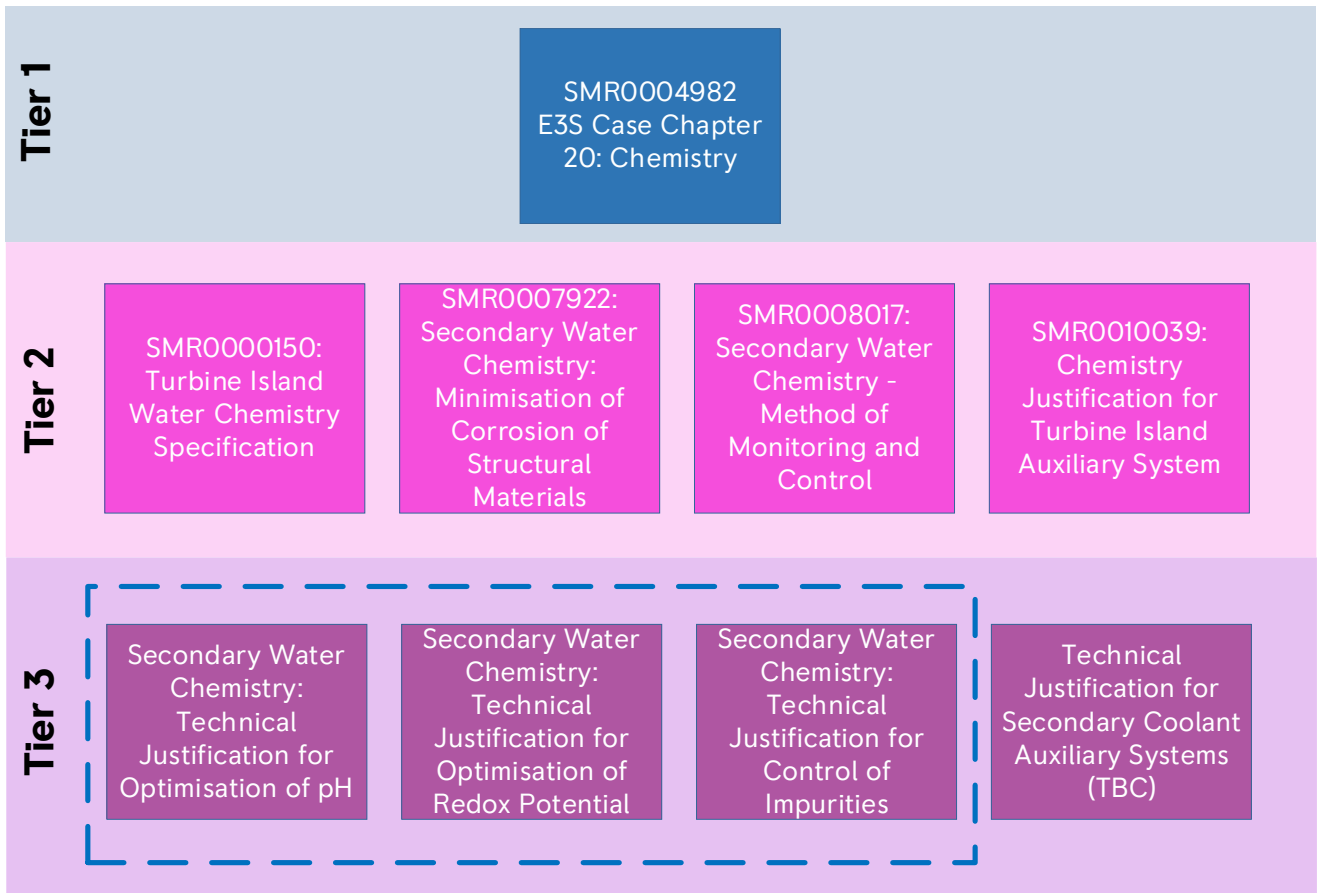


Figure 20.0-3: Chemistry document structure relating to Turbine Island [T01] systems.

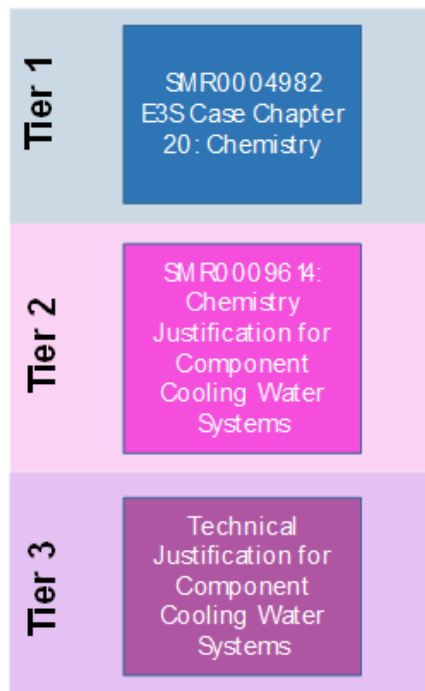


Figure 20.0-4: Chemistry document structure relating to CCW systems.

20.0.5 Applicable Regulations, Codes & Standards

E3S Case Version 2, Tier 1, Chapter 3: E3S Objectives & Design Rules (Reference [31]), outlines the E3S objectives and design rules applicable to the RR SMR. The E3S Design Principles (Reference [27]) have been used to guide and inform the ongoing design development process and the regulatory affairs group (RAG) Functional Manual (Reference [32]) presents the policy for the selection of codes and standards to help ensure sound engineering in design. The following guidelines are also of relevance when considering development of the RR SMR chemistry regime:

1. Office for Nuclear Regulation (ONR) Safety Assessment Principles (SAPs) (Reference [33]),
2. ONR Technical Assessment Guides (TAGs), in particular Chemistry of Operating Civil Nuclear Reactors (Reference [34]) and Chemistry Assessment (Reference [35]),
3. International Atomic Energy Agency (IAEA) Specific Safety Guide (SSG)-13: Chemistry Programme for Water Cooled Nuclear Power Plants (Reference [36]),
4. IAEA SSG-15: Storage of Spent Nuclear Fuel (Reference [37]),
5. IAEA NF-T-3.6: Management of Damaged Spent Nuclear Fuel (Reference [38]),
6. IAEA-TECDOC-1303: High Temperature On-Line Monitoring of Water Chemistry and Corrosion Control in Water Cooled Power Reactors (Reference [39]),
7. IAEA-TECDOC-1505: Data Processing Technologies and Diagnostics for Water Chemistry and Corrosion Control in Nuclear Power Plants (Reference [40]),
8. IAEA SSG-28: Commissioning of Nuclear Power Plants (Reference [41]),
9. European Utility Requirements for Light Water Reactor (LWR) Nuclear Power Plants (Reference [42]),
10. Electric Power Research Institute (EPRI) chemistry guidelines, in particular PWR Primary Water Chemistry Guidelines (Reference [4]), PWR Secondary Water Chemistry Guidelines (Reference [5]), Fuel Reliability Guidelines for PWR Fuel Cladding Corrosion and Crud (Reference [8]), and Closed Cooling Water Chemistry Guidelines (Reference [43]), and
11. The Ionising Radiation (Medical Exposure) Regulations (Reference [44]).

20.1 Role of Chemistry in Reducing Doses and Risks ALARP

Chemistry is an important consideration for the safe and reliable operation of a nuclear power station. Appropriate chemistry control supports the continued integrity, reliability, and availability of the SSCs that are important to safety, and that the plant operates within the design intent. For reactor chemistry, it also impacts the accumulation of radioactive material and therefore contributes to minimising associated worker-dose. Chemistry therefore plays an important role in delivering the fundamental functions to support the E3S objective of *protecting people and the environment from harm*.

As well as influencing the corrosion rates of structural materials, chemistry can impact the normal operation source term and hence worker and public radiation dose. In the 'E3S Design Principles' document (Reference [27]), there are numerical dose targets proposed for RR SMR that are consistent with ONR SAPs numerical targets, which are ONR SAPs Target 1 to 3 basic safety level (BSL) and basic safety objective (BSO) for normal operation. Similarly, there are faulted operation source term numerical targets for RR SMR consistent with ONR SAPs Target 4 BSL and BSO, and there are accident chemistry source term numerical targets for RR SMR consistent with ONR SAPs Target 5 to 9 BSL and BSO. If chemistry regimes are wrongly executed, the ability to meet targets can be undermined. The steps taken and optioneering exercises carried out to demonstrate these targets are met through appropriate chemistry choices are discussed in more detail in this section.

OpEx gained since the 1960s in operating nuclear power stations has shown that chemistry control can impact on the operation of a nuclear power station and can have a significant impact on the economics of power generation (Reference [6]). There have been numerous examples of corrosion failures resulting in costly downtime and replacement activities, as well as increased worker dose and additional waste discharge to the environment (References [4] and [5]). This has resulted on an increased focus on chemistry control during the design stage and ensuring the risk to material degradation is reduced ALARP.

The optimum chemistry regime is dependent on the conditions within a system. For example, the following factors need to be considered when determining the chemistry regime:

1. The chosen chemistry regime will need to be compatible with the materials of construction, ensuring corrosion is reduced ALARP (for fluid systems that are in contact with nuclear fuel, compatibility with the fuel cladding material also needs to be considered).
2. The operating environment within the system, in particular the temperature, pressure, flow conditions (e.g. turbulent flow, single / two-phase flow) and whether the fluid is exposed to radiation.

The optimum chemistry regime often involves trying to meet conflicting requirements i.e. the solution to achieve one objective may negatively impact the achievement of another. As an example, an increase in pH in the primary circuit results in a decrease in the corrosion rate of primary circuit materials and a lowering of plant radiation fields. However, if the pH is too high there is an increased risk of fuel cladding degradation. Therefore, designing an optimised chemistry regime typically involves striking a balance and a compromise.

There is no single chemistry regime that can be universally applied to all fluid systems within a nuclear power station, as the ALARP choices for the RR SMR plant are being determined holistically through optioneering and assessment, as described in E3S Case Version 2, Tier 1, Chapter 1:

Introduction (Reference [26]). The baseline chemistry choices for the primary coolant are summarised in Section 20.4.8.1, those for the secondary coolant are summarised in section 20.6, and those for auxiliary and CCW systems are covered in sections 20.5, 20.7 and 20.8. Aside from capturing chemistry decisions in lower tier chemistry documents, certain chemistry decisions are being captured in decision record documents. These documents consider why decisions are correct, such that doses and risks are reduced ALARP. The chemistry decision records produced so far discuss the selection of KOH as the alkalisating agent (Reference [17]), and the impacts of the decision not to use boron for duty reactivity control (Reference [16]). Potential options are evaluated in detail against a variety of factors (e.g. OpEx and RGP, compliance with requirements, impact of postulated initiating events (PIE), conventional health and safety, criticality safety, radiological protection, environment, security, human factors, cost and programme, reliability, availability, etc.) and a Pugh Matrix Assessment is typically used to guide decision making and encourage evaluation of options against key criteria. The decision record process followed for chemistry is governed by the design decision-making process 'C3.2.2-2 Conduct design optioneering' (Reference [45]) which demonstrates the best available techniques (BAT) and ALARP Safeguards by Design methodologies are followed, along with the E3S assessment process 'C3.2.2-3 Engineer safe, secure, safeguarded and environmentally sound products' (Reference [46]).

The Tier 2 chemistry documents typically describe why chemistry regimes have been chosen on an individual topic basis. For example, the 'Primary Water Chemistry: Minimisation of Corrosion of Structural Materials' document (Reference [47]) considers the impact of parameters such as pH, impurity concentrations or redox potential specifically on corrosion rates in the primary circuit. The Tier 3 reports that will be written in the future will consider the impact of these parameters more holistically. For example, the 'Primary Water Chemistry: Technical Justification for Optimisation of pH' document (Figure 20.0-2) will consider the effects of pH on fuel cladding corrosion rates, its effects on radioactivity, in addition to its effects on the corrosion rates of the range of structural materials within the RR SMR primary circuit and the ability of systems to monitor and control pH. The Tier 3 reports will be used to derive or confirm a balanced target range and appropriate limits for parameters within the Reactor Island [R01] and Turbine Island [T01] water chemistry specifications (References [1] and [2]). Some of the ALARP chemistry choices for the RR SMR plant are summarised within E3S Case Version 2, Tier 1, Chapter 20: Chemistry. For example, pH control in the primary circuit is summarised in section 20.4.6.2 and the use of a high all-volatile treatment (High-AVT) regime for pH and oxygen control in the secondary circuit is summarised in section 20.6.3.2.

RR SMR ALARP principles are described in the 'E3S Design Principles' document (Reference [27]). The overarching summary of how RR SMR reduces risks to ALARP based on the design and safety information across the E3S chapters is presented in E3S Case Version 2, Tier 1, Chapter 24: ALARP Summary (Reference [10]). The top-level claim in Chapter 24 is:

Claim 24: The design of the RR SMR reduces nuclear and conventional safety risks to As Low As Reasonably Practicable through the lifecycle

A decomposition of this ALARP top-level claim into sub-claims and arguments, and links to the relevant evidence is provided in the CAE Route Map in Appendix A (section 20.13) of E3S Case Version 2, Tier 1, Chapter 24: ALARP Summary (Reference [10]). Information from other safety case chapters, including E3S Case Version 2, Tier 1, Chapter 20: Chemistry, is used as evidence in the CAE Route Map in Chapter 24.

Chemistry claims and links to where arguments and evidence are summarised in this document are presented in Table 20.13-1. The chosen chemistry regimes for RR SMR are considered to represent RGP and be equal to, or better than, current established practices with respect to meeting the overall aims for the chemistry programme. The chemistry choices are considered to represent the



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limits of what is reasonably practicable to do i.e. no further options exist and if they do exist the benefit they yield is small in comparison to the costs incurred.

20.2 Chemistry Specifications

During early concept design, initial chemistry specifications were established to support design development. These specifications were based on RGP and available information at the time, including previous revisions of the EPRI Water Chemistry Guidelines. The design maturity, operating philosophy and chemistry specifications are being progressed in parallel and are continually reviewed to ensure alignment. No major design changes have occurred, or are expected to occur in the future, because of further development and refinement of the chemistry specifications.

The chemistry specification documents provide summary tables of the specifications and do not provide any justification, which is presented within the wider chemistry case.

The chemistry specification tables are communicated to the wider RR SMR design teams as requirements that are placed on the relevant plant systems in the dynamic object orientated requirements system (DOORS) module. This provides confidence that the chemistry requirements are incorporated into the design and the ability to deliver these requirements is continually assessed as the design develops.

The current chemistry specifications for systems within Reactor Island [R01] and Turbine Island [T01] are provided in Reference [1] and [2] respectively. At this stage specifications have been considered for the standard modes of operation (i.e. Modes 1, 2, 3, 4A, 4B, 5A, 5B, 6A and 6B) described by the 'Power Station Operational Philosophy' document (Reference [48]), with expected values, upper limits and lower limits typically provided. Frequency of monitoring will be addressed in future revisions of the chemistry specification as the design evolves. It is also common for chemistry specifications to contain defined action levels (ALs), which enable defined actions to be taken in response to chemistry excursions, in a timely manner, ensuring that the chemistry stays within the bounds of the design envelope. ALs and corrective actions to take in response to chemistry excursions will also be developed as the design matures, considering both the capability of the RR SMR design and RGP. The overarching summary and entry point for operational limits and conditions (OLCs) in the RR SMR is provided in E3S Case Version 2, Tier 1, Chapter 16: Operational Limits and Conditions (Reference [49]).

In addition to the RCS [JE] a number of other systems, including the CVCS [KB], CCS [KAA], SFP [FAB10], CSCS [JNA], LUHS [JNK] and EBIS [JDK], are considered in the 'Reactor Island [R01] Water Chemistry Specification Tables' (Reference [1]). The Feedwater System [LA], Condensate System [LC], SGPS [LCQ] and TI-CCWS [PG] are considered in the 'Turbine Island Water Chemistry Specification' (Reference [2]). Specifications for other systems will be addressed in future revisions of these documents, commensurate with design maturity during GDA Step 3.

20.3 Monitoring and Control

20.3.1 Sampling and Monitoring

20.3.1.1 Sampling Systems

There are two main sampling systems currently incorporated into the RR SMR design:

1. RISS [KU], and
2. ANSS [QU].

The primary functional purpose of the RISS [KU] is to representatively monitor key fluids within the RCS [JE] and the interfacing auxiliary systems for the chemical parameters defined by the 'Reactor Island [R01] Water Chemistry Specification Tables' document (Reference [1]). A summary of how monitoring and control is achieved in the RR SMR to maintain compliance with the water chemistry specification for primary systems is provided in the Tier 2 document titled 'Primary Water Chemistry: Method of Monitoring and Control' (Reference [50])

Similarly, the primary functional purpose of the ANSS [QU] is to representatively monitor key fluids within the Feedwater System [LA], Condensate System [LC], and other auxiliary systems within Turbine Island [T01] for the chemical parameters defined by the Turbine Island Water Chemistry Specification (Reference [2]). A summary of how monitoring and control is achieved in the RR SMR to maintain compliance with the water chemistry specification for secondary systems is provided in the Tier 2 document titled 'Secondary Water Chemistry: Method of Monitoring and Control' (Reference [51]). It is noted that although the specification for SGPS [LCQ] is within the 'Turbine Island Water Chemistry Specification' document (Reference [2]), it is monitored by the AxSS [KUB].

Accurate analysis and the ability to control and maintain the water chemistry regimes in accordance with specifications is of the utmost importance. The sampling systems will include a range of integrated monitoring instrumentation (inline/online/atline) to provide continuous monitoring of selected chemistry parameters, as well as the ability to obtain local 'grab' samples that can be analysed within a laboratory. The water chemistry specifications (References [1] and [2]) define which chemistry parameters are to be monitored. The future operator of the RR SMR plant will be responsible for implementing a station specific *chemistry programme*, providing the means to collect, store and trend chemistry data to provide overall condition monitoring for the plant enabling the early identification of adverse trends and anomalies.

This is captured in the following commitment on the future dutyholder/licensee:

Commitment on Future Dutyholder/Licensee C20.1: *The future operator of the RR SMR plant will be responsible for implementing a chemistry programme aligned to the E3S Case.*

20.3.1.2 Design Maturity

The RISS [KU] and the ANSS [QU] are both included within the scope of E3S Case Version 2, Tier 1, Chapter 28: Sampling and Monitoring (Reference [52]).

Within the RISS [KU], SDDs for the NSS [KUA], AxSS [KUB] and PERMS [KUK] are available in References [53], [54] and [55] respectively. There will be a Hot Laboratory System [XRG] within

Reactor Island [R01] for the safe and efficient processing of radioactive and potentially radioactive species, in addition to capability to support wider plant analysis for non-active sample characterisation.

20.3.2 Control of Chemistry Parameters

20.3.2.1 Chemistry Control

To achieve appropriate chemistry control, it is important that suitable chemical addition and purification systems are provided to demonstrate the chemistry specification for each system can be achieved.

Adequate capability shall also be provided for the removal from the coolant of radioactive substances, including activated corrosion products (CPs) and fission products (FPs) deriving from the fuel, as well as non-radioactive substances.

The relevant RR SMR plant systems that are responsible for controlling the chemistry are described in sections 20.5.1 and 20.6. These systems are comprised of:

1. Chemical addition systems, which add chemicals to the system to provide chemical conditioning. For example, the Chemistry Control System [KBD] is used to control primary coolant chemistry, and the Chemical Supply System (CSS) [QC] and the Central Gas Supply System [QJ] are used to dose secondary circuit systems.
2. Purification systems, which remove chemical species from the system. For example, the CPS [KBE] is used to purify primary coolant and it is expected that a mobile Condensate Polishing System [LD] will remove impurities from the SGs [JEA] during start-up operations (Reference [56]).
3. Let down/blow-down systems, which remove water from the system, but do not directly perform a purification function. For example, the LVCS [KBA] for the primary coolant and the SGPS [LCQ] for secondary coolant.

20.3.2.2 Design Maturity

In terms of Tier 1 chapters, chemical addition and purification systems associated with the primary coolant system are included in the scope of E3S Case Version 2, Tier 1, Chapter 5: Reactor Coolant System and Associated Systems (Reference [57]). Those associated with the secondary coolant system are included in the scope of E3S Case Version 2, Tier 1, Chapter 10: Steam and Power Conversion Systems (Reference [58]), and those associated with auxiliary systems are contained within E3S Case Version 2, Tier 1, Chapter 9A: Auxiliary Systems (Reference [59]).

SDDs for the LVCS [KBA], the Chemistry Control System [KBD], the CPS [KBE] and the SGPS [LCQ] are available in References [60], [61], [62] and [63] respectively.

20.3.3 Tier 2 Chemistry Reports

As described in section 20.3.1, Tier 2 documents entitled 'Primary Water Chemistry: Method of Monitoring and Control' (Reference [50]) and 'Secondary Water Chemistry: Method of Monitoring and Control' (Reference [51]) summarise how monitoring and control is achieved in order to maintain compliance with chemistry specifications. There are currently two Level 2 claims that relate to



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monitoring and control. The claims both fall under both argument 20.4 and are presented in Appendix A (section 20.13) as claims 20.4.1 and 20.4.2.

20.4 Primary Coolant Chemistry

20.4.1 Design Overview

Systems discussed in Section 20.4 include the following:

1. RPV [JAA],
2. RCS [JE], including:
 - a. SGs [JEA],
 - b. RCP System [JEB], and
 - c. RCPS [JEF]
3. SFP [FAB10],
4. FPPS [FAL],
5. CVCS [KB], including:
 - a. LVCS [KBA],
 - b. Chemistry Control System [KBD], and
 - c. CPS [KBE].

The primary function of the RPV [JAA] is to interface with the RCS [JE] so that cold coolant can flow to the core and hot coolant can be taken to the SGs [JEA]. The baseline architecture for the RCS [JE] consists of three vertical U-tube SGs [JEA] with associated pipework loops and a single RCP in each loop, mounted to the SG [JEA] outlet. The configuration of the SG [JEA], pipework and pump layout in each loop encourage a robust thermal driving head for natural circulation flow in emergencies.

The primary function of the CVCS [KB] is to control the chemistry and volume of the reactor coolant within the RCS [JE]. The CVCS [KB] maintains reactor coolant chemistry within specification and maintains the RCPS [JEF] level within a required operating band. The CVCS [KB] takes coolant from downstream of the RCP System [JEB], cools it, removes impurities, reheats it, and returns it upstream of the RCP System [JEB]. The CVCS [KB] takes coolant from SG pipework loops and it is comprised of three sub-systems: the LVCS [KBA], the Chemistry Control System [KBD] and the CPS [KBE].

An overview of the RCS [JE] and associated systems is also found in E3S Case Version 2, Tier 1, Chapter 5: Reactor Coolant System & Associated Systems (Reference [57]). SDDs for the RCS [JE], SGs [JEA] and RCPS [JEF] are found in References [64], [65] and [66] respectively.

20.4.2 Historical Development of the PWR Primary Coolant Chemistry Regime

The objective of the primary coolant chemistry regime is to:

1. Maintain the structural integrity of SSCs in the primary circuit system by minimising corrosion.
2. Maintain the integrity of the fuel cladding and fuel performance by minimising corrosion and crud.
3. Minimise out-of-core radiation fields, waste, and discharges.

Designing the optimal chemistry regime to deliver against all these objectives may generate conflicting requirements. The optimal solution to achieve one objective may negatively impact the achievement of another. For example, chemicals are added to mitigate corrosion, but this increases the chemical loading in the reactor water, can potentially increase the level of radioactivity and decrease the lifetime of ion-exchange resins (and therefore can increase the volume of radioactive waste). Therefore, the optimised primary circuit chemistry regime must be a balance and compromise between these three objectives. The role of chemistry in reducing doses and risks ALARP is discussed in section 20.1.

The primary coolant chemistry regimes for LWRs have evolved since the first reactors were developed in the 1950s. The early reactors adopted a pure water chemistry regime, without any chemical additions. The reactivity of the core was controlled by the control rods, and it was believed that pure water (with low levels of impurities) would be sufficient to mitigate corrosion. However, several performance issues were encountered during the 1950s and 1960s, which resulted in chemical additions being applied to the primary coolant, with continuous modifications continuing to the present day (Reference [6]).

During the early operation of PWRs in pure water chemistry, it was observed that irradiated surfaces tend to accumulate CPs and heavy fuel deposits were observed (Reference [6]). The two main issues associated with heavy fuel deposits are an increase in flow friction, resulting in a pressure drop across the core, and localised overheating of the fuel cladding. The deposits are the result of corrosion of the plant materials, and it was determined that operating under slightly alkaline conditions reduces the amount of corrosion and therefore reduces the amount of deposition on the fuel. Early investigations considered LiOH, KOH and ammonia as the alkali agent.

During the development of the first LWRs, the susceptibility of structural materials to corrosion in an irradiated environment was not understood. Even in pure water conditions, with low levels of impurities, the oxidising environment that results from radiolysis of water is sufficient to drive corrosion, with SCC proving particularly problematic. To mitigate the harmful effects of corrosion, hydrogen addition was adopted to allow hydrogen to combine with the oxidising species generated by radiolysis and create reducing conditions within the primary coolant.

As the design developed further, soluble boron (in the form of boric acid) was introduced into the primary coolant to provide a “chemical shim”. The boron provided reactivity control, reducing the number of control rods that were required. One of the main drivers for implementing a chemical shim was the cost savings achieved through the reduced number of control rods. To offset the acidity of the boric acid, higher concentrations of LiOH in western PWRs or KOH in water-water energetic reactors (VVERs) are required to maintain slightly alkali conditions.

Finally, a more recent development in PWR chemistry during the mid-1990s was the implementation of zinc addition. Cobalt-60 (Co-60) is one of the main sources of operator dose during operation and maintenance of nuclear reactors. Co-60 is released through corrosion and wear of structural materials and is subsequently incorporated into the oxide layers that are present on the surface of metallic components. It was found that at sufficiently high concentrations zinc is preferentially incorporated into the surface oxide films; the zinc replaces the cobalt which is then released back

into the coolant and subsequently sequestered on the coolant purification system. This reduces the amount of Co-60 that is incorporated in the oxide films of plant surfaces, thereby reducing the dose to operators during operation and maintenance activities. Most plants that have adopted zinc addition have applied it retrospectively, but a few recently built PWRs have chosen to implement it from the start of operations.

20.4.3 Structural Integrity

20.4.3.1 Introduction to Degradation Mechanisms

Although there are numerous degradation mechanisms relating to RCS materials that must be managed, the two dominant classes of corrosion mechanisms that have had the largest influence on the chemistry regime are:

1. General corrosion, which poses less risk to structural failure, but due to the surface area, can result in large volumes of CPs being released into the primary coolant, which are redistributed through the system and contribute to the level of radioactivity in the plant.
2. Localised corrosion, which is the main threat to structural integrity and includes pitting corrosion, crevice corrosion, SCC and EAF.

Structural integrity and material degradation are also addressed in E3S Case Version 2, Tier 1, Chapter 23: Structural Integrity (Reference [12]). Both Chapter 23 and E3S Case Version 2, Tier 1, Chapter 20: Chemistry are supported by the Tier 2 RR SMR AMP document (Reference [24]).

The AMP document is supported by a suite of Tier 3 TJ documents relating to material degradation mechanisms of concern for RR SMR. This currently includes a General Corrosion TJ (Reference [19]), a SCC TJ (Reference [20]), an EAF TJ (Reference [21]), an IASCC TJ (Reference [22]), and an Irradiation Embrittlement TJ (Reference [67]). It is expected that these TJs will be updated and further TJs will be produced during GDA Step 3. The TJs present literature, arguments, technical discussions, and a CAE structure to demonstrate the RR SMR is robust against each degradation mechanism.

Furthermore, the Tier 2 chemistry document 'Primary Water Chemistry: Minimisation of Corrosion of Structural Materials' (Reference [47]) demonstrates that RR SMR primary chemistry regime has been optimised to reduce corrosion of structural materials ALARP. This will be supported with more detailed evidence provided in Tier 3 documents produced during GDA Step 3.

20.4.3.2 General Corrosion

General corrosion is an oxidation process that occurs almost uniformly over the metal surface, converting the base metal into a metal oxide. If the chemistry is appropriately controlled, the oxide film that is formed at the metal surface provides a stable barrier between the metal and fluid, reducing the rate of oxidation. As the oxide film thickens, the growth rate decreases, and a steady-state equilibrium is reached between oxide thickness and corrosion rate. If the chemistry is appropriately controlled and the oxide film remains stable, then a very low corrosion rate is achieved that poses a low risk to material integrity.

Even if the general corrosion rate is low, the large metallic surface area within the RCS (particularly within the SG tubes) means that the volume of CP that is released may be significant. Some of the CPs that are released will be transported to the reactor core, where they can be deposited on the fuel surface. The deposits are exposed to irradiation and undergo activation, producing activation

products (APs) that can be subsequently released and redistributed throughout the RCS. The APs deposit on piping and component surfaces and increase the radiation dose rates during maintenance operations and outages. The term “crud” is commonly used to describe CPs that are deposited on the fuel surface and on structural surfaces throughout the RCS; section 20.4.4.

Within the RCS of a PWR, materials selection, pH, and redox potential are the factors that have the largest impact on rates of general corrosion and generation of crud. Although the current level of design maturity is such that material selection decisions have not yet been made for all components within the RCS [JE] of the RR SMR, the majority are expected to be constructed from austenitic stainless steel (AuSS) and nickel-based alloy (NBA) materials, which both have good corrosion resistance in alkali conditions ($\text{pH} > 7$) (Reference [47]). General corrosion is one of several deleterious corrosion phenomena that can occur above critical redox potentials. In PWRs, the main substances that affect redox potential are oxygen, hydrogen, and hydrogen peroxide. Achieving high pH and deoxygenated / reducing conditions within the RCS [JE] reduces rates of general corrosion and reduces the volume of crud generated. This is discussed further in section 20.4.6.

20.4.3.3 Localised Corrosion

Whereas general corrosion occurs uniformly over the surface of a metal, localised corrosion is concentrated into a small surface area. Localised corrosion occurs on materials that are generally resistant to corrosion; the bulk of the surface remains passive, with corrosion occurring at localised sites where defects (e.g. scratches or inclusions) are present, or in occluded regions where there is reduced flow and impurities can concentrate, creating localised aggressive environments. The material release rates are low compared to general corrosion, but the risk of perforation and failure is significantly higher. Within PWRs, aggressive halide ions and sulfate ions are the dominant impurities that have resulted in the occurrence of localised corrosion. Conservative limits of <{REDACTED} for chloride, sulfate, and fluoride are proposed for RR SMR during normal operating modes, as defined in reference [1]; this is aligned to limits imposed for typical PWR units (Reference [4]). Adherence to Materials Compatibility Requirements (Reference [68]) and Cleanliness Requirements (Reference [69]), defined by RR SMR will also help to minimise the presence of these impurities. Furthermore, resin beds present in the CPS [KBD] provide continual removal of impurities to help ensure water quality remains high.

The mechanisms for localised corrosion that are of most relevance to the primary circuit of PWRs are as follows:

1. Pitting: localised pits form on the surface of the metal, which break through the surface oxide layer and penetrate the underlying metal. At the expected operating chemistry for PWRs, with low concentrations of impurities, together with the corrosion resistant materials of construction, pitting corrosion presents a low risk of degradation and structural failure.
2. Crevice corrosion: occurs in crevices, such as flanges and bolts, where there is an occluded region with reduced flow. High concentrations of impurities can accumulate and result in very aggressive chemistries forming within the crevice. Crevice corrosion is generally mitigated through the plant design, removing the occurrence of crevices (e.g. using welded joints instead of bolted/flanged).
3. SCC: requires a susceptible material, the presence of stress and a corrosive environment. The combination of stress and a corrosive environment may result in a crack forming in the metal, that can grow and result in catastrophic failure of high-pressure systems. Aggressive anions, such as chloride and sulfate, together with oxygenated conditions, act as the driving force for SCC. Mitigation to SCC is achieved using resistant materials, applying stress relaxation

techniques, or removing the corrosive environment (Reference [20]). From a chemistry perspective, SCC can be mitigated by maintaining low concentrations of impurities (in particular chloride and sulfate) and operating under reducing conditions. Under typical PWR operating conditions, NBA material has a superior resistance to SCC, compared to AuSS.

4. Primary water stress corrosion cracking (PWSCC): this is a particular form of SCC that occurs in NBAs at low redox potentials, even in the presence of low oxygen and low impurity concentrations. Alloy 600 was widely used for the SG tube material of older PWRs, and this proved particularly susceptible to PWSCC. Thermally treated Alloy 690 (690TT), with increased chromium content, has proved to have far superior resistance to PWSCC and will be used as SG tube material for the RR SMR (Reference [70]). It is generally accepted that material selection and the occurrence of stress are the dominant factors that influence PWSCC susceptibility, with chemistry being a secondary factor.
5. IASCC: this is a particular form of SCC that occurs for susceptible materials under a sustained tensile stress in a 'corrosive' environment following exposure to irradiation. This mechanism is therefore primarily a concern for reactor pressure vessel internals (RPVI) since it is judged that neutron damage levels of 3 dpa or more are required for this mechanism to lead to issues based on OpEx. Therefore, in the RR SMR design this degradation mechanism predominantly applies to AuSS. IASCC data suggest that neutron damage and stress dominate IASCC and so other effects such as material grade and primary water environment cannot be easily distinguished (Reference [22]).
6. EAF: this is essentially fatigue that is aggravated by corrosion reactions. It is proven from a history of EAF testing and research that LWR environments can significantly lower the fatigue lives of reactor components under certain conditions. With regards to chemistry related parameters, EAF performance is nominally only a function of oxygen concentration, according to the environmental correction factor (F_{en}) equations and PWR fatigue crack growth (FCG) laws in the literature that describe the effect of environment (Reference [21]). The control of oxygen within the primary coolant to {REDACTED} during Mode 1 will help minimise the risk of EAF (and other corrosion mechanisms) for the RR SMR (Reference [1]).

20.4.4 Fuel Cladding Integrity

20.4.4.1 Introduction

Zirconium (Zr) alloy is widely used as fuel cladding material in operational nuclear reactors, being highly corrosion resistant under PWR reactor circuit conditions and having a low neutron capture cross-section. In early nuclear reactors pure Zr was used but alloying additions were later introduced to improve properties. Zr alloys for cladding use have since been optimised further to improve corrosion resistance, mechanical properties, and dimensional stability. The Zr alloy 'Optimised ZIRLO™' (trademarked by Westinghouse) is selected as the baseline cladding for the RR SMR design.

Generally, under typical PWR operating chemistries and impurity concentrations, Zr alloy cladding is resistant to corrosion and the risk of cladding failure is low. However, the presence of crud can create localised environments where the concentration of chemical species at the fuel cladding surface can be significantly increased from that of the bulk coolant. The presence of crud can also increase radioactivity on plant and potentially worker dose rate. There are also certain crud-related phenomena that can promote corrosion of fuel cladding, which are discussed further below.

Fuel cladding corrosion is summarised below and is also covered in more detail in the 'Primary Water Chemistry: Minimisation of Fuel Cladding Corrosion' Tier 2 chemistry document (Reference [71]) which demonstrates that the RR SMR primary water chemistry regime has been optimised to reduce fuel cladding corrosion ALARP.

20.4.4.2 Cladding Corrosion

The corrosion of Zr alloy cladding results in two important processes occurring:

1. Thinning of the cladding and formation of a zirconium dioxide (ZrO_2) on the cladding surface.
2. Absorption of hydrogen into the Zr alloy, which embrittles the cladding.

The main parameters that control the rate of fuel cladding corrosion are highlighted in the points below:

1. Temperature: as well as forming a barrier and maintaining containment of the fuel pellets and FPs, the cladding serves an important purpose in acting as the heat transfer medium, allowing heat from the fuel pellets to be transferred to the primary coolant. The temperature of the fuel cladding is always higher than that of the bulk coolant and the temperature at the metal to oxide interface at the cladding surface is the primary parameter controlling the rate of corrosion. As the oxide layer on the cladding surface thickens, the interface temperature increases, and this results in an increased corrosion rate.
2. Microstructure and composition of Zr alloy: any defects or local variations in the cladding material can impact on the rate of corrosion and therefore careful control is applied during the manufacturing process by the selected fuel vendor.
3. pH agent: many PWRs operate with LiOH as the pH modifier and experimental testing has shown that very high concentrations of LiOH can accelerate cladding corrosion. Fuel vendors place upper limits on the LiOH concentration allowable in the bulk coolant to reduce the risk of cladding failure. The requirement for an equivalent limit for KOH is yet to be determined for the RR SMR design. Fuel vendor recommendations will be taken into consideration when finalising the operating ranges and upper limits for KOH, which are provisionally provided in Reference [1]. For a soluble boron-free primary coolant regime, lower concentrations of KOH are required to achieve the same pH in comparison to a borated regime. An advantage of this is that there is likely to be a higher margin with respect to fuel vendor limits.
4. pH: under typical PWR operating conditions, pH has been shown to have little direct impact on cladding corrosion as Zr alloys have high corrosion resistance. However, pH does have an influence on the corrosion rate of other structural materials within the RCS [JE], as discussed in section 20.4.3. This has an influence on the formation of fuel crud deposits, which can impact cladding corrosion. Crud also acts as a thermally insulating layer, increasing cladding temperatures which accelerates rates of corrosion. The high and constant pH associated with the soluble boron-free primary coolant regime is expected to result in reduced cladding corrosion in comparison to a borated regime.
5. Oxygen: the presence of dissolved oxygen creates oxidising conditions within the primary coolant, accelerating the rate of general corrosion, as discussed in section 20.4.3. Under typical PWR operating conditions, the low oxygen concentrations achieved should result in minimal direct impact on the rate of Zr alloy corrosion.

6. Hydrogen: the hydrogen generated from oxidation that occurs between oxidising species and Zr fuel cladding generates hydrogen that can be incorporated into the cladding's metallic matrix. Furthermore, hydrogen can also be present in the clad from the manufacturing and welding processes used prior to service. This can ultimately embrittle the cladding and cause a degradation process often referred to as delayed hydride cracking (DHC).
7. Chloride, fluoride and sulfate: Zr alloy has far greater resistance than AuSS to chloride and sulfate induced SCC. However, there may be some stainless steel (SS) components in the fuel assembly that are susceptible to SCC, especially if they are cold worked e.g. core structure bolts. High concentrations of fluoride have also been shown to accelerate corrosion of Zr alloy.
8. Aluminium, calcium, magnesium, and silica: although having limited direct influence on cladding corrosion, these species can deposit on the fuel cladding surface and form thermally insulating layers, increasing the cladding temperature and indirectly increasing the corrosion rate. Silica is often detected in SFPs of PWRs and can potentially be transferred to the refuelling water storage tank, which in turn may be transferred to the RCS. Expected values and upper limits have been defined for each of these impurities, as well as for chloride, sulfate, and fluoride (Reference [1]).

20.4.4.3 Crud Formation

The RCS [JE] is designed so that heat from the fuel is transferred to the reactor coolant, which in turn transfers heat to the secondary system via the SGs [JEA]. As discussed, the fuel cladding surface is always hotter than the bulk coolant and in addition to this, the upper region of the fuel assembly is hotter than the lower region. Depending on the core design, the onset of nucleate boiling (ONB) can occur in the upper region of the fuel assembly; ONB is a type of boiling that occurs when the fuel cladding surface temperature is greater than the local liquid saturation temperature, but the bulk fluid remains below the saturation temperature. Bubbles are formed on the fuel cladding surface that collapse as they are cooled by the bulk coolant.

As the primary coolant enters the lower core region and flows over the fuel, the temperature of the bulk coolant increases, which can influence the solubility of species dissolved in the primary coolant. The ONB acts as a driving force for most of the deposition of crud on the fuel, causing precipitation of solution species and accumulation of CPs. The crud layer is therefore typically thicker in the upper fuel assembly regions, compared to the lower regions.

Crud is an important factor in the performance of the fuel, as deposited crud will result in increased fuel cladding temperatures. Understanding crud behaviour and having the ability to model crud thickness and cladding temperatures is important to maintain compliance with the thermal limits and restrictions placed on the fuel. As described elsewhere, chemistry controls are in place to minimise corrosion and thus the quantity of CPs present in the bulk coolant. Furthermore, design parameters are in place such as a peak cladding temperature limit and restrictions of heat flux and burnup rate of the plant to reduce the extent of degradation via ONB. They will be referenced in future iterations of E3S Case Version 2, Tier 1, Chapter 4: Reactor (Fuel and Core); Reference [72].

20.4.4.4 Crud-Induced Localised Corrosion (CILC)

Crud-induced localised corrosion (CILC) is accelerated corrosion of Zr alloy cladding caused by a combination of crud-induced cladding temperature increases, crud thickness increases and an accumulation of CPs. In the worst case this can result in fuel failure and release of FPs into the system.

20.4.4.5 Crud-Induced Power Shifts (CIPS)

Crud-induced power shifts (CIPS), formerly known as axial offset anomaly (AOA), occur because of boron-containing species precipitating within porous crud deposits under sub-cooled boiling conditions. By its nature, boron will absorb neutrons released during nuclear fission reactions in the fuel. The presence of locally high levels of boron incorporated within crud means the reactivity within a crud region is suppressed and thus reactivity becomes non-uniform across the core height. The detrimental effect of this is less efficient operation of plant and / or loss of control of fuel rod reactivity. Alternatively, to control a CIPS event, power stations must operate under reduced power output. As discussed in section 20.0, the RR SMR primary coolant chemistry regime will not include boron during normal operation, therefore CIPS is prevented.

20.4.4.6 Ultrasonic Fuel Cleaning (UFC)

Ultrasonic fuel cleaning (UFC) is an available technology that has been used in PWRs previously to effectively remove CPs from fuel assemblies to reduce the likelihood of CIPS and CILC occurring. It is reported that as of April 2013, a total of 100 UFC campaigns have been performed to remove crud at 24 PWRs (Reference [4]). The RR SMR design has included provision for UFC within the design. However, with the material and chemistry choices that RR SMR will implement, it is expected that crud loading will be relatively small as corrosion rates of materials will be minimised ALARP during operation. The crud inventory on fuel is also dependent on factors such as the method of shutdown and dosed zinc concentration which have not been finalised yet; section 20.4.7.

20.4.5 Radioactivity

20.4.5.1 Introduction

Managing primary coolant water chemistry is of key importance for minimising the distribution of radioactivity within the primary circuit. The main contributors to radiation field generation (and thus to the collective dose during outages) are CPs. To limit radiation field generation from corrosion there are two options:

1. Limit corrosion of materials (through chemistry and/or material selection).
2. Limit the concentration of elements known to significantly contribute to radiation fields and therefore occupational radiation exposure (ORE), such as cobalt in these materials (material selection).

APs also contribute to radiation fields; these are generated from chemicals purposely injected into the coolant and activation of the coolant (e.g. nitrogen-16 [N-16] production from water).

Minimisation of radioactivity is covered in more detail in the Tier 2 document titled 'Primary Water Chemistry: Minimisation of Radioactivity' (Reference [73]), which demonstrates that the RR SMR primary chemistry regime has been optimised to minimise radioactivity ALARP. This Tier 2 report is limited to the chemistry considerations to meet the first part of Objective 3 (stated in section 20.4.2) for the RCS [JE] i.e. "minimise out-of-core radiation fields".

The development of radioactivity within the primary circuit is dictated by the following three steps:

1. Generation of radionuclides,
2. Deposition of radionuclides, and
3. Accumulation of radionuclides.

Reference [73] provides evidence to demonstrate the RR SMR chemistry regime places suitable controls in place to minimise generation, optimise deposition, and minimise accumulation of radioactivity within the primary circuit ALARP. A summary of each of the steps is provided below.

20.4.5.2 Generation of Radionuclides

Chemistry parameters are optimised to reduce corrosion ALARP (Reference [47]), which means there are less non-active CPs generated in the primary coolant; sections 20.4.3 and 20.4.6. This means there is less deposition on the fuel surface and thus less CPs formed and released which can deposit on out of core surfaces. Therefore, the minimisation of corrosion of structural materials in the RR SMR primary circuit also contributes to the minimisation of radioactivity and dose rates. The planned injection of zinc on fresh surfaces (i.e. during HFT) has also been shown to improve the corrosion resistance of structural materials (Reference [74]).

Chemistry parameters are also optimised to reduce fuel cladding corrosion ALARP; section 20.4.4. This reduction in fuel cladding corrosion minimises the risk of a fuel clad breach which would result in the release of FPs and actinide products (ActPs) into the RCS [JE].

As RR SMR will not inject boric acid and will utilise KOH in place of LiOH, tritium levels will be significantly reduced; section 20.4.6. Several APs such as N-16, nitrogen-17 (N-17) and carbon-14 (C-14) are unavoidable due to activation of the oxygen atom present in water. However, reducing air content via mechanical degassing during start-up will reduce the generation of argon-41 (Ar-41). Moreover, reduction of impurity limits {REDACTED} helps reduce levels of chlorine-36 (Cl-36).

RR SMR will also have Materials Compatibility Requirements (Reference [68]) and Cleanliness Requirements (Reference [69]) in place to minimise the ingress of potentially detrimental species.

20.4.5.3 Deposition of Radionuclides

Fuel Surface Deposition

RR SMR is expected to inject KOH to achieve a $\text{pH}_{300\text{ }^\circ\text{C}}$ of 7.4 and is expected to dose hydrogen between {REDACTED} (Reference [1]). Solubility plots provided in Reference [73] show that there are clear benefits for operating at elevated pH in terms of minimisation of deposition through the core. The benefits of increasing or decreasing hydrogen concentration are directly related to the Ni/Fe ratio. In high Ni/Fe ratios, increasing hydrogen has clear benefits to reduce nickel solubility, whereas the opposite is true for low Ni/Fe ratios. RR SMR will further investigate this issue during GDA Step 3 when expected RR SMR soluble primary coolant values of iron and nickel are better understood.

Out of Core Surface Deposition

The injection of zinc into the primary coolant at {REDACTED} is expected to reduce dose rates primarily from the deposition of radiocobalts on out of core surfaces. Zinc is expected to be dosed during HFT thus there is an expectation that oxide layers will become saturated with zinc during their formation. This is expected to provide protection from radiocobalt incorporation from the beginning of operations.

20.4.5.4 Accumulation of Radionuclides

Purification systems play a major role in decreasing activity concentration in the primary coolant and have a major influence on ORE during outages for refuelling and/or maintenance. Ideally any radionuclides present within the primary coolant will become bound to either the ion exchange resins or filters present within the CPS [KBE] in the CVCS [KB]. This allows controlled accumulation of radiation in a known location and allows an operator to decide when and how to process accumulated radioactivity. The purification system in the CPS [KBE] also removes other impurities such as chloride, fluoride and sulfate which contribute to corrosion, as well as non-active CPs which may otherwise become activated in the core.

The minimisation of dissolved and airborne activity in the SFP [FAB10] area is also important to minimise dose rates ALARP. The primary means to minimise SFP [FAB10] activity is through the SFP [FAB10] purification system which includes demineralisers and filters. The FPPS [FAL] will remove impurities present in the SFP [FAB10] and uphold the water chemistry specification defined in Reference [1].

20.4.6 Chemistry Control Parameters

20.4.6.1 Introduction

Sections 20.4.3 and 20.4.4 describe the main chemistry-related parameters that influence corrosion of the structural materials within the primary coolant system, as well as fuel cladding integrity. The most significant parameters are pH, redox potential, and impurities; controlling these parameters supports achievement of the overall three chemistry objectives of reducing structural corrosion, reducing fuel cladding corrosion and reducing radiation fields. These three parameters, as well as the addition of zinc, are discussed in more detail in the sub-sections below.

20.4.6.2 pH Control

Control of pH during the reactor cycle is important to minimise corrosion of the primary circuit materials, but also once CPs are formed, pH impacts the solubility of CPs in the primary coolant, the thermodynamics and kinetics of in-core deposition, and release and redeposition on out-of-core surfaces. The optimum pH regime represents a balance between lowering plant radiation fields, controlling corrosion of structural materials and maintaining fuel cladding integrity.

As discussed, western PWRs typically operate with LiOH as the pH modifier and boric acid for reactivity control, both of which influence the pH that is achieved. At the start of the cycle, when core reactivity is highest, a higher concentration of boron is required in the primary coolant and the concentration of dissolved boron subsequently decreases over the course of the operating cycle. PWRs have OpEx of maintaining pH_T (where T is typically defined as temperature at 300 °C, or at average at-power operating temperature, T_{av}) in the range of 6.9 to 7.4 (Reference [4]). pH is a temperature dependent parameter and pure water would be $pH_{300\text{ }^\circ\text{C}} \sim 5.7$. At 25 °C, the $pH_{25\text{ }^\circ\text{C}}$ of pure water is 7.

The minimum of the typical pH target range ($pH_T = 6.9$) is aimed at reducing the rate of general corrosion within the reactor circuit and reducing the corrosion of the fuel cladding. In recent years some plants have implemented 'elevated' pH regimes, where the pH_T is maintained at $pH_T > 7.2$ for the entire operating cycle.

As well as influencing the rate of general corrosion and the release of CPs, the pH has also been shown to influence the solubility of CPs within the core, therefore influencing the volume of crud deposited on the fuel. Increasing the pH has been shown to reduce the amount of crud deposited on the fuel, whereas operating at a $\text{pH}_T < 6.9$ results in increases in the amount of crud deposited. Experimental testing with pressurised in-pile loops has confirmed that out-of-core radioactivity is minimised by increasing the pH of the coolant, with observations from operating plants supporting this conclusion, with most modern plants targeting an elevated pH_T .

To reduce the corrosion of primary coolant system materials, minimise the amount of crud deposition and out-of-core deposition, it is beneficial to operate at as high a pH as practicable. The majority of PWRs therefore adopt a pH_T between 6.9 and 7.4, with the upper limit imposed to control the maximum lithium concentration, usually driven by fuel vendor limits, due to concerns of accelerated cladding corrosion at high lithium concentrations (Reference [4]). Within the range 6.9-7.4, pH_T has been shown to have minimal influence on the rates of SCC and PWSCC.

For the RR SMR design, removing the requirement for soluble boron for reactivity control means that the primary coolant pH can be controlled by a strong base only. KOH is the pH raiser selected for the baseline design and it offers several benefits over LiOH. The benefits, which are discussed in more detail in (Reference [17]), include the following:

1. Surety of chemical supply (KOH vs LiOH). KOH is readily available to purchase in the UK, whereas there is more of a shortage of lithium which is produced outside of the UK.
2. Potassium does not need to undergo an enrichment process whereas lithium has to be isotopically enriched to remove ^6Li before being used in a civil plant as LiOH. This enrichment process has a high energy demand and requires a large quantity of mercury to be used. Mercury is toxic and its use leads to the formation of mercury-containing waste products.
3. Mitigating known accelerated fuel cladding corrosion concerns, which are a concern in the presence of high concentrations of LiOH.
4. Reduction in tritium generation (neutron reactions with lithium are the second highest contributor to tritium generation in PWR coolant, with boron being the highest contributor), potentially resulting in substantially lower primary coolant discharge. As a result of eliminating soluble boron, the RR SMR does not require regular let down of primary coolant during a cycle to dilute boron as required for duty reactivity control. This provides the opportunity to explore the potential for a different type of operation, more akin to closed cycle operation. Closed cycle operation has minimal impact on steady state coolant concentrations of most nuclides present in PWRs. The exception to this is tritium, as it is not removed by current technologies available in coolant purification systems.

A bulk coolant $\text{pH}_{300\text{ }^\circ\text{C}}$ of 7.4 is anticipated in the primary circuit of the RR SMR based on the expected potassium concentration. It is assumed that potassium will be control parameter and pH will be a diagnostic parameter in the RCS [JE] of the RR SMR (Reference [1]). As there will be no boric acid dosed, it should be possible to achieve a higher constant pH value from beginning of cycle (BOC), and a lower dose of KOH is required (compared to that which would be required in the presence of boric acid). A value of $\text{pH}_{300\text{ }^\circ\text{C}} = 7.4$ has been shown to reduce general corrosion and reduce the solubility of CPs.

As discussed in Reference [71], the removal of boron has removed the risk of CIPS events occurring since this is dependent on boron-containing precipitates forming. Minimising the risk of CILC and

the underpinning justification is discussed in Reference [71], and will be further demonstrated in Tier 3 documentation during GDA Step 3.

pH control in the primary coolant is further discussed in Reference [47], and the detailed technical underpinning (evidence) for pH control in the primary coolant will be provided in a Tier 3 document titled 'Primary Water Chemistry: Technical Justification for Optimisation of pH', for inclusion in the next version of the E3S Case.

20.4.6.3 Redox Potential

In simplistic terms, the redox potential can be considered the driving force for corrosion; generally, metallics are more susceptible to corrosion when exposed to high redox potentials and are more resistant to corrosion at lower redox potentials. Chemical oxidising agents, such as oxygen, serve to raise the redox potential and can significantly impact on the corrosion susceptibility of components within the RCS. Even low concentrations of oxygen have a strong impact on the redox potential, and this is of particular concern when in the presence of chloride and sulfate, which serve to enhance the susceptibility of AuSS to SCC.

The susceptibility of AuSS to SCC has long been recognised, with control of aggressive impurities and oxygen being considered in the design of early PWRs. The increased resistance to SCC of NBAs was a primary consideration in their use as SG tubing material. However, the influence of radiation on the primary coolant and the generation of oxidising species because of radiolysis was not fully understood and this process has resulted in corrosion-related performance issues being encountered in numerous PWRs.

Radiolysis is the dissociation of molecules when exposed to radiation. In PWRs, water is used as both the primary coolant and the moderator; when exposed to radiation, the water molecules decompose into several products, most noticeably hydrogen, oxygen, and peroxide. The radiolytic decomposition of water is a complex series of reactions.

Oxygen and peroxide are oxidants and increase the redox potential within the primary coolant, with OpEx showing that the increase is sufficient to promote SCC in AuSS, even in low concentrations of chloride and sulfate. The increase in redox potential has also proven to be sufficient to promote PWSCC in Alloy 600, which was widely used as the tubing material within the SGs.

The radiolytic decomposition of water involves a series of equilibrium reactions and when excess hydrogen is present, the reaction is suppressed, and a steady state is reached where low concentrations of oxygen and peroxide are formed. Hydrogen injection is therefore implemented to promote reducing conditions within the primary coolant and mitigate SCC and PWSCC. The reducing conditions also have the advantage of reducing the rate of general corrosion of structural materials, reducing the release of CPs that could deposit on the fuel, as well as increasing the CP solubility across the core, which again is beneficial for reducing the amount of crud deposition. The minimum hydrogen concentration required to suppress radiolysis is dependent on the radiation levels within the reactor core; at lower radiation levels, less hydrogen is required to suppress radiolysis.

Although resistant, the RR SMR materials of construction still have some susceptibility to SCC and PWSCC under oxidising conditions. To achieve a reducing environment in the RR SMR primary coolant oxygen concentration will be lowered within the coolant and controlled at low levels. During start-up oxygen will be lowered, potentially using a combination of mechanical and chemical methods, to bring oxygen down to {REDACTED} prior to entering Modes 1 and 2 (Reference [1]), which is considered sufficient to minimise various types of corrosion. As oxygen will be produced during

operation via radiolysis, hydrogen will be injected to suppress these reactions. The addition of excess hydrogen serves to scavenge residual dissolved oxygen in the coolant water. Hydrogen optimisation for RR SMR is an ongoing process but it is recognised that the hydrogen concentration will likely fall between {REDACTED} (standard temperature and pressure [STP]) during normal operation (Reference [1]).

The influence of redox potential in the primary circuit is discussed in more detail in Reference [47], and the detailed technical underpinning (evidence) for redox potential control in the primary coolant will be provided in a Tier 3 document titled 'Primary Water Chemistry: Technical Justification for Optimisation of Redox Potential', for inclusion in the next version of the E3S Case.

20.4.6.4 Zinc Injection

Evidence from plant measurements and experiential studies indicates that the rate of incorporation of radiocobalt into oxide films on out-of-core surfaces is significantly reduced due to the presence of zinc in the coolant. This results in reduced out-of-core radiation fields and therefore exposure to operators. The likely mechanism for this is the competition between zinc and cobalt for available sites in the oxide films. Data also shows that zinc addition may reduce general corrosion rates and can reduce propagation rates of existing cracks in low stress components. Zinc is typically injected at a target concentration of {REDACTED} for dose reduction purposes and {REDACTED} for PWSCC mitigation of Alloy 600 materials (Reference [4]). As discussed in section 20.4.3, RR SMR will implement Alloy 690TT for SG tubing material which is highly resistant to PWSCC. The majority of PWR plants operating with Alloy 690TT SG tubing dose zinc at {REDACTED}.

Additional benefit is anticipated for plants operating with zinc injection from the first cycle, with zinc injected during HFT leading to the uptake of zinc into growing films. The addition of zinc also appears to reduce the release rate of significant activated CPs from the fuel surface, as well as their incorporation into oxide films on out-of-core oxide surfaces.

It is anticipated that RR SMR will inject zinc in the form of depleted zinc acetate from HFT, such that the production of radiologically significant zinc-65 (Zn-65) is also minimised. It is likely that zinc will be a diagnostic parameter in the RCS [JE] for Modes 1, 2, 3 and 4A with an expected value in the range of {REDACTED} (Reference [1]).

The influence of zinc injection in the primary coolant is further discussed in References [47] and [71], where aspects such as the mechanism of action, influence on general corrosion and PWSCC, minimisation of zinc silicate formation through impurity control measures, and the benefits of injection during HFT are discussed in more detail. The detailed technical underpinning (evidence) for zinc addition in the primary coolant will be provided in a Tier 3 document titled 'Primary Water Chemistry: Technical Justification for Zinc Addition', for incorporation into the next version of the E3S Case.

20.4.6.5 Impurity Control

Management of the chemical environment to minimise corrosive impurities is an important factor in mitigating the risk of SCC and fuel cladding failure, in conjunction with the inherent resistance of the materials of construction. The ionic impurities of chloride, fluoride and sulfate in the primary coolant are of most concern and must be carefully monitored.

1. AuSS is susceptible to SCC in the presence of chloride, with highly stressed components being susceptible even in low oxygen concentration.

2. The relationship of sulfate and SCC in the PWR environment is less well studied than that of chloride, but sulfate can also enhance the susceptibility of SSs, particularly sensitised steels such as produced from welding, and NBAs to SCC in deaerated conditions.
3. Fluoride is controlled due to the increased risk of fuel cladding corrosion at elevated fluoride concentrations.

Chloride, fluoride, and sulfate are all control parameters in the RCS [JE] for all modes of operation (Reference [1]), with expected values and limits in line with those provided by industry guidelines.

The influence of impurity control in the primary coolant is further discussed in Reference [47], and the detailed technical underpinning (evidence) for impurity control in the primary coolant will be provided in a Tier 3 document titled 'Primary Water Chemistry: Technical Justification for Control of Impurities', for incorporation into the next version of the E3S Case.

20.4.7 Start-up and Shutdown Chemistry

20.4.7.1 Introduction

The information presented in sections 20.4.3 to 20.4.6 is predominantly focussed on chemistry control during at-power operations; although the principles of chemistry control that are outlined are applicable to all modes of operation, the changes that occur during mode changes have an impact on chemistry control.

20.4.7.2 Shutdown Chemistry for Refuelling Outage

As discussed, general corrosion of the RCS [JE] materials results in the formation of a protective oxide layer on the metal surface and the slow release of CPs into the primary coolant.

During a refuelling outage, the reducing conditions achieved during power operations cannot be maintained as the reactor circuit is opened to air when the reactor head is removed. The change in chemistry environment can cause changes to the oxide layer. Uncontrolled 'crud bursts' (release of CPs driven by changes in the chemistry environment) during shutdown can cause operational challenges, increased outage dose rates and extensions to the outage duration.

The approach to shutdown chemistry control and crud management will be informed as the RR SMR design and operating philosophy develops and it will be discussed in more detail in the next version of the E3S Case. The design will have the ability to inject peroxide during shutdown to purposely achieve controlled oxidising conditions prior to reactor head removal. This will allow for controlled clean up and removal of any excessive CPs generated by a crud burst. The parameters currently defined in the Reactor Island [R01] Water Chemistry Specification Tables are based on the assumption that the chemistry will be changed from alkali reducing operating conditions in Mode 1 and 2 to a neutral oxygenated demineralised water chemistry conditions prior to the RPV head lift (Mode 6); Reference [47].

20.4.7.3 Start-Up Chemistry

The start-up philosophy for RR SMR is also yet to be finalised. During refuelling outages in typical PWRs the head of the reactor is removed and flood-up occurs, enabling fuel to be removed and transferred to the SFP. The primary coolant is exposed to the environment within the reactor

building, resulting in the dissolved oxygen concentrations increasing. In addition, impurities that are present can dissolve into the primary coolant, increasing the impurity concentrations.

Corrosion is a temperature dependent process, with the corrosion rate typically increasing with increasing temperature. During outages the primary coolant temperature and pressure are significantly reduced, compared to at-power operations. This means that the risk of corrosion is reduced during refuelling outages and a higher concentration of impurities and dissolved oxygen can be tolerated. However, it is important that the impurity concentrations are reduced before the reactor commences heat up and the transition to at-power operations.

On completion of refuelling operations, the reactor head is replaced, creating a sealed environment within the RCS [JE]. The coolant is circulated through the CVCS [KB] to remove impurities and condition the chemistry in preparation for heat-up operations. The primary coolant is deaerated to reduce the concentration of dissolved gases, most noticeably the dissolved oxygen concentration. As the reactor temperature and pressure are increased, dissolved hydrogen injection and pH raising are implemented to achieve alkaline, reducing conditions prior to transferring to at-power operations (Mode 1). It is currently expected that hydrogen dosing will restart in Mode 4A or Mode 3 prior to criticality. With regards to pH, potassium dosing is expected to be restarted during Mode 4B, Mode 4A or Mode 3 and at least prior to criticality and may be raised to normal power operation expected values.

It is important to minimise dissolved oxygen ALARP during start-up to minimise the risk of SCC. To accelerate the removal of dissolved oxygen and reduce the outage duration, it is common practice for PWRs to inject hydrazine during warm-up operations. Hydrazine is an oxygen scavenger, reacting with oxygen to form water and nitrogen. The requirement for hydrazine is currently under review as the design matures. It may be used alongside mechanical degassing. It is anticipated that addition would be during Mode 5A and possibly into Mode 4B during heat-up (Reference [1]). As the RR SMR design and operating philosophy develops, outage durations and target durations will be refined and confirmed for inclusion in the next version of the E3S Case.

20.4.8 Design Development

20.4.8.1 Baseline Chemistry Regime

The baseline chemistry regime for the primary coolant is as follows:

1. KOH as the alkali agent, increasing the pH to minimise corrosion and deposition of CPs onto the fuel.
2. A boron-free chemistry regime, which results in benefits such as elimination of a waste stream, simplification of waste and chemistry equipment and prevention of CIPS.
3. Hydrogen addition, to suppress radiolysis and create a reducing environment within the primary coolant, mitigating SCC and PWSCC.
4. Zinc addition, to control out-of-core dose rates.
5. Control of impurities that may negatively impact on corrosion or fuel performance.

There have been no major changes to the proposed chemistry philosophy since the PCD stage.

20.4.8.2 Further Development

As stated in section 20.2, the design maturity, operating philosophy, and chemistry specifications are being developed in parallel and are continually reviewed to ensure alignment. If evidence gaps are identified, or additional underpinning required, these will be considered for incorporation into the developing V&V strategy discussed in section 20.0.2. More specific information on future work that will be, or may be carried out, is provided each in the future work sections of Tier 2 chemistry documents related to primary coolant chemistry (References [47], [73], [71], [1] and [50]).

20.4.9 Tier 2 Chemistry Reports

The Tier 2 documents which have been produced in relation to the primary coolant chemistry regime are listed below. Associated claim IDs of most relevance to section 20.4 are also listed, with the claims presented in Appendix A (section 20.13).

1. Reactor Island [R01] Water Chemistry Specification Tables (Reference [1])
2. Primary Water Chemistry: Method of Monitoring and Control (Reference [50])
3. Primary Water Chemistry: Minimisation of Corrosion of Structural Materials (Reference [47]): there is currently one Level 2 claim and four Level 3 claims that relate to minimisation of corrosion of structural materials in the primary circuit. They fall under argument 20.1 and are claims 20.1.1, 20.1.1.1, 20.1.1.2, 20.1.1.3 and 20.1.1.4.
4. Primary Water Chemistry: Minimisation of Fuel Cladding Corrosion (Reference [71]): there are four Level 2 claims relating to minimisation of fuel cladding corrosion. They fall under argument 20.2 and are claims 20.2.1, 20.2.2, 20.2.3 and 20.2.4.
5. Primary Water Chemistry: Minimisation of Radioactivity (Reference [73]): there are numerous Level 2 and Level 3 claims relating to minimisation of radioactivity. They fall under argument 20.3 and are claims 20.3.1, 20.3.1.1, 20.3.1.2, 20.3.1.3, 20.3.2, 20.3.2.1, 20.3.2.2, 20.3.2.3, 20.3.3, 20.3.3.1, 20.3.4, 20.3.4.1, 20.3.5 and 20.3.6.

20.5 Primary Auxiliary System Chemistry

20.5.1 Introduction

The Tier 2 report produced entitled ‘Chemistry Justification for Primary Coolant Auxiliary Systems’ (Reference [75]) provides the technical basis for the chemistry controls used to minimise corrosion and support reliable operation within the primary auxiliary systems during all modes of normal and emergency injection operations. The auxiliary systems currently covered by this document, and those to be covered in future revision(s), are listed below.

1. Reactor Reactivity Control Systems [JD], including:
 - a. EBIS [JDK],
2. Reactor Heat Removal Systems [JN], including:
 - a. CSCS [JNA],
 - b. LPIS [JNG],
 - c. HPIS [JND],
 - d. LUHS [JNK],

**This system is the ultimate heat sink for Emergency Core Cooling (ECC) [JN01] and containment cooling.*

3. Internal Fuel Storage [FA] systems, including:
 - a. Spent Fuel Storage and Cask Loading [FAB] (including SFP [FAB10]),
 - b. Refuelling Cavity [FAE] (to be covered in future),
 - c. Refuelling Pool [FAF] (to be covered in future),
 - d. FPCS [FAK],
 - e. FPPS [FAL],
 - f. FPSS [FAT],
4. CVCS [KB] systems (to be covered in future), and
5. RISS [KU] systems (to be covered in future).

The following safety measures are also referred to:

1. ECC [JN01],
2. Passive Decay Heat Removal (PDHR) [JN02],

3. Alternative Shutdown Function (ASF) [JD02], and
4. Low Temperature Decay Heat Removal (LTDHR) [JN04].

Design information, key chemistry controls, materials selection, and degradation mechanisms relevant to the Internal Fuel Storage [FA] systems are discussed in section 20.5.2. Those relevant to the key safety systems are discussed in section 20.5.3.

20.5.2 Spent Fuel Pool and Spent Fuel Pool Cooling System Coolant

20.5.2.1 Introduction to Chemistry Controls

Chemistry controls are required for Internal Fuel Storage [FA] systems to maintain water clarity, minimise dissolved and airborne activity, and minimise corrosion of structural materials and fuel assemblies.

20.5.2.2 Design Information

The SFP [FAB10] stores new and spent fuel as well as used filter and other pieces of equipment, and its primary function is to remove residual heat from fuel assemblies, maintain subcriticality and provide shielding. The FPCS [FAK] removes heat from the fuel pools to maintain fuel pool temperature below 50 °C, the FPPS [FAL] removes impurities from the fuel pools to maintain the water chemistry specification, and the FPSS [FAT] maintains the water level within specification in the fuel pools and contains the Refuelling Water Storage Tank (RWST) [FAT33] which can store and supply water when needed.

Further design information, including development activities, is contained within E3S Case Version 2, Tier 1, Chapter 9A: Auxiliary Systems (Reference [59]). Design information is also contained within SDDs for the Spent Fuel Storage and Cask Loading System [FAB] (Reference [76]) and the various Fuel Pool Fluid Systems (Reference [77]). Furthermore, information regarding material choices is contained within functional bill of materials (FBoM) documents for the FPCS [FAK], FPPS [FAL] and the FPSS [FAT] (References [78], [79] and [80]).

20.5.2.3 Water Clarity

Water clarity is important to ensure fuel movements, visual checks, and UFC can be performed to an appropriate standard by an operator. The presence of CPs, silica and impurities from microbiological growth are influencing factors. Turbidity, suspended solids, silica, and microbial growth are monitored for trending as diagnostic parameters for the SFP [FAB10], and an expected value of {REDACTED} nephelometric turbidity units (NTU) for turbidity is currently specified. OpEx indicates that the combination of the use of ion exchange columns (IXCs) and filters in the FPPS [FAL] will be effective in maintaining SFP [FAB10] water clarity (Reference [4]).

20.5.2.4 Minimisation of Dissolved and Airborne Activity

The minimisation of dissolved and airborne activity in the SFP [FAB10] is important to maintain dose rates ALARP. The chemistry parameters that control the behaviour of radioactive species, including their influence on the SFP [FAB10] dissolved and airborne activity, are considered in the 'Primary Water Chemistry: Minimisation of Radioactivity' document (Reference [73]). The effectiveness of the FPPS [FAL] filters and IXC resins in removing activity are considered.

20.5.2.5 Minimisation of Corrosion of Structural Materials and Fuel Assemblies

The two key factors that control rates of corrosion of SFP [FAB10] structural materials, fuel assemblies and other equipment are levels of impurities and pH. The main degradation mechanisms of concern are general corrosion, localised corrosion (e.g. SCC, crevice corrosion, pitting, intergranular attack [IGA], etc.), microbiologically induced corrosion (MIC), and neutron absorber material degradation. Chloride, fluoride, and sulfate are control parameters, each with expected values of {REDACTED}, in the SFP [FAB10] water chemistry specification (Reference [1]). These values are in line with those provided by the latest EPRI PWR Primary Water Chemistry Guidelines (Reference [4]), which is widely and successfully used throughout the industry. A decision has not been made with regards to the SFP [FAB10] pH because it is defined by fuel criticality control and the shutdown chemistry which is still under review; Section 20.4.7. It is noted that a range of SFP water chemistries are used in LWRs although all absorb oxygen and carbon dioxide from the atmosphere. Some SFPs (e.g. for boiling water reactors (BWRs) and Canada deuterium uranium (CANDU) reactors) are filled with demineralised water (pH = 5.8 to 7.5), whereas the SFPs of PWRs and VVERs are typically filled with a dilute boric acid solution (pH = 4.3 to 5.5).

20.5.3 Control of Safety System Chemistry

20.5.3.1 Introduction to Safety System Chemistry

Several auxiliary systems are necessary to support the safe operation of the RR SMR primary circuit during normal operations and accident scenarios. The chemical regimes for all safety systems that interface with the primary coolant must be compatible with the primary coolant in terms of water chemistry specification.

20.5.3.2 Design Information

In the event of a Scram [JD01], the EBIS [JDK] delivers borated solution to the HPIS [JND] and the Refuelling Pool [FAF], which direct the solution into the primary circuit. The EBIS [JDK] boron storage tank will hold potassium tetraborate solution enriched in B-10 (Reference [81]).

The ECC [JN01] consists of three cooling trains which are each connected to the Reactor System [JA]. Pressure blowdown of the RCS [JE] is provided by the Automatic Depressurisation System [JNF], Reactor System [JA] injection is provided by the LPIS [JNG], and ultimate heat removal is provided by the LUHS [JNK].

The primary function of the CSCS [JNA] is to provide normal operations decay heat removal (i.e. LTDHR [JN04]) at plant temperatures below 120 °C and plant pressures below 2 MPa(a). It consists of a single supply and a single return connection to the Reactor Coolant Pipework System [JEC].

Further design information, including development activities, is contained within E3S Case Version 2, Tier 1, Chapter 6: Engineered Safety Features (Reference [82]). SDDs for the EBIS [JDK], HPIS [JND], ECC [JN01], LPIS [JNG] and the LUHS [JNK] are included in References [83], [84], [85], [86] and [87] respectively. The CSCS [JNA] is described in E3S Case Version 2, Tier 1, Chapter 5: Reactor Coolant System and Associated Systems (Reference [57]) and the SDD is in Reference [88].

20.5.3.3 EBIS [JDK] Chemistry Control

Key factors to consider are the solubility and boron concentration of the chosen neutron moderator in its storage environment, pH, corrosion susceptibility, and activation. The selection of potassium

tetraborate tetrahydrate has been made for the RR SMR as it shows very good solubility in comparison to boric acid and other alternative borates (Reference [89]). Furthermore, it shows stable pH characteristics and crystalline stability is not expected to be an issue. Corrosion is considered unlikely to occur in the EBIS [JDK] due to the use of corrosion resistant material (i.e. AuSS) and the low temperature, alkaline, and borated environment. Potassium isotopes' (potassium-40 [K-40] and potassium-42 [K-42]) contribution to the total coolant activity will be significantly less in comparison to the sodium isotope (sodium-24 [Na-24]); therefore, a potassium-based moderator is favoured over a sodium-based moderator.

In the latest version of the Reactor Island [R01] Water Chemistry Specification Tables (Reference [1]), boron is a control parameter for the EBIS [JNK] (although expected values have not been defined yet). It is expected that grab samples of the tanks will also be taken to monitor the diagnostic parameters iron, conductivity, and pH.

20.5.3.4 ECC [JN01] Chemistry Control

The ECC [JN01] has similar design to the Emergency Core Coolant System (ECCS) of current PWRs and BWRs. The LPIS [JNG] and LUHS [JNK] systems are made from AuSS and hold non-borated demineralised water. In the ECC [JN01], the presence of dissolved oxygen, sulfates, fluorides, and chlorides can potentially provide the necessary environments for SCC to occur. However, SCC very rarely occurs in AuSS under 60 °C, and these temperatures are not typically expected to be reached in LPIS [JNG] accumulators and LUHS [JNK] tanks. Furthermore, other forms of localised corrosion and general corrosion are considered unlikely to occur due to low levels of impurities.

In the latest version of the Reactor Island [R01] Water Chemistry Specifications Tables (Reference [1]), chloride, fluoride, and sulfate are control parameters for LUHS [JNK], with expected values of <math><50 \mu\text{gkg}^{-1}</math> provided to reduce the likelihood of corrosion occurring. pH is also a control parameter with an expected range of 5.5 to 8.0. It is anticipated that the LUHS [JNK] tanks will also be dosed with a biocide to prevent biological growth that could clog heat exchangers or cause MIC. It is also expected that grab samples of the tanks will be taken to monitor the diagnostic parameters iron, conductivity, and microbiological activity.

20.5.3.5 CSCS [JNA] Chemistry Control

The chemistry regime for the CSCS [JNA] is still to be determined and will be reviewed as the design evolves. When in operation the water chemistry requirements are likely to be the same as those of the RCS [JE]. The start-up and shutdown chemistry for the RR SMR is still to be confirmed, therefore justification for the CSCS [JNA] layup chemistry (i.e. oxygen control) cannot be made at this stage.

20.5.4 Tier 2 Chemistry Reports

The Tier 2 documents which have been produced that relate to the primary auxiliary system chemistry regime are the 'Reactor Island [R01] Water Chemistry Specification Tables' document (Reference [1]) described earlier, and the 'Chemistry Justification for Primary Coolant Auxiliary Systems' document (Reference [75]). More detailed technical underpinning (evidence) for chemistry control in primary auxiliary systems will be provided in Tier 3 documentation which will be produced during GDA Step 3. In terms of future development work more specific information on work that will be, or may be carried out, is provided in the future work section of the Tier 2 report (Reference [75]).



SMR

There are currently several Level 2 and Level 3 sub-claims that relate to primary auxiliary systems. They fall under both arguments 20.1 and 20.4 and are listed in the Appendix A (section 20.13) as claims 20.1.3, 20.1.3.1 and 20.4.2.

20.6 Secondary Coolant Chemistry

20.6.1 Design Overview

The main plant items that are within Turbine Island [T01], or that see secondary coolant chemistry, relevant to this section include:

1. SGs [JEA],
2. Feedwater System [LA],
3. Steam System [LB],
4. Condensate System [LC], including
 - a. SGPS [LCQ],
5. Condensate Polishing System [LD],
6. ANSS [QU], and
7. Steam Turbine System [MA].

Heat from the nuclear fuel is transferred from the RCS [JE] to the secondary system coolant in the three SGs [JEA]. Feedwater present in the SGs [JEA] is converted to steam which is then routed through the high pressure and low pressure turbines. The turbines are coupled to and rotate a generator, thereby generating the plant's electrical output. The steam leaving the low pressure turbines is condensed by heat exchange with the cooling water in the Main Cooling Water System (MCWS) [PA] system. The resulting condensate is then deaerated, pre-heated, and fed back into the SGs [JEA].

There is a bleed from the SGs [JEA] through the SGPS [LCQ] to control impurities in the secondary system coolant. Feedwater is provided from the demineraliser plant.

Additional information on the design and maturity of these systems is provided in E3S Case Version 2, Tier 1, Chapter 10: Steam and Power Conversion Systems (Reference [58]) and there is a SDD for the SGPS [LCQ] in Reference [63]. A more limited number of SDDs are currently available for systems within Turbine Island [T01] than for systems within Reactor Island [R01].

20.6.2 Historical Development of Secondary System Chemistry

The SG tubes facilitate the transfer of heat from the RCS to the secondary system coolant; this not only enables cooling of the nuclear fuel, but provides the heat required to convert the water in the secondary system to steam, providing the energy required to drive the steam turbines and ultimately generate electricity. As the boundary between the reactor coolant and secondary system coolant, the SG tubes also form part of the reactor coolant pressure boundary and prevent the spread of radioactivity.

The boiling of water that occurs within the SGs results in the concentration of non-volatile species, which can create corrosive environments and wastage of the SG materials, potentially resulting in

failure of the tubes and the release of primary coolant into the secondary system coolant. CPs from the steam, condensate and feedwater systems are also concentrated through boiling, resulting in fouling of the SG tubing and a reduction in heat transfer efficiency.

The two main objectives of chemistry control in the secondary system are to:

1. Reduce corrosion of the SG tube materials ALARP.
2. Reduce performance losses within the secondary system by reducing corrosion in the water and steam system and subsequent transport of CPs into the SGs, ALARP.

Due to its resistance to SCC under primary coolant conditions, early PWRs adopted Alloy 600 as the SG tubing material and carbon steel (CS) and low alloy steel (LAS) were widely used in the steam and feedwater systems. Secondary chemistry control in early PWRs was based on that in fossil stations, with most PWR units using disodium phosphate or sodium hydroxide to achieve alkaline conditions, combined with impurity and oxygen control (although plants using sodium hydroxide quickly changed to trisodium phosphate). Phosphate is a weaker base than sodium hydroxide, enabling phosphate to buffer contaminants entering the system. However, SG tubes soon started to suffer from corrosion problems due to the presence of phosphate-rich sludges; these sludges consolidated onto surfaces within the SGs and had high compressive strength, meaning they were difficult to remove. The sludges allowed the accumulation of aggressive species that caused corrosion of the SG materials. Phosphates (and sodium hydroxide) have low volatilities, meaning that they accumulate in the water phase and do not evaporate and transfer to the steam phase, resulting in no chemical conditioning of the steam and condensates that form.

To prevent the formation of consolidated sludges, plants adopted an “all volatile treatment” (AVT) of the secondary system and phosphate dosing was phased out of PWRs from the mid-1970s to late 1980s. The two main components of an AVT are an alkalisng agent used to control the pH around the circuit, and an oxygen scavenger used to remove dissolved oxygen. The pH is optimised to protect the condensate and feedwater piping from corrosion and to minimise iron transport. An appropriate pH range for protection is selected according to the plant design, material choices and operating conditions. A low oxygen concentration in the feedwater is important in reducing the susceptibility of plant materials to corrosion. Advantages of an AVT regime over a phosphate regime are that it generally results in less sludge formation within which impurities can concentrate, it causes less wastage, and it results in less corrosion of steam lines, wetted turbine components, condensers, and the condensate system. A disadvantage of an AVT regime is that, since the reagents are volatile, they will not concentrate in boiling crevices and protect these vulnerable areas. Early implementation of AVT typically used ammonia for pH control, combined with hydrazine for oxygen control.

Although ammonia is volatile and transfers into the steam system, it preferentially remains in the steam phase and only a small proportion transfers to water upon condensation. Ammonia therefore provides limited protection in the two-phase regions of the steam system. To provide additional corrosion protection within the two-phase regions, and therefore reduce the volume of CPs transferred to the SGs, alternative amines or a High-AVT regime have been adopted. Alternative amines, such as ethanolamine (ETA) or methiopropamine (MPA), have higher distribution coefficients, resulting in a greater proportion remaining in the water phase and therefore increased alkalinity of condensates in the two-phase regions of the steam system, providing increased corrosion protection. Alternative amines may be used alone, or in combination with ammonia. Use of a combination of ammonia and ETA has recently been implemented in many French PWRs. A High-AVT treatment uses higher concentrations of ammonia to increase the pH of condensates formed; due to the high ammonia concentrations, a High-AVT regime is not compatible with the condensate

purification system being operated at full flow. The condensate polishing system is typically only in service during start-ups and to correct impurity ingress.

20.6.3 Corrosion of Steam Generator Tubes

20.6.3.1 Introduction

Corrosion of the SG tubes has been the predominant issue that has influenced the evolution of the secondary system chemistry regime; this is due to SG tube corrosion being the most significant issue experienced in the secondary system, SGs being the most expensive/difficult component to repair in the secondary system and the important role that the SG tubes play in maintaining containment of the primary coolant. There has been a significant amount of research conducted on SG tubing corrosion, with most work focussing on mill-annealed Alloy 600 (600MA), as this was the tubing material used in early PWRs and which has suffered several corrosion-related issues. To mitigate these issues, several alternative materials have been used, which have increased resistance to corrosion (*order from lowest to highest resistance*):

1. Alloy 600MA: operational experience has shown that this is the alloy that has experienced the most corrosion-related issues in PWR SGs, with IGA and SCC being the dominant corrosion mechanisms.
2. Stress relieved Alloy 600 (600SR): this alloy has experienced serious corrosion issues in operating PWRs, but to a lesser extent than 600 MA.
3. Thermally treated Alloy 600 (600TT): this alloy has been used in SGs since 1980 and there have been limited cases of IGA/SCC. Although it has increased resistance to secondary side IGA/SCC, laboratory testing has shown that this alloy is susceptible to PWSCC.
4. Nuclear grade Alloy 800 (800NG): this alloy has been used in SGs since 1972 and experienced some corrosion issues whilst operating with phosphate chemistry. There have been limited cases of IGA/SCC under AVT, although other issues have been encountered.
5. Thermally treated Alloy 690 (690TT): this alloy has been used in SGs since 1989 and to date, there have been no confirmed cases of IGA/SCC. Alloy 690TT has a high resistance to IGA/SCC, even under aggressive test conditions, and has increased resistance to PWSCC compared to the other grades of NBAs.

The main alloying elements present in these alloys are nickel, chromium, and iron. Under typical secondary system operating chemistries, nickel, chromium, and iron all experience greater stability as oxides, rather than metals. Although the metals are reactive under secondary system chemistry conditions, the formation of protective oxide films provides protection and results in low corrosion rates being experienced. The protective films result in high resistance to general forms of corrosion, but if the film is damaged, the materials can be susceptible to localised forms of corrosion. IGA, SCC (including lead-induced SCC [PbSCC]) and pitting are the main localised corrosion mechanisms of concern regarding the SG tubes. Denting, pitting, vibration-induced degradation, and fouling are other degradation mechanisms that have been experienced in SGs in the past, with each of these strongly linked to the build-up of sludge from iron oxide pick-up in the condensate system.

The main chemistry parameters that influence corrosion are as follows:

1. pH: the pH of the system influences both general corrosion and localised corrosion. At typical SG operating temperatures (i.e. 280-300 °C) chromium, nickel and iron are susceptible to

general corrosion when exposed to low and high pHs. However, they form stable oxides at mid-range pHs (~pH 6-9). Experimental testing has shown that at low pH, Alloy 600 is susceptible to acidic attack and vulnerable to SCC under oxidising conditions, whilst at higher pHs the alloy is susceptible to alkaline SCC and IGA under oxidising and reducing conditions.

2. Redox Potential: in common with the primary coolant system, corrosion of SGs tubes is accelerated under highly oxidising conditions (high redox potentials) but a stable protective oxide is formed when redox potentials are reduced. As the alloys rely on a stable oxide layer for corrosion protection, some mildly oxidising conditions are beneficial, as this provides the driving force for corrosion and the formation of the oxide film. However, if the redox potential increases and conditions become highly oxidising, then the alloys are susceptible to SCC and IGA, with the stable oxide film breaking down and localised corrosion occurring.
3. Impurities/Aggressive Species: aggressive species can potentially accelerate the rate of corrosion by affecting the local conditions experienced, by changing the pH and/or redox potential. Some aggressive species affect the corrosion rate by impacting on the formation and integrity of the protective oxide layer that is formed on the SG tube material.

20.6.3.2 pH and Oxygen/Redox Potential

As described in section 20.6.2, a High-AVT regime or an alternative amine regime are commonly used for secondary system chemistry control. The amines are dosed into the feedwater to achieve a mildly alkaline regime at SG operating temperatures, which is equivalent to a pH of ~10 at 25 °C in the case of a High-AVT regime. A mildly alkaline pH and low dissolved oxygen concentration provide the optimum conditions for the formation of a protective oxide to form on the SG tube materials, ensuring passivity and protection from general and localised forms of corrosion.

Oxygen Control / Redox Potential Control

Within the secondary system, the presence of dissolved oxygen has the greatest effect on redox potential. Although the secondary system operates under vacuum conditions, dissolved oxygen is present in the make-up water and general ingress into the system. Hydrazine is typically injected into the feedwater system to act as an oxygen scavenger, ensuring a low dissolved oxygen concentration is achieved when the feedwater enters the SGs. The exact concentration of hydrazine required is dependent on the oxygen concentration, with the ratio of hydrazine to oxygen being considered more significant than the specific hydrazine concentration.

To help achieve a low dissolved oxygen concentration in the RR SMR secondary coolant the current intention is for hydrazine to be dosed as the oxygen scavenger because it is almost exclusively used in PWRs and there is high confidence in its effectiveness. There is also a large amount of OpEx available from plants that use hydrazine, and it is of lower cost than many alternatives (Reference [90]). Both oxygen and hydrazine are control parameters in the Feedwater System [LA] during Modes 1, 2, 3, 4A and 4B (Reference [2]). Expected values and limits, where defined, are in line with RGP taken from the EPRI PWR Secondary Water Chemistry Guidelines (Reference [5]). Specifications for Modes 5A, 5B, 6A and 6B in the Feedwater System [LA] will be developed as the design progresses.

The influence of redox potential and the importance of a low oxygen concentration are discussed in more detail in Reference [90], and the detailed technical underpinning (evidence) for redox potential control and the use of hydrazine in the secondary coolant will be provided in a Tier 3 document titled 'Secondary Water Chemistry: Technical Justification for Optimisation of Redox Potential', for inclusion in the next version of the E3S Case.

pH Control

It is currently intended for ammonia to be used for pH control at $\text{pH}_{25\text{ }^\circ\text{C}} = 9.8$ to 10.1 for the RR SMR, primarily because there is high confidence in its effectiveness for minimising iron oxide pickup in the condensate system, minimising sludge build up in the SGs and in protecting plant materials from corrosion. Ammonia is also of low cost, simple to implement and unlike organic amine alternatives such as ETA or morpholine, its use does not result in the production of organic acids from decomposition and/or reaction with oxygen. The main advantage of organic acids not being produced is that there is no resultant cation conductivity increase. Therefore, the cation conductivity can easily be used for analysis as it is the most sensitive online indicator of impurity concentration in the final feedwater.

Ammonia is currently a control parameter in the Feedwater System [LA] during Modes 1, 2, 3, 4A and 4B (Reference [2]) with an expected value of {REDACTED} selected to achieve the pH range of $\text{pH}_{25\text{ }^\circ\text{C}} = 9.8$ to 10.1. pH is currently a diagnostic parameter during Mode 1 and a control parameter during Modes 2, 3, 4A and 4B. Expected values and limits, where defined, are in line with RGP taken from the EPRI PWR Secondary Water Chemistry Guidelines (Reference [5]). Ammonia and pH specifications for Modes 5A, 5B, 6A and 6B for the Feedwater System [LA] will be developed as the design progresses.

The influence of pH control is discussed in more detail in Reference [90], and the detailed technical underpinning (evidence) for the use of ammonia in a High-AVT regime will be provided in a Tier 3 document titled 'Secondary Water Chemistry: Technical Justification for pH control', which will be available for incorporation into the next version of the E3S Case.

Impurities/Aggressive Species

There are several chemical species that, when present in the secondary system coolant, have been shown to increase the risk of SG tube corrosion (Reference [5]). The main species that can impact on the integrity of the SG tubes are:

1. Sodium: high sodium concentrations can potentially lead to excessive caustic formation in crevices which can increase the possibility of IGA and caustic SCC of Alloy 600, especially under oxidising conditions. Whilst SG tubing in the RR SMR is made from Alloy 690TT, which has much greater corrosion resistance, it is still susceptible to the same degradation mechanisms as Alloy 600.
2. Lead: lead is a species that has been shown to cause SCC of Alloy 690 in laboratory conditions and has resulted in failures of Alloy 600 SG tubing due to contamination events.
3. Sulfate: sulfate has been shown to accelerate local attack of Alloy 600 during cold shutdown conditions and reduced forms of sulfur species have been known to cause IGA and pitting of NBAs. Again, Alloy 690TT is more resistant to sulfur-related IGA/SCC than Alloy 600.
4. Chloride: chloride can be deleterious to NBAs. High concentrations of chloride have been shown to accelerate pitting of Alloy 600 during acidic/oxidising cold shutdown conditions. If high chloride concentrations and oxidising conditions are achieved because of fault conditions (e.g. condenser tube leakage and ingress of cooling water), then both NBA and AuSS material can be susceptible to pitting corrosion, especially if sludge deposits are present in the SGs. Again, SG tubing will be made from Alloy 690TT, which has lower corrosion susceptibility than Alloy 600.

5. Organic acids: organic acids are soluble impurities that do not concentrate locally due to their volatility. If ETA were used for pH control in the RR SMR, it could produce organic acids from thermal decomposition, which could potentially enhance the acidity of contaminants and thus the corrosion of turbine materials.
6. Iron oxides: insoluble impurities such as iron oxides are transported mainly by the feedwater to SGs and their presence in excessive quantities can be harmful as they deposit on SG tubes, in crevices or on the top of tube sheets.

Control of Aggressive Species

Impurities will be monitored and minimised during all phases of operation including wet layup periods, start-up, power operation and shutdown. In the latest version of the Turbine Island Water Chemistry Specification (Reference [2]) sodium, chloride and sulfate are control parameters for the SGPS [LCQ] during Modes 1, 2, 3, 4A and 4B. Total iron is a control parameter for the Feedwater System [LA] during Mode 1. Expected values and upper limits, where defined, in line with those provided by the EPRI PWR Secondary Water Chemistry Guidelines (Reference [5]). Specifications for Modes 5A, 5B, 6A and 6B for the SGPS [LCQ] will be developed as the design progresses. Where levels are outside the expected range during power operation, SG blowdown should be increased. Efforts should be made to identify and isolate sources of impurity ingress.

ALs and corrective actions to take in response to impurity excursions will be developed further as the design matures, considering the capability of the RR SMR design and in accordance with RGP. A Chloride Protection System will be used to provide protection against a condenser tube leak in the secondary circuit of the RR SMR. It is likely to contain an alarm and isolation valve trip that is based on direct conductivity. The timescales on which operator initiation of the Chloride Protection System is required (as well as an automated responses in the event of large chloride excursions) are under consideration. These timescales and a justification will be available for incorporation into the next version of the E3S Case.

It is anticipated that a rigorous Pb exclusion policy in the RR SMR will minimise the risk of the presence of large amounts of Pb in the secondary circuit of the RR SMR. Lead is a diagnostic parameter for the Feedwater System [LA] during Mode 1 and concentrations in sludge and deposits will be regularly monitored.

The importance of maintaining low concentrations of impurities is discussed in more detail in Reference [90], and the detailed technical underpinning (evidence) for impurity control in the secondary coolant will be provided in a Tier 3 document titled 'Secondary Water Chemistry: Technical Justification for Control of Impurities'. Information in this document will be available for incorporation into the next version of the E3S Case.

20.6.4 Corrosion and Sludge Deposition

20.6.4.1 FAC and General Corrosion

OpEx from PWRs indicates that localised corrosion (IGA/SCC) is the degradation mechanism class of primary concern for the SG tubes, and flow assisted corrosion (FAC) and general corrosion are the main degradation mechanisms that impact on the feedwater and steam systems, although they also have an impact on some components within the SGs themselves (References [5] and [90]).

Under typical secondary system chemistry regimes, CS undergoes oxidation to form either magnetite (deoxygenated conditions) or haematite (oxygenated conditions), which provide reasonable corrosion protection at system operating temperatures. The rate of general corrosion (i.e. uniform corrosion across the surface) is predictable and can be managed by ensuring that pipework wall thicknesses have an appropriate corrosion allowance.

FAC can occur in different alloys, but CS is recognised as the most susceptible, which has resulted in significant operational issues at operational nuclear and fossil power stations. FAC is the accelerated corrosion that occurs under turbulent flow conditions and causes higher than predicted rates of corrosion. Although a passive film can form on the CS, this is degraded by the turbulent flow conditions, resulting in localised attack of the metal. If undetected, this can result in catastrophic failure of feedwater and steam system pipework.

The main parameters that influence the occurrence of FAC in CS pipework are:

1. Temperature: experimental studies have shown that a bell-shaped dependence on temperature is observed, with the FAC rates increasing at temperatures above ~100 °C, reaching a peak at ~180 °C and then decreasing at higher temperatures (noting the exact temperatures will be dependent on plant and system specific details). At low temperatures the rate of corrosion is generally low and any degradation that occurs is attributed to wear/impingement, rather than corrosion. At high temperatures the CS suffers increased rates of general corrosion, so localised FAC rates decrease.
2. Flow conditions and geometry: FAC requires turbulent flow conditions, with the turbulence resulting in accelerated breakdown of the protective oxide film on the CS surface. Components with geometries that promote increased velocity and turbulence tend to experience more severe FAC.
3. Oxygen concentration: under deoxygenated conditions, the oxide layer formed on the CS surface is magnetite, which is susceptible to FAC. Under oxygenated conditions, a haematite oxide layer forms on the CS surface, which has increased resistance to FAC.
4. pH: alkaline conditions promote the formation of a stable oxide layer, and therefore higher pH conditions result in increased resistance to FAC.
5. Chromium content: increasing the chromium content of CS results in chromium being present in the oxide layer. LAS have sufficiently high chromium content that they are essentially resistant to FAC.
6. Fluid phase: FAC can occur in both single phase (water) and two phase (water/steam) conditions, with higher rates possible in two-phase regions due to the increased temperature and high steam flow rates.

20.6.4.2 Sludge Deposition and Materials Selection

At the PCD stage, the baseline assumption was that the secondary system will utilise LAS to provide resistance to FAC. Although the risk of failure of LAS pipework and components is low, low rates of FAC still occur, generating CPs that are transported to the SGs. It is therefore important that the secondary system chemistry regime is optimised to reduce the rate of FAC occurring in the feedwater system and two-phase regions of the steam system.

It is likely that CS and LAS will make up much of the piping in the secondary circuit, although it is not confirmed whether LAS will make up the entirety. In areas where FAC will potentially be an issue, SA-335M P22 alloy will be used due to its high resistance to FAC, with ER90S-B3 used as the weld material (References [91] and [92]). All LAS grades would require full post weld heat treatment (PWHT) to be applied to welds to restore fracture toughness, which is why certain utilities have not applied LAS as widely as they could have and have suffered FAC, particularly in two-phase zones.

20.6.4.3 Chemistry Control

From a chemistry perspective, the two parameters that can be varied to control FAC and general corrosion are pH and dissolved oxygen content. Historically, many plants back-fitted oxygen injection systems to increase the dissolved oxygen content of the feedwater and promote the formation of a haematite oxide layer. For PWRs, this is not desirable, as dissolved oxygen creates oxidising conditions, increasing the risk of corrosion occurring in the SG tubes. pH is therefore the main chemistry parameter that is controlled to reduce the rate of FAC and general corrosion of pipework and thus reduce the generation and transportation of CPs. Parameters for pH and ammonia concentration in the secondary coolant are discussed in section 20.6.3.

As described in section 20.6.2, AVT and alternative amines have the advantage of being volatile, evaporating on boiling and transferring to the steam phase. This provides increased protection against two-phase FAC and general corrosion within the steam and condensate system and is beneficial in reducing the quantities of SG sludge deposits.

20.6.5 Design Development

The baseline chemistry regime for the secondary coolant is as follows:

1. High-AVT treatment with ammonia used to increase the pH of the system and provide corrosion protection to the single phase and two-phase regions.
2. Hydrazine injection to scavenge oxygen and lower the redox potential within the SGs, promoting the formation of a passive oxide layer and reducing the risk of IGA and SCC.

There have been no major changes to the proposed chemistry philosophy since the PCD stage.

20.6.6 Further Development

As stated in section 20.2, the design maturity, operating philosophy, and chemistry specifications are being developed in parallel and are continually reviewed to ensure alignment.

Examples of key activities to be carried out in the future are optimisation of the chemistry regime for pH control, further evaluation of hydrazine and evaluation of hydrazine alternatives for oxygen scavenging, and development of a comprehensive FAC strategy to manage FAC risk if CS were selected for used as piping material. With regards to the Turbine Island Water Chemistry Specification (Reference [2]), specifications for SG sample and fill water during modes 5A, 5B, 6A and 6B will be defined, and options for destruction of hydrazine (or a suitable alternative) following lay-up (i.e. offsite treatment, mobile treatment plant on site, or destruction in secondary circuit) will be considered during GDA Step 3. More specific information on further development activities that will be, or may be carried out, is provided in the future work section of the 'Secondary Water Chemistry: Minimisation of Corrosion of Structural Materials' document (Reference [90]).

20.6.7 Tier 2 Chemistry Reports

In relation to the secondary coolant chemistry regime, the Tier 2 documents which have been produced are listed below. Associated claim IDs of most relevance to section 20.6 are also listed with the Level 2 and Level 3 claims presented in Appendix A (section 20.13)

1. Turbine Island Water Chemistry Specification (Reference [2])
2. Secondary Water Chemistry: Method of Monitoring and Control (Reference [51])
3. Secondary Water Chemistry: Minimisation of Corrosion of Structural Materials (Reference [90]): there is a Level 2 claim and numerous Level 3, and Level 4 claims that relate to minimising corrosion of structural material in the secondary circuit through chemistry control. The Level 4 claims relating to specific degradation mechanisms that affect both the SGs, and the water and steam systems. All claims fall under argument 20.1. The claim IDs are 20.1.2, 20.1.2.1, 20.1.2.1.1, 20.1.2.1.2, 20.1.2.1.3, 20.1.2.1.4, 20.1.2.1.5, 20.1.2.1.6, 20.1.2.2, 20.1.2.2.1, 20.1.2.2.2, and 20.1.2.3.

It is anticipated that a specific claim on chemistry control during SG lay-up will be developed for inclusion in the next version of the E3S Case.

20.7 Component Cooling Water Systems Chemistry

20.7.1 Introduction

The Tier 2 report entitled 'Chemistry Justification for Component Cooling Water Systems' (Reference [93]) provides the technical basis for the chemistry controls used to minimise corrosion within the CCW systems of the RR SMR. The two CCW systems currently covered by this document are the reactor CCS [KAA] and the TI-CCWS [PG]. The CWS [KJ] is another CCW system that will be in scope in future as the design matures.

Design information relevant to the CCS [KAA] is discussed in section 20.7.2, and that relevant to the TI-CCWS [PG] is discussed in section 20.7.3. The water chemistry specification for the CCS [KAA] is covered within the Reactor Island [R01] Water Chemistry Specification Tables (Reference [1]) and that for TI-CCWS [PG] is within the Turbine Island Water Chemistry Specification (Reference [2]). Currently the chemistry regimes for both CCWs are broadly the same, although the specifications will be subject to review as the design matures and the selection of materials is confirmed. Therefore, degradation mechanisms of concern for both systems are summarised in section 20.7.4 and chemistry controls for both systems are summarised in section 20.7.5.

20.7.2 Component Cooling System [KAA]

20.7.2.1 Design Information

The CCS [KAA] transfers heat from several reactor systems and components to the Essential Service Water System (ESWS) Cooling Towers [PBD] during all modes of plant operation. Make-up of the CCS [KAA] is provided from the Demineralised Water Supply System (DWSS) [GHC] and chemical dosing is manually performed by flushing chemicals into the system from the CSS [QC].

Further design information on the CCS [KAA] is contained within E3S Case Version 2, Tier 1, Chapter 9A: Auxiliary Systems (Reference [59]) and the SDD is in Reference [94]. Additionally, there is an associated FBoM in Reference [95]. Most materials used for key components (valves, tanks, etc.) in the CCS [KAA] are likely to be made from CS, and the pumps are likely to be made from SS.

20.7.3 Turbine Island Closed Cooling Water System [PG]

20.7.3.1 Design Information

The TI-CCWS [PG] system transfers heat from various auxiliary components located within the Turbine Hall to the Auxiliary Cooling and Makeup System (ACMS) [PE]. Like the CCS [KAA], the make-up and chemical dosing of the TI-CCWS [PG] is provided by the DWSS [GHC] and CSS [QC]. The current baseline design for TI-CCWS [PG] includes a chemical addition tank to facilitate mixing of any chemicals before injection into the system.

Further design information on the TI-CCWS [PG], including development activities, is contained within E3S Case Version 2, Tier 1, Chapter 9A: Auxiliary System (Reference [59]) and the SDD is in Reference [96]. The TI-CCWS [PG] material specifications are also yet to be confirmed but will be developed in collaboration with a vendor in the future.

20.7.4 Degradation Mechanisms

The key degradation mechanisms of concern in the RR SMR CCW systems are general corrosion, FAC, galvanic corrosion, MIC and localised corrosion (including pitting, crevice corrosion, under-deposit corrosion, IGA and SCC). Each of these mechanisms are summarised below with respect to CCW systems and are discussed in more detail in Reference [93].

1. General corrosion: in CCW systems general corrosion can result in thinning of components such as pipes, pumps, and heat exchanger tubes. General corrosion is influenced by pH, oxygen concentration, impurities, and inhibitors.
2. FAC: CS is susceptible to FAC under specific conditions. However, it is anticipated that the low temperature and alkali environment associated with CCW systems reduces the risk of FAC.
3. Galvanic corrosion: this is defined as accelerated corrosion of a metal because of an electrical contact with a more noble metal or non-metallic conductor in a corrosive environment. It typically occurs in CCW systems that contain both copper and steel alloys. However, it is currently assumed the RR SMR CCW systems will not contain any copper alloys (Reference [93]).
4. MIC: although this can occur on CS and SS, CCW systems generally contain low levels of the nutrients essential for microbial growth. Biofilms may be removed by chemical or physical treatments, noting that chemical biocides that may result in corrosion should not be used.
5. Localised corrosion: localised forms of corrosion are largely caused by acidic environments developing from impurity ingress and concentrations behind deposits. Reducing impurities and increasing pH can minimise risk.
 - a. SCC: the most common causes for SCC in CCW systems are SS being exposed to high concentrations of chloride and copper alloys being exposed to ammonia and elevated oxygen. Reducing chloride levels can minimise risk and it is assumed that copper alloys will not be used.

20.7.5 Chemistry Control

The main chemistry factors that control rates of degradation in CCW systems are pH, dissolved oxygen, corrosion inhibitors, and impurities. In addition to minimisation of corrosion, the objectives of chemistry control in CCW systems are to control microbiological growth, control deposition of suspended solids and prevent scale deposition. These factors are summarised below with respect to CCW systems and are discussed in more detail in Reference [93].

20.7.5.1 Corrosion Inhibitors

Corrosion inhibitor regimes typically used in CCW systems include chromate, nitrite, molybdate, orthophosphate, silicate, hydrazine, zinc, phosphonate, polyphosphonate, and azole-based regimes, as well as mixed inhibitor regimes. The RR SMR current preferred option is a nitrite/molybdate regime as it offers good protection for ferrous metals and has reduced toxicity compared to many of the alternatives. In the latest versions of the RR SMR water chemistry specifications (References [1] and [2]), nitrite and molybdate are control parameters for the CCS [KAA] and the TI-CCWS [PG]. Expected values and limits currently proposed are in line with those typically used for nitrite/molybdate regimes, such as those provided by the latest EPRI Closed Cooling Chemistry

Guidelines (Reference [43]) which is widely used throughout the industry. Values will be confirmed and reviewed as the design matures and the material selection has been established.

20.7.5.2 pH

pH control in CCW systems is undertaken to keep pH in a range where corrosion is minimised and where treatment chemicals are most effective. In the latest versions of the RR SMR water chemistry specifications (References [1] and [2]), pH is a control parameter for CCS [KAA] and TI-CCWS [PG]. Again, expected values (i.e. $\text{pH}_{25\text{ }^\circ\text{C}} = 8.5$ to 11) and limits proposed are in line with those typically used for a nitrite/molybdate regimes, such as those provided by the latest EPRI Closed Cooling Chemistry Guidelines (Reference [43]). The preferred alkalisng agent and precise pH limits will be finalised and justified when the material and corrosion inhibitor choice have been made.

20.7.5.3 Impurities

Impurities such as chloride, fluoride and sulfate, are aggressive ions that can increase corrosion rates in CCW systems. In the latest versions of the RR SMR water chemistry specifications (References [1] and [2]), chloride is a control parameter for both the CCS [KAA] and the TI-CCWS [PG], and sulfate is a control parameter for the CCS [KAA] and a diagnostic parameter for the TI-CCWS [PG]. Expected values and limits have not yet been finalised, although it is anticipated that they will also be in line with those provided by the latest EPRI Closed Cooling Chemistry Guidelines (Reference [43]).

20.7.5.4 Dissolved Oxygen

Most nuclear stations do not control air ingress in CCW systems. In a closed system with no air in-leakage it is expected that oxidation of the CCW system materials reduces the oxygen concentration to the hundred ppb range within the piping system. It is noted that for molybdate treatments, an oxidising agent such as oxygen or nitrite, must be present for effective corrosion inhibition. Control and monitoring of dissolved oxygen concentrations is therefore not applied for the RR SMR CCW systems with the preferred regime being nitrite/molybdate. This is in line with EPRI Guidelines (Reference [43]).

20.7.5.5 Microbiological Control

Microbiological fouling in closed systems is typically unfavourable as there is no pathway for organics. Some CCW systems have experienced microbiological growth due to the breakdown of some chemical additives providing nutrients. However, it has not been observed in high pH control systems. Therefore, microbiological controls have not yet been assigned to the RR SMR CCW systems, although nitrate (which can be produced by certain types of bacteria that feed on nitrite) and microbiological levels are provisionally diagnostic parameters.

20.7.6 Tier 2 Chemistry Reports

The Tier 2 chemistry documents which have been produced that relate to CCW systems of the RR SMR are the 'Reactor Island [R01] Water Chemistry Specification Tables' document (Reference [1]), the 'Turbine Island Water Chemistry Specification' document (Reference [2]), and the 'Chemistry Justification for Component Cooling Water Systems' document (Reference [93]). More detailed technical underpinning (evidence) for chemistry control in CCWs will be provided in a Tier 3 document which will be produced for incorporation into a future version of the E3S Case.



SMR

There is currently one Level 2 claim and three Level 3 claims that relate to CCW systems. They both fall under argument 20.1 and are presented in Appendix A (section 20.13) as claims 20.1.4, 20.1.4.1, 20.1.4.2, and 20.1.4.3.

20.8 Turbine Island Auxiliary System Chemistry

20.8.1 Introduction

Chemistry specifications for Turbine Island [T01] auxiliary systems are generally within the scope of the 'Turbine Island Water Chemistry Specification' document (Reference [2]), which currently includes specifications for the Feedwater System [LA], SGPS [LCQ], Condensate System [LC] and TI-CCWS [PG] only. Water chemistry specifications for other Turbine Island [T01] auxiliary systems will be further addressed in future revisions of Reference [2] during GDA Step 3 as the design matures. It is noted that a chemistry specification for the PSCS [JNB] is currently covered within the 'Reactor Island [R01] Water Chemistry Specification Tables' document (Reference [1]).

The Tier 2 report entitled 'Chemistry Justification for Turbine Island Auxiliary Systems' (Reference [97]) discusses chemistry controls used to minimise corrosion and support reliable operation within Turbine Island [T01] auxiliary systems during all modes of normal and emergency injection operations. It covers Turbine Island [T01] components wetted by the steam, feedwater, and condensate (i.e. components that are not captured by either the 'Secondary Water Chemistry: Minimisation of Corrosion of Structural Materials' (Reference [90]) or the 'Chemistry Justification for Component Cooling Water Systems' (Reference [93]) Tier 2 documents).

Turbine Island [T01] auxiliary systems covered by Reference [97] are as follows:

1. CST [LCP],
2. Auxiliary Feedwater System [LJ],
3. Deaerator System [LAA],
4. Auxiliary Steam Piping System [LBG],
5. Auxiliary Steam Generating and Supply System [QH], which includes:
 - a. Permanent Boiler System [QHA],
 - b. Temporary Boiler System [QHR], and
 - c. Steam Distribution System [QHS].
6. Hydrogen Cooling System [MKG], and
7. PSCS [JNB].

The following safety measures are also referred to in Reference [97]:

1. PDHR [JN02], and
2. High Temperature Heat Removal (HTHR) [JN03], including:
 - a) HTHR Variant 2 – Faulted Condenser Decay Heat Removal (CDHR), and
 - b) HTHR Variant 3 – Atmospheric Steam Dump (ASD).

Design information, key chemistry controls, materials selection, and degradation mechanisms relevant to the CST [LCP] and the Auxiliary Feed System [LJ] are summarised in section 20.8.2; the Auxiliary Steam Generating and Supply System [QH], Deaerator System [LAA] and Auxiliary Steam Piping System [LBG] in section 20.8.3; the Hydrogen Cooling System [MKG] in section 20.8.4; and the PSCS [JNB] in section 20.8.5.

20.8.2 Condensate Storage Tanks [LCP] and Auxiliary Feedwater System [LJ]

20.8.2.1 Design Information

The Auxiliary Feedwater System [LJ] supplies auxiliary feedwater to the SGs [JEA] for removal of heat from the reactor core for HTHR [JNO3] and start-up situations. The CST [LCP] provides condensate to the Auxiliary Feedwater System [LJ] via the Deaerator [LAA] to the SG Feedwater inlet header. Further design information on the Auxiliary Feedwater System [LJ] can be found in the SDD in Reference [98]. An SDD for the CST [LCP] does not exist yet. Materials selections have also not yet been developed for these systems.

20.8.2.2 Chemistry Controls, Materials Selection and Degradation Mechanisms

It is expected that the Auxiliary Feedwater System [LJ] will have a chemistry regime which aligns with that stipulated for the Feedwater System [LA] (i.e. the High-AVT regime with low oxygen and low impurity loading described in section 20.6). This will be achieved through the CSS [QC]. It is also expected that a mobile Condensate Polishing System [LD] will be used to help remove impurities where required. As discussed in Reference [90], in areas where FAC has the potential to be an issue (e.g. small bore piping such as drains lines around the turbine and feedwater train), use of materials robust to FAC will be considered.

Due to the current level of design maturity, the 'Turbine Island [T01] Water Chemistry Specification' (Reference [2]) has not yet considered the CST [LCP]. It is expected that future revisions will include control parameters for the CST [LCP] and these parameters will include pH and dissolved oxygen. A low oxygen, low impurity, and high pH environment in the CST [LCP] will aid to reduce levels of corrosion, noting that temperatures will likely not exceed circa 40 °C.

It is anticipated that due to the presence of ammonia, an approximate pH range of pH = 8.5 to 10.6 will be specified for the CST [LCP]. This range will account for operations following a refuelling outage where the bulk SG [JEA] lay-up water may be drained into the CST [LCP] before treatment to remove hydrazine. The upper pH limit should therefore align with what may be possible in SG [JEA] wet lay-up. To facilitate the low oxygen requirements for feedwater, aid the function of the Deaerator [LAA] and minimise hydrazine usage, a low oxygen content within the CST [LCP] is expected. Potential methods for minimising oxygen concentration (e.g. nitrogen sparging, application of floating deck seals, etc.) are discussed in Reference [97].

Corrosion can be further mitigated through appropriate material choices and potential application of liners, although liners may present challenges such delamination and degradation. MIC is not expected to be an issue in the CST [LCP] as there is no organic feedstock to provide the carbon for growth and carbon dioxide from the air will be excluded.

20.8.3 Auxiliary Steam Generating and Supply System [QH], Deaerator System [LAA] and Auxiliary Steam Piping System [LBG]

20.8.3.1 Design Information

The primary functions of the Auxiliary Steam Generating and Supply System [QH] are to:

1. Receive demineralised water or potable water from the Treated Water Distribution System [GH], deaerate the feedwater during start-up, and use it as feedwater to supply the auxiliary boilers for steam generation.
2. Generate saturated steam at the required pressure utilising electric / fired type steam boilers.
3. Supply saturated steam to Turbine Island [TO1] for the turbine gland seals to seal the turbine glands during RR SMR plant start-up and shutdown operations during fault scenarios.
4. Supply saturated steam to the Deaerator [LAA] during start-up to remove dissolved oxygen from the feedwater.

The Auxiliary Steam Generating and Supply System [QH] contains several sub-systems; the Permanent Boiler System [QHA], the Temporary Boiler System [QHR] and the Steam Distribution System [QHS]. Further design details on these sub-systems are provided in an SDD in Reference [99].

The Deaerator System [LAA] and Auxiliary Steam Piping System [LBG] sit under the Feedwater System [LA] and Steam System [LB] respectively. However, these systems transport and receive auxiliary steam produced and transported by the Auxiliary Steam Generating and Supply System [QH] subsystems noted above. The interdependency of these sub-systems therefore warrants their consideration in this sub-section. Additional design information regarding the Auxiliary Steam Piping System [LBG] is reported within the SDD for the Steam System [LB] (Reference [100]). A description of the function of the Deaerator [LAA], which is to remove dissolved gases from the feedwater through contact with heating steam, is described in the SDD for the Feedwater System [LA] (Reference [101]) and in E3S Case Version 2, Tier 1, Chapter 10: Steam & Power Conversion Systems (Reference [58]).

The design of all of the systems described above is generally in an immature position and will be developed with vendor engagement for inclusion in a future version of the E3S Case.

20.8.3.2 Chemistry Controls and Materials Selection

Materials selection for the Auxiliary Steam Generating and Supply System [QH] system will be developed in future with vendor engagement, although a FBoM has been produced for each sub-system (Reference [102], [103] and [104]). Materials selection for the Deaerator [LAA] has not yet been fully explored.

Several vendor requirements have been identified in terms of feedwater; notably potable water and demineralised water, chemical dosing (i.e. for pH and oxygen control [expected to be achieved using hydrazine]) and pressurised deaeration (References [99] and [105]). Boiler water pH and conductivity will be served as key monitoring and indication functions. The quality of steam produced by the

auxiliary boiler will meet the requirements for the associated downstream systems (i.e. low oxygen and impurity loading) (Reference [97]). Chemistry monitoring on the chemical dosing/metering skids may be present for conductivity, hydrazine, and to characterise alkali dosing. It is noted that potable water has high total dissolved solids (TDS) levels. It is expected that a water softener be used to remove scale (calcium carbonate) first, before undergoing reverse osmosis. After undergoing reverse osmosis, the water can be supplied to the boilers.

20.8.4 Hydrogen Cooling System [MKG]

20.8.4.1 Design Information

The Hydrogen Cooling System [MKG] is responsible for managing and distributing cooling hydrogen between the generator and the heat exchangers that interface with the TI-CCWS [PG]. The generator uses hydrogen cooling for the rotor and the stator, with hydrogen supplied by the Central Gas Supply [QJ]. Almost all modern alternators in power plants are cooled by hydrogen circulating in a closed circuit. Advantages on the use of hydrogen as a cooling medium are discussed in more detail in Reference [93]; they include lower ventilation losses and easier heat exchange compared to air, low cost, and easy management.

The current baseline design for stator cooling is through the sole use of hydrogen. The detailed design and material selection decisions for the Hydrogen Cooling System [MKG] have not been fully explored and will be developed with vendor engagement for incorporation into a future version of the E3S Case. However, some limited design information is presented in the SDD for the Generator System [MK] in Reference [106].

20.8.4.2 Chemistry Controls, Materials Selection and Degradation Mechanisms

Loss of chemistry control can lead to degradation of insulation which can produce a range of volatile organic species. The insulation tends to be mainly a form of epoxy mica based upon phenol formaldehyde resins. Monitoring for insulation degradation products in hydrogen gas can be done using equipment or monitoring techniques such as generator condition monitors (GCM), flame ionisation detectors (FID), infra-red (IR) detectors and gas chromatography (GC) (Reference [107]). Control of hydrogen gas purity is another important aspect to consider as failure to control hydrogen purity with air ingress can lead to development of explosive mixtures. Another important consideration is monitoring and control of moisture within the generator to prevent surface moisture contamination, which could lead to potential flashovers. Most generator sets are fitted with hydrogen drying systems to address very small transient leaks. Various types of dryers are in use, and the system design will depend upon the vendor.

20.8.5 Passive Steam Condensing System [JNB]

20.8.5.1 Design Information

The PSCS [JNB] is dedicated to supporting PDHR [JN02] and is described in Reference [108]. During PDHR [JN02] operation, steam is transported from the Main Steam Line [LBA20] to the PSCS [JNB] heat exchanger (HX). The HX transfers heat to the LUHS [JNK] through condensation of the steam in the HX tubes. The condensate is subsequently returned to the Main Feedwater System [LAB] via a penetration which is located in the portion of the main feed line piping downstream of the main feed isolation valve and inside the Containment [JMA] building. It is noted the chemistry and design of the LUHS [JNK] system is described in a separate section of this document (section 20.5.3).

20.8.5.2 Chemistry Controls, Materials Selection and Degradation Mechanisms

The majority of material used in the PSCS [JNB] is likely to be Low Alloy Ferritic Steel SA-335M Grade P22, and the HX is likely to be fabricated from SS.

From a chemistry control viewpoint, condensate is formed from SG Main Steam and so is of high purity (i.e. low levels of contaminants such as chloride), deoxygenated and it will always carry a significant amount of ammonia, meaning that it is alkaline and so minimises risk of corrosion.

During PDHR [JN02] the PSCS [JNB] has the potential to experience elevated temperatures where steam will enter the system. Due to the material selection, the chemistry of the steam (low oxygen, high pH) and the limited time/frequency, significant degradation of the system would not be expected.

20.8.6 Tier 2 Chemistry Reports

The Tier 2 documents which have been produced that relate to the Turbine Island [T01] auxiliary systems chemistry regimes are the 'Turbine Island Water Chemistry Specification Tables' document (Reference [2]) described earlier, and the 'Chemistry Justification for Turbine Island Auxiliary Systems' document (Reference [97]). More detailed technical underpinning (evidence) for chemistry control in Turbine Island [T01] auxiliary systems will be provided in Tier 3 documentation which will be produced for inclusion into a future version of the E3S Case. In terms of future development work more specific information on work that will be, or may be carried out, is provided in the future work section of the Tier 2 report (Reference [97]).

There is currently one Level 2 claim that specifically relates to Turbine Island [T01] auxiliary systems. It falls under argument 20.1 and is presented in Appendix A (section 20.13) as Claim 20.1.5. Claims will be developed further as Turbine Island [T01] auxiliary system designs mature.

20.9 Normal Operation Source Term

20.9.1 Purpose

The source term describes the types, quantities and physical and chemical forms of the radionuclides present in a nuclear reactor that have the potential to give rise to exposure to ionising radiation to workers, the public and the environment.

The purpose of generating the RR SMR source term is to quantify the radioactive inventory of the RR SMR so that the radioactive hazard in the reactor, supporting systems and circuits can be understood. The source term is used to support the development of the RR SMR design and the E3S Case to demonstrate that risks relating to radioactivity have been reduced ALARP and that BAT has been applied, so resulting impacts are as low as reasonably achievable (ALARA).

The normal operation source term is a sub-set of the overall source term for the RR SMR, which also consists of the:

1. Activated structures source term: this covers the concentration of radionuclides activated within structural materials subject to neutron flux (e.g. RPV internals).
2. Spent fuel source term: this covers the radionuclide inventory of partially and fully spent fuel assemblies.

Downstream source terms such as radioactive waste system, decommissioning and activated structures source terms will be developed in conjunction with E3S Case Version 2, Tier 1, Chapter 11: Management of Radioactive Waste, E3S Case Version 2, Tier 1, Chapter 12: Radiation Protection and E3S Case Version 2, Tier 1, Chapter 21: Decommissioning & End of Life Aspects (References [11], [14] and [109]).

The normal operation source term is used to underpin assessments related to the following technical areas:

1. Waste management:
 - a) Radioactive waste system design,
 - b) Waste categorisation (package assessment), and
 - c) Disposability assessments.
2. Radiation protection:
 - a) Worker dose (internal and external),
 - b) Public dose from direct shine, and
 - c) Shielding design.
3. Routine environmental discharges:
 - a) Aqueous and gaseous radioactive effluent discharge limit assessments, and

- b) Radiological impact assessment.
4. Decommissioning:
- a) Decommissioning waste disposability assessments, and
 - b) Decommissioning shielding design.
5. Fault Studies:
- a) Design basis (DB) event dose assessments, and
 - b) Design extension condition dose assessments.

20.9.2 Radionuclide Groups

The normal operation source term is comprised of the following four radionuclide groups:

1. FPs: This covers radionuclides that originate from fission of fissile materials in the reactor core. FPs can be present in the primary coolant due to the presence of tramp uranium on the fuel assembly surface, uranium impurities in the fuel cladding material, migration, and release through small cladding defects or through fuel failures.
2. CPs: This covers radionuclides that originate from the surface degradation (e.g. wear and corrosion) of primary circuit materials. During operation, primary circuit materials will corrode and release metallic impurities into the primary coolant. Some of these impurities will deposit on the fuel surface and subsequently become activated and re-released into the coolant, while some remain suspended in the coolant and can become activated while flowing through the reactor core.
3. APs: This covers radionuclides that originate from the activation of the primary coolant, as well as impurities contained in the primary coolant. It also covers activation of substances that are purposefully injected into the primary coolant to control its chemistry.
4. ActPs: This covers radionuclides that are produced as a result of neutron activation of uranium, subsequent activation and radioactive decay. ActPs can be present in the primary coolant due to the presence of tramp uranium on the fuel surface, uranium impurities within the fuel cladding or due to fuel failures.

20.9.3 Categories of Source Term Value

Given one of the primary functions of the normal operation source term is to inform technical areas and facilitate technical assessments to support and develop the design, more than one type of source term value is required to be derived for each of the radionuclide groups outlined above. The source term values are subdivided into the following categories for all radionuclides:

1. Best estimate (BE): This gives an overall best estimate of the source term expected in the RR SMR. This is a representative condition that is realistic so as not to result in over-specification of the source term for plant systems. The BE value is used for areas such as disposability assessments and routine environmental discharges.

2. DB: This gives a conservative maximum value for the source term which is considered to be a bounding limit for the plant design. The DB value is not expected to be exceeded during operation, even during transients and when expected events such as fuel failures occur. The DB value is important for key safety related applications such as shielding calculations to provide confidence that doses to the operators and public are minimised.
3. Cycle average (CA): This gives a source term that is averaged over the entire fuel cycle, including start-up, power operation, shutdown, and refuelling outage phases. The CA values are determined for both BE and DB values and include expected events such as fuel failures and unplanned shutdowns.

20.9.4 Source Term Types

The normal operation source term is derived for multiple locations around the RR SMR primary circuit and supporting plant systems that contain radioactivity. The normal operation source term is derived focussing on the source term in the reactor core and using this as a basis for deriving the source term for supporting plant systems. The overall normal operation source term for the RR SMR is made up of the following constituent source terms:

1. Primary source term (PST): This considers the initial formation of radionuclides in the primary coolant in the reactor core. It includes FPs, CPs, APs and ActPs. The PST represents the most important dataset in the normal operation source term suite and is used as the starting point for all other system source terms subsequently derived, as summarised below.
2. Primary systems source term (PSST): This covers the radioactive inventory in the coolant and gaseous streams in primary circuit systems, as well as any deposited radioactivity on the inner surface of system components which become fixed on primary circuit surfaces by absorption into primary circuit materials.
3. Secondary systems source term (SSST): This covers the radioactive inventory in the coolant and steam of secondary circuit systems which may be produced by a SG tube leak.
4. Fuel crud source term (FCST): This covers the radioactive inventory of the fuel crud. Fuel deposits impact the PST due to the activation and resuspension of deposited material from the fuel surface.

20.9.5 Source Term Derivation Methodology

20.9.5.1 Primary Source Term

The PST is predominantly based on OpEx from analogous plants from the EPRI chemistry monitoring and assessment (CMA) database. Where relevant OpEx data are not available or applicable for aspects of the source term, industry-validated computer codes/models are used to support the derivation of the source term, as well as calculations from first principles.

The FP and ActP PST represents operation with intact fuel for BE values. FPs and ActPs will be present in the primary coolant due to recoil and knock-on reactions from tramp uranium and uranium impurities within the fuel cladding under these conditions. Given the physical nature of these release mechanisms, the FP and ActP radionuclides are derived based on OpEx data from analogous plants. Conversely, DB values represent operation with failed fuel. FPs and ActPs are derived based on a maximum fuel pin inventory (derived using the SCALE Code System) and a series

of experimentally derived escape rate coefficients. The resulting steady-state concentration of FPs and ActPs is normalised using the limiting condition for operation for dose equivalent iodine-131 (DEI) for the RR SMR.

CPs will predominantly be present in the primary coolant due to corrosion and release of metallic impurities and subsequent activation in the reactor core. One of the primary methods of controlling corrosion in PWRs is chemistry control; section 20.4.6. Given that the RR SMR will operate with a boron-free primary chemistry regime and KOH will be used as the pH raising agent, no OpEx data are available from plants with the same water chemistry regime as the RR SMR. Both BE and DB values for CP radionuclides have been derived from OpEx data from analogous plants, on the basis that corrosion rates and release rates for a boron-free KOH regime are equal to or less than a standard LiOH/boric acid regime given the broad similarities in the target pH, redox regime and material selection. An experimental programme has been established that has the primary objective of understanding the difference in material release rates and cobalt deposition rates between the RR SMR chemistry regime and that employed in standard western PWRs. It is expected that the outcome of this work will validate the use of OpEx data from analogous plants for derivation of CP radionuclides and will support the development of an Activity Transport Model that simulates the behaviour of CP radionuclides under RR SMR primary circuit conditions.

APs are produced due to activation of the coolant as well as impurities that are unavoidably and intentionally present in the coolant. These radionuclides are only produced in the presence of a neutron flux and do not exhibit transient behaviour. The PST for all APs is calculated using FISPACT-II code (an enhanced multiphysics, inventory and source-term code system) coupled with design data to reflect removal from the primary coolant.

Tritium is considered as an AP radionuclide, primarily due to its production via activation of deuterium in the primary coolant. However, unlike other radionuclides in the AP group, fuel represents an additional source, with tritium being present due to diffusion through the fuel cladding and release from the fuel in the event of a fuel failure. The contribution from both phenomena have been assessed based on a fuel pin inventory derived using the SCALE Code System.

20.9.5.2 Primary Systems Source Term

The PSST covers the radioactive inventory in the coolant of primary circuit systems, as well as any deposited radioactivity on the inner surface of system components. The PSST also covers the inventory of any gaseous volumes in the primary circuit.

The PSST is split into primary circuit systems with a number of calculation points for each primary system. Typically, there is a calculation point that captures each of the key operations of a system, e.g. there is a calculation point upstream and downstream of the demineralisers in the Coolant Purification System [KBE].

The coolant PSSTs are calculated using a primary circuit mass and activity balance model, taking the PST as the principal input and applying operational parameters to assess the source term at each calculation point. The model takes account of radioactive decay and system operations.

The piping deposit PSSTs are calculated based on the coolant PSSTs and a series of deposition coefficients, one for each relevant CP radionuclide. These deposition coefficients are based on a mixture of OpEx, experimental data and coefficients published in the literature. Experimental data produced as part of the related RR SMR experimental programme will be used to underpin the derived values, as well as an Activity Transport Model.

20.9.5.3 Secondary Systems Source Term

The SSST covers the radioactive inventory in the coolant and steam of secondary systems. The SSST also covers the inventory of any gaseous volumes in the secondary system.

Like the PSST, the SSST is split into secondary coolant systems with a number of calculation points for each secondary system, with a calculation point that captures each of the key operations of a system.

The coolant SSSTs are calculated by assuming the presence of SG tube defects that result in radionuclide concentrations in the secondary coolant. The PST is used as one of the principal inputs along with a primary-to-secondary leak rate. A secondary circuit mass and activity balance model is used to assess the SSST at each relevant calculation point by applying operational parameters that reflect the operation of the RR SMR secondary system.

20.9.5.4 Fuel Crud Source Term

The FCST covers the radioactive inventory of any deposited material on the surface of the fuel. An Activity Transport Model will be used to quantify the mass and composition of fuel deposits (crud) by simulating boiling based on a core wide average sub-cooled nucleate boiling rate derived using VIPRE code (a reactor core thermal-hydraulics analysis code).

20.9.6 Design Maturity and Documentation

Details on the strategy for the derivation of the normal operation source term for the RR SMR is provided in the Normal Operation Source Term Strategy Report (Reference [28]). This report defines what is required to derive the normal operation source term, covering its scope and general principles for derivation and justification. It also covers the main interfaces with the normal operation source term, in addition to how the normal operation source term is developed, structured and delivered. The normal operation source term document structure is also described in the strategy report; it shows how the source term will be produced in a structured and staged approach with three tiers of information.

The radionuclide list (and related methodology) associated with the normal operation source term for the RR SMR is documented in the Normal Operation Source Term Radionuclide Selection Report (Reference [29]). The development of this list takes account of RGP in the form of codes and standards, and datasets from similar technologies, and considers design choices specific to the RR SMR. It outlines the rationale and technical basis for why radionuclides are included in the normal operation source term.

The OpEx data used to derive the PST for the RR SMR is primarily sourced from the EPRI CMA database which contains RCS coolant concentration data from PWR plants operating worldwide. An OpEx data selection process is implemented independently for each radionuclide group to maximise the breadth and depth of data used to derive the PST. Supplementary plant information is used to derive radionuclide generation rates for each plant from the CMA database, which are in turn used to derive generation rates and subsequent coolant concentrations for the RR SMR, representing the PST. The PSSTs and SSSTs are calculated using mass and activity balance models, taking the PST as one of the principal inputs.

Datasets for each of the constituent source terms of the normal operation source term are recorded as live datasets in DOORS, as separate module.

20.10 Accident Chemistry

20.10.1 Introduction

As part of the development of the RR SMR, the performance of the plant during fault and accident sequences will be assessed to demonstrate compliance with the RR SMR numerical targets (Reference [13]).

During a fault or accident sequence, numerous chemical effects are at play which can impact the mobilisation, transport, and release of radionuclides both in and from a plant to the external environment. It is important to understand such phenomena so that their consideration in system design and impact on the radiological consequences of a fault/accident can be understood, and appropriate account of them taken when assessing such consequences.

In the context of accident chemistry, the chemistry discipline feeds into the design of systems impacting FP control, combustible gas control and in-vessel retention (IVR).

20.10.2 Radiological Consequence Analysis

Numerous chemical effects can impact the mobilisation, transport, and release of radionuclides both in and from a plant to the external environment during fault and accident sequences. The most important radionuclide group to consider when assessing chemical effects is FPs, given the fuel and fuel clad gap inventories represent the dominant source of radioactivity in a plant under fault and accident conditions. The radiological effect of FPs depends on a number of physical, chemical and biological properties. The physical properties include decay constant and energy of emitted radiation. The chemical properties include oxidation state, solubility, and volatility. The biological conditions include metabolic affinity, mode of ingestion and size of ingested particles.

The most important FPs from a radiological standpoint are the noble gases, iodine, and caesium. The chemistry of the noble gases in all fault and accident sequences is relatively simple, in that they are unreactive, and on release from the fuel they will remain in the gas phase. In DB and beyond DB faults, the chemistry of caesium is also simple, in that the aqueous phase species is the involatile caesium cation. Caesium cations will therefore be associated with aqueous phase flow. In events outside of normal operation that constitute a severe accident (SA) and in particular molten core situations, caesium will also be in the form of soluble caesium iodide, and the remainder as caesium molybdate and caesium hydroxide.

In contrast, the chemistry of iodine is complex owing to its wide range of oxidation states and volatility of some of the species. Iodine exists in a number of oxidation states, some of which are stable, and others are reactive such that their lifetimes are very short under fault and accident conditions. The variety of species and the ease of oxidation or reduction cause iodine chemistry to be complex. The well-known stable ions and molecules are iodide (I^-), molecular iodine (I_2), hypoiodous acid (HOI), iodate (IO_3^-), and periodate (IO_4^-). Of these species, the main concern regarding iodine volatility is I_2 as well as the less volatile HOI, owing to the potential release to the environment via the gas phase. High pH and high temperatures favour the production of HOI and I^- via hydrolysis, with I_2 production favoured at low temperatures and low pH. In addition, organic iodine species can be formed in the presence of organic material, which are also volatile.

The radiological consequence analysis will take account of the different chemical effects that impact the mobilisation, transport, and release of radiologically significant radionuclides both in and from the RR SMR during fault and accident sequences.

20.10.3 Design Maturity and Documentation

Details on the strategy and approach taken to consider accident chemistry effects in the design and radiological consequence analysis for the RR SMR are covered in the 'Accident Chemistry Strategy Report' (Reference [30]). The strategy report also outlines the interfaces accident chemistry has with other topic areas, highlighting the inputs/dependencies, and the work accident chemistry feeds into. How uncertainty of nuclear significant chemistry effects will be treated and accounted for in both system design and radiological consequence analysis is also detailed.

There is an argument and a Level 2 claim that relate to FP control within E3S Case Version 2, Tier 1, Chapter 20: Chemistry. These are argument 20.5 and claim 20.5.1 and are presented in Appendix A (section 20.13). Claims and arguments relating to combustible gas control and IVR are presented in E3S Case Version 2, Tier 1, Chapter 15: Safety Analysis (Reference [13]).

20.11 Conclusions

20.11.1 Conclusions

E3S Case Version 2, Tier 1, Chapter 20: Chemistry of the E3S Case presents evidence to support the top-level chapter claim that the RR SMR chemistry systems design, reduces risks ALARP during all normal operating modes and accident conditions for all phases of the lifecycle, which contributes to the overall E3S objective to protect people and the environment from harm, and the demonstration that risks are reduced ALARP. This is the final version of the chapter delivered towards the end of GDA Step 2. It is developed in support of the RD7 design, corresponding to the DRP1 for the GDA. It incorporates information from Tier 2 documents, including updated CAE.

For the systems within the scope of this revision of the chapter, the chemistry regime at the current stage of development is summarised, discussion of how the chemistry regime has been developed to reduce risks to ALARP is presented, and future development and verification activities that are required to substantiate the chemistry aspects of the RR SMR design are introduced. The complete suite of evidence to underpin the Claim will be developed in line with CAE Route Map and reported in future revisions of the E3S Case.

20.11.2 Assumptions and Commitments on Future Dutyholder / Licensee / Permit Holder

Table 20.11-1: Assumptions and Commitments on Future Dutyholder / Licensee / Permit Holder

Assumption/ Commitment	ID	Description
Assumption	A20.1	The final decision on the optimum commissioning chemistry regime for the RR SMR plant will be deferred until the site-specific licensing period. During safety case and design development, RGP for commissioning PWRs will be presented and it will be demonstrated that the RR SMR design does not foreclose certain options.
Commitment	C20.1	The future operator of the RR SMR plant will be responsible for implementing a chemistry programme aligned to the E3S Case.

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20.13 Appendix A

Table 20.13-1 provides a mapping of the E3S Case Version 2, Tier 1, Chapter 20: Chemistry claims to the corresponding sections that summarise the arguments and/or evidence. The full decomposition of claims and link to underpinning Tier 2 and Tier 3 information containing the detailed arguments and evidence is presented in the E3S Case Route Map (Reference [25]).

{Redacted}. It is acknowledged that the claims and sub-claims, as currently presented, are not finalised. It is expected that claims will be refined, and further claims will be added in future issues during GDA Step 3. For example, it is likely that there will be further claims around accident chemistry; this topic is awaiting further maturation of the radiation consequences analysis. There are also likely to be claims relating to layup chemistry, start-up chemistry and shutdown chemistry.

Table 20.13-1: Mapping of Claims to Chapter Sections

Claim	Section of Chapter 20 containing Arguments / Evidence summary
20: The RR SMR chemistry regime and development of the chemistry systems design, reduces risks as low as reasonably practicable (ALARP) during all normal operating modes and accident conditions for all phases of the lifecycle.	20
20.1 (argument) The RR SMR chemistry regime has been optimised in order to reduce the corrosion of structural materials ALARP.	20.4
20.1.1 The reactor coolant chemistry is optimised in order to reduce corrosion of structural materials ALARP.	20.4
20.1.1.1 The reactor coolant chemistry is optimised to minimise general corrosion rates of structural materials ALARP.	20.4.6
20.1.1.2 For Modes 1, 2, 3 and 4a, the redox potential in the reactor coolant is controlled in order to reduce corrosion ALARP.	20.4.6
20.1.1.3 The concentration of impurities in the reactor coolant are controlled in order to reduce corrosion ALARP.	20.4.6
20.1.1.4 The reactor coolant pH is controlled through additions of KOH in order to reduce corrosion ALARP.	20.4.6
20.1.2 The secondary circuit chemistry is optimised in order to reduce corrosion of structural materials and fouling of heat transfer surfaces ALARP.	20.6
20.1.2.1 The secondary circuit chemistry is controlled in order to reduce corrosion of the steam generator materials ALARP.	20.6.3
20.1.2.2 The secondary circuit chemistry is controlled in order to reduce corrosion in the water and steam system and	20.6.4

Claim	Section of Chapter 20 containing Arguments / Evidence summary
subsequent transport of corrosion products into the steam generators, ALARP.	
20.1.2.3 The secondary circuit chemistry is controlled in order to reduce turbine corrosion ALARP.	20.6
20.1.3 The primary auxiliary chemistry is controlled in order to reduce corrosion of the structural materials ALARP.	20.5
20.1.3.1 The concentrations of impurities are controlled in order to reduce corrosion ALARP.	20.5
20.1.4 The chemistry of the component cooling water systems is controlled in order to reduce corrosion of the structural materials ALARP.	20.7
20.1.4.1 The concentrations of impurities are controlled in order to reduce corrosion ALARP.	20.7
20.1.4.2 The type and concentration of corrosion inhibitors are controlled in order to reduce corrosion ALARP.	20.7
20.1.4.3 The pH is controlled in order to reduce corrosion ALARP.	20.7
20.1.5 The chemistry of the Turbine Island [T01] auxiliary systems is optimised in order to minimise corrosion of structural materials ALARP.	20.8
20.2 (argument) The RR SMR chemistry regime has been optimised in order to reduce the risk of fuel cladding corrosion ALARP.	20.4
20.2.1 Corrosion product deposition on fuel cladding is minimised ALARP.	20.4.4, 20.4.6
20.2.2 The reactor coolant pH is controlled through additions of KOH, reducing the risk of fuel cladding corrosion ALARP.	20.4.4, 20.4.6
20.2.3 For modes 1, 2, 3 and 4a, the redox potential in the reactor coolant is controlled in order to reduce fuel cladding corrosion ALARP.	20.4.4, 20.4.6
20.2.4 The concentration of impurities in the reactor coolant and spent fuel pool is controlled in order to reduce fuel cladding degradation ALARP.	20.4.6, 20.4.5
20.3 (argument) Radioactivity in the RR SMR is minimised ALARP to minimise worker and public dose.	20.4
20.3.1 Generation of radionuclides in the reactor coolant is minimised ALARP.	20.4.5

Claim	Section of Chapter 20 containing Arguments / Evidence summary
20.3.1.1 The reactor coolant chemistry is optimised to minimise general corrosion rates of structural materials ALARP.	20.4.5, 20.4.6
20.3.1.2 The reactor coolant chemistry is optimised to minimise fuel cladding corrosion ALARP.	20.4.4, 20.4.5
20.3.1.3 The chemical quality of make-up water and chemical additives are controlled to reduce radioactivity ALARP.	20.4.5, 20.4.6
20.3.2 Deposition of radionuclides in the primary circuit is minimised ALARP.	20.4.5
20.3.2.1 The reactor coolant pH is optimised to reduce deposition of non-active corrosion products on fuel surfaces ALARP.	20.4.5, 20.4.6
20.3.2.2. The reactor coolant hydrogen concentration is optimised to reduce deposition of non-active corrosion products on fuel surfaces ALARP.	20.4.5, 20.4.6
20.3.2.3 Zinc is injected into the reactor coolant to minimise deposition of radiocobalts on out of core surfaces ALARP.	20.4.5, 20.4.6
20.3.3 Accumulation of radionuclides in the reactor coolant is minimised ALARP.	20.4.5
20.3.3.1 The Coolant Purification System (CPS) [KBE] design minimises accumulation of radionuclides in the reactor coolant ALARP.	20.4.5, 20.4.6
20.3.4 Accumulation of radioactivity in the spent fuel pool is minimised ALARP.	20.4.5, 20.5
20.3.4.1 The Fuel Pool Purification System (FPPS) [FAL] design minimises accumulation of radionuclides in the Spent Fuel Pool ALARP.	20.4.5, 20.5
20.3.5 Accumulation of radionuclides in the reactor coolant is minimised ALARP.	20.4.5, 20.4.6
20.3.6 Release of radioactivity to the environment is minimised ALARP.	20.4.5
20.4 (argument) Systems, structures and components are provided within the RR SMR design in order to monitor and control chemistry.	20.3, 20.5
20.4.1 Systems are designed to enable representative sampling of plant fluid system chemistry.	20.3
20.4.2 Systems are designed to allow plant fluid system chemistries to be controlled in accordance with the Water Chemistry Specifications.	20.3 and 20.5



Claim	Section of Chapter 20 containing Arguments / Evidence summary
20.5 (argument) Radioactivity released during accident conditions is minimised ALARP to minimise worker and public dose.	20.10
20.5.1 The sump pH is sufficient under accident conditions that result in coolant being released to the containment such that the release of radioactive iodine is reduced ALARP.	20.10

20.14 Abbreviations

ACMS	Auxiliary Cooling and Makeup System
ActP	actinide products
AL	action level
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
AMP	ageing management plan
ANS	American National Standards
ANSI	American National Standards Institute
ANSS	Auxiliary Non-Nuclear Sampling System
AOA	axial offset anomaly
AP	activation product
Ar-41	argon-41
ASD	Atmospheric Steam Dump
ASF	Alternative Shutdown Function
AuSS	austenitic stainless steel
AVT	all-volatile treatment
AxSS	Auxiliary Sampling System
BAT	best available techniques
BE	best estimate
BOC	beginning of cycle
BoP	Balance of Plant
BSL	basic safety level
BSO	basic safety objective
BWR	boiling water reactor
C-14	carbon-14
CA	cycle average
CAE	claims, arguments, evidence
CANDU	Canada deuterium uranium
CCS	Component Cooling System
CCW	Component Cooling Water
CDHR	Condenser Decay Heat Removal

CILC	crud-induced localised corrosion
CIPS	crud-induced power shifts
Cl-36	chlorine-36
CMA	chemistry, monitoring and assessment
Co-60	cobalt-60
CP	corrosion product
CPP	Condensate Polishing Plant
CPS	Coolant Purification System
CS	carbon steel
CSCS	Cold Shutdown Cooling System
CSS	Chemical Supply System
CST	Condensate Storage Tank
CVCS	Chemical and Volume Control System
CWS	Chilled Water System
DB	design basis
DEI	dose equivalent iodine-131
DHC	delayed hydride cracking
DOORS	dynamic object orientated requirements system
DRP1	design reference point 1
DSEAC	Design, Safety, Environmental Advisory Committee
DWSS	Demineralised Water Supply System
E3S	Environment, Safety, Security and Safeguards
EAF	environmentally assisted fatigue
EBIS	Emergency Boron Injection System
ECC	Emergency Core Cooling
ECCS	Emergency Core Coolant System
EPRI	Electric Power Research Institute
ESWS	Essential Services Water System
ETA	ethanolamine
FAC	flow assisted corrosion
FBoM	functional bill of materials
FCG	fatigue crack growth

FCST	fuel crud source term
Fen	environmental correction factor
FID	flame ionisation detector
FP	fission product
FPCS	Fuel Pool Cooling System
FPPS	Fuel Pool Purification System
FPSS	Fuel Pool Supply System
GC	gas chromatography
GCM	generator condition monitor
GDA	generic design assessment
GRETS	Gaseous Radioactive Effluent Treatment System
HFT	hot functional testing
High-AVT	high all-volatile treatment
HOI	hypoiodous acid
HPIS	High Pressure Injection System
HTHR	High Temperature Heat Removal
HX	heat exchanger
IAEA	International Atomic Energy Agency
IASCC	irradiation assisted stress corrosion cracking
ID	identification
IGA	intergranular attack
I ⁻	iodide
I ₂	molecular iodine
IO ₃ ⁻	iodate
IO ₄ ⁻	periodate
IPR	independent peer review
IR	infra-red
IVR	in-vessel retention
IXC	ion exchange column
K-40	potassium-40
K-42	potassium-42

KOH	potassium hydroxide
LAS	low alloy steel
LiOH	lithium hydroxide
LPIS	Low Pressure Injection System
LRETS	Liquid Radioactive Effluent Treatment System
LTDHR	Low Temperature Decay Heat Removal
LUHS	Local Ultimate Heat Sink
LVCS	Level and Volume Control System
LWR	light water reactor
MA	mill-annealed
MIC	microbiologically induced corrosion
MPA	methiopropamine
MCWS	Main Cooling Water System
N-16	nitrogen-16
N-17	nitrogen-17
Na-24	sodium-24
NBA	nickel-based alloy
NG	nuclear grade
NSS	Nuclear Sampling System
NTU	nephelometric turbidity units
OLC	operational limits and conditions
ONB	onset of nucleate boiling
ONR	Office for Nuclear Regulation
OpEx	operational experience
ORE	occupational radiation exposure
PbSCC	lead-induced stress corrosion cracking
PCC	Passive Containment Cooling
PCD	preliminary concept definition
PDHR	Passive Decay Heat Removal
PERMS	Process & Emissions Radiation Monitoring System

PIE	postulated initiating events
PSCS	Passive Steam Condensing System
PST	primary source term
PSST	primary system source term
PWHT	post weld heat treatment
PWR	pressurised water reactor
PWSCC	primary water stress corrosion cracking
RAG	regulatory affairs group
RCP	Reactor Coolant Pump
RCPS	Reactor Coolant Pressurising System
RCS	Reactor Coolant System
RD5	reference design 5
RD7	reference design 7
RDS-PP	reference designation system for power plants
RGP	relevant good practice
RISS	Reactor Island Sampling System
RPV	Reactor Pressure Vessel
RPVI	reactor pressure vessel internals
RR SMR	Rolls-Royce Small Modular Reactor
RWST	Refuelling Water Storage Tank
SA	severe accident
SAP	safety assessment principle
SCC	stress corrosion cracking
SDD	system design description
SFAIRP	so far as is reasonably practicable
SFP	Spent Fuel Pool
SG	Steam Generator
SGPS	Steam Generator Purification System
SR	stress relieved
SS	stainless steel
SSC	structure, system and component
SSG	specific safety guide
SSST	secondary system source term

STP	standard temperature and pressure
TAG	technical assessment guide
T _{av}	average at-power operating temperature
TDS	total dissolved solids
TI-CCWS	Turbine Island Closed Cooling Water System
TJ	technical justification
TT	thermally treated
UFC	ultrasonic fuel cleaning
UK	United Kingdom
V&V	verification and validation
VVER	water-water energetic reactor (translated from Russian)
Zn-65	zinc-65
Zr	zirconium
ZrO ₂	zirconium dioxide