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| ONR Assessment Report  Generic Design Assessment of the Rolls-Royce SMR – Step 2 Assessment of Chemistry |



ONR Assessment Report

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**Report Title**: Step 2 Assessment of Chemistry

**Authored by**: [Redacted], ONR

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# Executive Summary

This report presents the outcomes of my chemistry assessment of the Rolls-Royce Small Modular Reactor (SMR) as part of Step 2 of the Office for Nuclear Regulation (ONR) Generic Design Assessment (GDA). This assessment is based upon the information presented in version 2 of Rolls-Royce SMR Limited’s Environmental, Safety, Security and Safeguards (E3S) case chapters and supporting documentation.

ONR’s GDA process calls for a step-wise assessment, which increases in detail as the project progresses. The focus of my assessment in this step was towards the fundamental adequacy of the Rolls-Royce SMR design and safety case, and the suitability of the methodologies, approaches, codes, standards and philosophies which form the building blocks for the design and generic safety and security cases.

I targeted my assessment, in accordance with my assessment plan, at the content of most relevance to chemistry against the expectations of ONR’s Safety Assessment Principles (SAPs), Technical Assessment Guides (TAGs) and other guidance which ONR regards as relevant good practice.

I targeted the following aspects in my assessment of the Rolls-Royce SMR E3S case:

* The safety justification for the operating chemistry to be applied to the primary circuit, secondary circuit, and relevant ancillary systems, including the development of the demonstration that all relevant risks are reduced to as low as reasonably practicable (ALARP);
* The demonstration that chemistry maintains pressure boundary and key component integrity and that the chemistry needs of circuit materials, fouling and impurity control are adequately balanced;
* The demonstration that the risks associated with the main accident chemistry topics will be appropriately modelled and adequately included in the safety case;
* The adequacy of the approach to defining and justifying the normal operation source term; and
* The adequacy of the overall chemistry safety case as it develops.

Based upon my assessment, I have concluded the following:

* In general, the scope, structure and content of the E3S case meet my expectations for this stage of GDA from a chemistry perspective. Further work will need to be undertaken in Step 3 of GDA by the Requesting Party (RP) to develop the underlying evidence supporting the chemistry claims and arguments.
* The major chemistry parameters, which would be expected to form part of the plant operating rules, have in most cases been defined. Further work will need to be undertaken in Step 3 of GDA by the RP to develop the justification for the normal operating envelope and associated limits.
* The chemistry implications of adopting a boron-free potassium hydroxide primary circuit and SFP chemistry are well documented in the E3S submissions, except for those aspects relating to shutdown chemistry. Relevant benefits, including a reduction in tritium production, are identified and initial evidence for these is presented. However, further justification is required to substantiate a number of related claims. Whilst key aspects of this substantiation are reliant on the results of a laboratory test programme which is not expected to yield results until Step 3 of GDA, based on the initial evidence presented I have confidence, at this stage, that the RP will be able to further develop the necessary evidence to support this important aspect of the E3S case. Insufficient information was provided by the RP during Step 2 to enable me to form a judgement on the feasibility and implications of the shutdown chemistry approach; this is a residual matter on which I will seek further information early in Step 3.
* Whilst I consider that appropriate chemistry controls have been identified to minimise the generation and transport of radioactivity in the primary circuit, further evidence is required in Step 3 to support the proposed operating ranges for the specific Rolls-Royce SMR design. Further to this, on shutdown chemistry and fuel cleaning, insufficient detail has been presented to form a judgement on the adequacy of the information; these are residual matters on which I will seek further information in Step 3.
* A suitable strategy has been developed by the RP through which it will seek to demonstrate that the effects of chemistry during fault and accident conditions are understood and that risks are reduced so far as is reasonably practicable (SFAIRP). A robust justification will need to be provided during Step 3 to support the RP’s current position that no purposeful sump pH control provision is required in the design. This is a residual matter that I will follow up in Step 3.

Overall, based on my assessment to date, and subject to the provision and assessment of suitable and sufficient supporting evidence, I have not identified any fundamental safety shortfalls that could prevent ONR permissioning the construction of a power station based on the generic Rolls-Royce SMR design.

# List of Abbreviations

ALARP As low as is reasonably practicable

ANSS Auxiliary Non-nuclear Sampling System

AxSS Auxiliary Sampling System

CAE Claims arguments and evidence

CCS Chemistry Control System

CILC Crud induced localised corrosion

CIPS Crud induced power shift

CPS Coolant Purification System

CVCS Chemistry and Volume Control System

DAC Design Acceptance Confirmation

DRP Design Reference Point

E3S Environment, Safety, Security and Safeguards

EBIS Emergency Boron Injection System

FAC Flow accelerated corrosion

FPPS Fuel Pool Purification System

GDA Generic Design Assessment

H-AVT High-All Volatile Treatment

HPIS High Pressure Injection System

IAEA International Atomic Energy Agency

NLR Nuclear Liabilities Regulation

NRW Natural Resources Wales

NSS Nuclear Sampling System

ONR Office for Nuclear Regulation

OPEX Operating experience

RCP Reactor coolant pump

RGP Relevant good practice

RP Requesting Party

RPV Reactor pressure vessel

RQ Regulatory Query

SAP Safety Assessment Principle(s)

SG Steam generator

SGPS Steam Generator Purification System

SFAIRP So far as is reasonably practicable

SFP Spent Fuel Pool

SCC Stress corrosion cracking

SMR Small Modular Reactor

SSC Structure, system and component

TAG Technical Assessment Guide(s) (ONR)

TSC Technical Support Contractor

VVER Voda Voda Energo Reactor

WENRA Western European Nuclear Regulators’ Association

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# Introduction

1. This report presents the outcomes of my chemistry assessment of the Rolls-Royce Small Modular Reactor (SMR) as part of Step 2 of the Office for Nuclear Regulation (ONR) Generic Design Assessment (GDA). This assessment is based upon the information presented in version 2 of Rolls-Royce SMR Limited’s Environmental, Safety, Security and Safeguards (E3S) case chapters (refs. [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], and [17]) and supporting documentation.
2. Assessment was undertaken in accordance with the requirements of the Office for Nuclear Regulation (ONR) Management System and follows ONR’s guidance on the mechanics of assessment, NS-TAST-GD-096 (ref. [18]). The ONR Safety Assessment Principles (SAPs) (ref. [19]) together with supporting Technical Assessment Guides (TAGs) (ref. [20]), have been used as the basis for this assessment.
3. This is a Major report (refer to NS-TAST-GD-108 (ref. [21])).
   1. Background
4. The ONR’s GDA process (ref. [22]) calls for a step-wise assessment of the Requesting Party's (RP) submissions with the assessments increasing in detail as the project progresses. Rolls-Royce SMR Limited is the RP for the GDA of the Rolls-Royce SMR design.
5. In April 2022 ONR, together with the Environment Agency and Natural Resources Wales (NRW), began Step 1 of the GDA for the generic Rolls-Royce SMR design. Step 1, which is the preparatory part of the design assessment process and mainly associated with initiation of the project and preparation for technical assessment in later steps, was successfully completed in 12 months.
6. Step 2 commenced in April 2023. This is the first substantive technical assessment step. The focus of ONR’s assessments in this step is towards the fundamental adequacy of the design and safety and security cases, and the suitability of the methodologies, approaches, codes, standards and philosophies which form the building blocks for the design and generic safety and security cases. The objective is to undertake an assessment of the design against regulatory expectations to identify any fundamental safety or security shortfalls that could prevent ONR permissioning the construction of a power station based on the design.
7. Prior to the start of Step 2 I prepared a detailed Assessment Plan for chemistry (ref. [23]). This has formed the basis of this assessment and was also shared with the RP to maximise openness and transparency.
8. This report is one of a series of Assessments which support ONR’s overall judgements at the end of Step 2 which are recorded in the Step 2 Summary Report (ref. [24]).
   1. Scope
9. The assessment documented in this report is based upon the E3S case for the Rolls-Royce SMR as summarised in the E3S case chapters and supporting documentation.
10. The overall scope of the Rolls-Royce SMR GDA is described in (ref. [25]). Rolls-Royce SMR Limited has indicated that it intends to complete a three step GDA, with the objective of receiving a Design Acceptance Confirmation (DAC) from ONR and have aligned their GDA scope with this objective. The GDA scope defines the generic plant and layout and includes all systems, structures and components that are identified as being important to safety, security and safeguards, all modes of operation, and all stages of the plant lifecycle.
11. However, given the step-wise assessment during GDA, information has not been submitted for all aspects within the GDA Scope during Step 2. The following aspects of the E3S case are therefore out of scope of this assessment:

* The RP’s approach to commissioning chemistry and alignment with Relevant Good Practice (RGP). Chemistry choices during hot functional testing can have significant impacts on the future operation of the plant and on dose rates. I will assess this aspect during Step 3 of the GDA.

1. My assessment has considered the following aspects:

* Primary circuit chemistry – the RP’s safety justification for the operating chemistry to be applied to the primary circuit and ancillary systems, including the development of the demonstration that chemistry reduces all relevant risks to as low as is reasonably practicable (ALARP). Additionally, the chemistry aspects associated with the deposition of corrosion products on the fuel cladding surface.
* Secondary circuit chemistry – the RP’s safety justification for the operating chemistry to be applied to the secondary circuit, including the development of the demonstration that it reduces all relevant risks to ALARP.
* Accident chemistry – the RP’s demonstration that the risks associated with the three main accident topics (fission product chemistry, combustible gas chemistry, and core melt and in-vessel retention) will be appropriately modelled and adequately included in the safety case.
* Materials selection – the RP’s demonstration that chemistry maintains pressure boundary and key component integrity and that the chemistry needs of circuit materials, fouling and impurity control are adequately balanced.
* Normal operation source term – the adequacy of the RP’s approach to defining and justifying the source term, including that it will be developed using appropriate methods, cover all appropriate systems and sources of radioactivity, and that it will be appropriately integrated into the safety case.
* The adequacy of the overall chemistry safety case as it develops, focussing at this stage on the adequacy of the claims and arguments.
* I also considered a range of matters from within the chemistry related aspects of the RP’s safety case at a high level to gain a general appreciation of the approach and the case being developed by the RP. These included the:
  + chemistry specifications and any related limits and conditions;
  + adequacy of the plant design to deliver the specified chemistry;
  + chemistry sampling and monitoring systems; and
  + Spent Fuel Pool (SFP) chemistry and the design of the SFP cooling and treatment system.

# Assessment standards and interfaces

1. For ONR, the primary goal of the GDA Step 2 assessment is to reach an independent and informed judgment on the adequacy of a safety, security and safeguards case for the reactor technology being assessed.
2. ONR has a range of internal guidance to enable Inspectors to undertake a proportionate and consistent assessment of such cases. This section identifies the standards which have been considered in this assessment.
3. This section also identifies the key interfaces with other technical topic areas.
   1. Standards
4. The ONR Safety Assessment Principles (SAPs) (ref. [19]) constitute the regulatory principles against which the RP’s case is judged. Consequently, the SAPs are the basis for ONR’s assessment and have therefore been used for the Step 2 assessment of the Rolls-Royce SMR.
5. The International Atomic Energy Agency (IAEA) safety standards (ref. [26]) and nuclear security series (ref. [27]) are a cornerstone of the global nuclear safety and security regime. They provide a framework of fundamental principles, requirements and guidance. They are applicable, as relevant, throughout the entire lifetime of facilities and activities.
6. Furthermore, ONR is a member of the Western European Nuclear Regulators Association (WENRA). WENRA has developed Reference Levels (ref. [28]), which represent good practices for existing nuclear power plants, and Safety Objectives for new reactors (ref. [29]).
7. The relevant SAPs, IAEA standards and WENRA reference levels are embodied and expanded on in the TAGs (ref. [20]). The TAGs provide the principal means for assessing the chemistry aspects in practice.
   * 1. Safety Assessment Principles (SAPs)
8. The key SAPs applied within my assessment are:

* ECH.1, in my consideration of whether, by applying a systematic process, the RP’s safety case addresses all chemistry effects important to safety;
* ECH.2, in determining whether, where the effects of different chemistry parameters conflict with one another, the safety case demonstrates that an appropriate balance for safety has been achieved;
* ECH.3, in determining whether suitable and sufficient systems, processes and procedures are provided to maintain chemistry parameters within the limits and conditions identified in the safety case; and
* ECH.4, in my consideration of whether suitable and sufficient systems are provided for monitoring, sampling and analysis so that all chemistry parameters important to safety are properly controlled.

1. A list of the SAPs used in this assessment is recorded in Appendix 1.
   * 1. Technical Assessment Guides (TAGs)
2. The following TAGs have been used as part of this assessment:

* NS-TAST-GD-096 – Guidance on Mechanics of Assessment (ref. [18])
* NS-TAST-GD-088 – Chemistry of Operating Civil Nuclear Reactors (ref. [30])
* NS-TAST-GD-089 – Chemistry Assessment (ref. [31])
* NS-TAST-GD-005 – Regulating duties to reduce risks to ALARP (ref. [32])
* NS-TAST-GD-051 – The purpose, scope and content of safety cases (ref. [33])
  + 1. National and international standards and guidance

1. The following international standards and guidance have been used as part of this assessment:

* IAEA, Chemistry Programme for Water Cooled Nuclear Power Plants, Specific Safety Guide No. SSG-13 (ref. [34]). This safety guide contains relevant guidance and international good practice, and is applicable to the development of new chemistry programmes.
  1. Integration with other assessment topics

1. I have worked closely with other topics (including the Environment Agency and NRW assessors) as part of my chemistry assessment. Similarly, other assessors sought input from my assessment. These interactions are key to the success of GDA to prevent or mitigate any gaps, duplications or inconsistencies in ONR’s assessment.
2. The key interactions with other topic areas were:

* Structural Integrity took the lead on assessing the case for the integrity of metallic components and structures. I assessed the effects of the operating chemistry on susceptibility to material degradation mechanisms, including where integrity may not be threatened but corrosion is still important;
* I provided input to the cladding corrosion and crud aspects of the Fuel and Core assessment. The effects of the primary circuit chemistry on these aspects was led by me, as was the assessment of chemistry-related consequences (e.g. on radioactivity or deposition). Non-chemistry related consequences were led by the Fuel and Core inspector;
* The Fault Studies and Severe Accidents assessments were led by their respective disciplines; I provided input in areas where chemistry effects are important in determining the consequences or effectiveness of mitigation measures; and
* I took the lead regarding normal operation radiological source terms, collaborating with a team of inspectors from other disciplines, (Environment Agency, Radiological Protection and Nuclear Liabilities Regulation (NLR)) to assess the adequacy of the methodology for deriving and justifying the normal operation source term. I provided input specifically with regards to the impact of the operating chemistry on the source term.
  1. Use of technical support contractors

1. During Step 2 I have not engaged Technical Support Contractors (TSCs) to support my assessment of the chemistry aspects of the Rolls-Royce SMR.

# Requesting party’s submission

1. Rolls-Royce SMR Limited submitted a series of E3S chapters, or summary reports, and other supporting references, which outline the E3S case for the generic Rolls-Royce SMR design. This section presents a summary of the RP’s safety case for chemistry. It also identifies the documents submitted by the RP which have formed the basis of my chemistry assessment of the Rolls-Royce SMR.
   1. Summary of the Rolls-Royce SMR design
2. The generic Rolls-Royce SMR design is a three loop Pressurised Water Reactor (PWR) with a target electrical power output of 470 MWe (from a thermal power of 1,358 MWth) and a design life of 60 years for non-replaceable components.
3. The Rolls-Royce SMR design has been developed by the RP based upon well-established PWR technology, in use all over the world. Innovation comes in the form of its modular approach to construction which would see the majority of the power station built in factory conditions and assembled on site.
4. The reactor itself is of a typical PWR design, including a steel Reactor Pressure Vessel (RPV) holding fuel assemblies, Steam Generators (SG), Reactor Coolant Pumps (RCP) and piping, all held within a steel containment vessel. The reactor is equipped with a number of supporting systems for normal operations and a range of safety measures are present in the design to provide cooling, control criticality and contain radioactivity under fault conditions. Passive safety features are preferred to active components, reflecting the RP’s design philosophy.
5. Primary circuit chemistry choices can have a wide-ranging impact on plant operations in a PWR, including on the generation and transport of radioactivity and on the integrity of structures, systems and components important to safety. The Rolls-Royce SMR design adopts a primary circuit operating chemistry regime that differs from that of other operating civil PWRs, including Sizewell B, in that reactivity control is achieved using control rods rather than through the addition of soluble boron to the primary coolant in normal operations. Additionally the RP has selected potassium hydroxide, rather than lithium hydroxide, as the alkalising agent to achieve the desired pH in the primary circuit; whilst lithium hydroxide is the common choice amongst operating Western PWRs, a number of Eastern European PWRs (Voda Voda Energo Reactors (VVERs)) operate successfully with potassium hydroxide conditioning.
   1. E3S case approach and structure
6. Rolls-Royce SMR Limited has chosen to develop its cases in a holistic manner, as an Environment, Safety, Security and Safeguards (E3S) case. The overall objective for the E3S case is to demonstrate that the design will ‘protect people and the environment from harm’.
7. This means that, although the case made for each of the E3S purposes (i.e. environment, safety, security and safeguards) will inevitably be different at the top level, it will draw upon common evidence outputs (as well as other non-common outputs) to substantiate each of the purposes. This is claimed to offer benefits in terms of clarity, integration and understanding impacts from any changes to the case.
8. The E3S case is being developed using a three tier hierarchy and incorporating a Claim, Argument and Evidence (CAE) structure with the highest-level claims being derived from the RP’s own E3S principles. The highest level of the three tiers is the RP’s Tier 1 E3S chapters, with the lower tiers providing more detailed arguments and evidence. This is illustrated in Figure 1.

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**Figure 1: Claim, Argument and Evidence (CAE) structure within the E3S hierarchy** (ref. [1])

1. The structure of the E3S case largely aligns with the IAEA guidance for safety cases, SSG-61 (ref. [35]), supplemented to include UK specific expectations and expanded to include the other E3S purposes.
   1. Summary of the requesting party’s E3S case for Chemistry
2. The aspects covered by the Rolls-Royce SMR safety case in the area of chemistry can be broadly grouped under 8 headings which are summarised as follows:
   * 1. Primary circuit chemistry
3. The primary circuit chemistry aspects of the case are divided into 3 further sub-topic areas, covering the minimisation of radioactivity, the minimisation of fuel cladding corrosion, and the minimisation of corrosion of structural materials.
4. Under fuel cladding corrosion, claims are made that pH, redox potential and impurities are controlled to reduce fuel cladding corrosion SFAIRP. Additionally, corrosion product deposition on the fuel is claimed to be minimised SFAIRP through core design and chemistry controls in place to minimise the amount of corrosion product in the coolant that is available to deposit on the fuel.
5. Sub-claims on radioactivity minimisation assert that the generation, deposition and accumulation of radionuclides in the primary circuit is minimised SFAIRP, through optimisation of the primary coolant chemistry and the coolant purification system (CPS) design. Accumulation of radioactivity in the spent fuel pool (SFP) is said to be minimised SFAIRP through the optimisation of the fuel pool purification system (FPPS) design.
6. On the minimisation of corrosion of structural materials, sub-claims are made on the control of pH, redox potential and impurities.
7. Additional sub-claims are made on the design of relevant systems, including the chemistry and volume control system (CVCS), to allow chemistry to be controlled in accordance with chemistry specifications.
8. A water chemistry specification submission sets out the chemistry parameters and expected operating ranges for the reactor coolant system, the SFP, the local ultimate heat sink (LUHS) system and other primary auxiliary systems.
   * 1. Secondary circuit chemistry
9. The secondary circuit chemistry aspects of the case are focussed on the minimisation of corrosion of structural materials. Sub-claims assert that the secondary circuit chemistry is controlled to reduce corrosion of the steam generator materials SFAIRP. This claim is further sub-divided to consider the following degradation mechanisms: stress corrosion cracking (SCC), lead induced SCC (PbSCC), denting, pitting, vibration-induced degradation and fouling. Additional sub-claims cover the control of chemistry in order to minimise flow accelerated corrosion (FAC) and general corrosion in the feedwater system to reduce the transport of corrosion products into the steam generators.
10. Additional sub-claims are made on the design of relevant systems, including the steam generator purification system (SGPS), the condensate purification system and the chemical supply system, to allow chemistry to be controlled in accordance with chemistry specifications.
    * 1. Materials selection
11. Information on the RP’s processes for the selection and specification of materials is contained within E3S chapter 23 (ref. [16]) and its underlying references. A sub-claim within the chapter states that materials are selected and specified to ensure they are well-understood and characterised, based on operating experience (OPEX) and RGP.
12. Materials selection decisions are made using a design optioneering process, C3.2.2-2 (ref. [36]), which for key decisions, yields an output in the form of a decision record. The process prompts consideration of a range of factors including safety impact, legislative requirements, ALARP, cost, supply chain availability and standardisation.
13. The RP has set baseline water chemistry specifications to support the design development, including as input assumptions to materials optioneering; these are issued via the RP’s requirements management system.
    * 1. Normal operation source term
14. The RP’s strategy for deriving the normal operation source term for the Rolls-Royce SMR design is set out in a dedicated strategy report that sits under E3S chapter 20. The radionuclide list associated with the normal operation source term for the Rolls-Royce SMR is documented separately.
15. The strategy notes that the overall source term for the Rolls-Royce SMR design will be made up of four constituent source terms:

* the primary source term which considers the initial formation of radionuclides in the primary coolant in the reactor core;
* the primary system source term which 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;
* the secondary system source term which covers the radioactive inventory in the coolant and steam of secondary circuit systems; and
* the fuel crud source term which covers the radioactive inventory of deposits on the fuel.
  + 1. Accident chemistry

1. The E3S chapter level claim for chemistry (claim 20) asserts that the Rolls-Royce SMR chemistry regime is optimised to reduce risks ALARP during accident conditions (ref. [15]). An Accident Chemistry Strategy Report (ref. [37]) was submitted in support of chapter 20, setting out the RP’s strategy and plans for how the key chemistry assumptions and claims which have a nuclear safety significance will be evaluated for design basis faults and Design Extension Conditions (DEC-A and DEC-B), and for the development of the E3S case in this area.
   * 1. Chemistry sampling and monitoring
2. E3S chapter 20 sub-claims on chemistry sampling and monitoring are focussed around the optimisation of the design of the sampling systems (the nuclear sampling system (NSS), auxiliary sampling system (AxSS), and auxiliary non-nuclear sampling system (ANSS)) to provide representative sampling of chemistry parameters. Underlying tier 2 submissions present arguments to this end for the primary circuit and secondary circuit, alongside information on how structures, systems and components (SSC) provide for the control of chemistry parameters.
3. Limited information was provided on post-accident sampling capability during Step 2, due to the low design maturity of this aspect of the NSS.
   * 1. Reactor Island auxiliary system chemistry
4. The basis for the chemistry regime adopted in the auxiliary systems to the primary circuit is presented in E3S chapter 20 and a dedicated underlying tier 2 submission which focusses on the SFP and associated clean-up system, the component cooling water system, local ultimate heatsink system (LUHS), and the systems involved in delivering the alternative shutdown function (ASF).
5. The chemistry of the auxiliary systems to the primary circuit is claimed to be appropriately controlled in order to reduce corrosion of the structural materials.
   * 1. ALARP
6. The E3S chapter level claim for chemistry (claim 20) asserts that the Rolls-Royce SMR chemistry regime is optimised to reduce risks ALARP (ref. [15]).
7. A number of relevant chemistry sub-claims support claim 20 in this regard. Additionally, a dedicated ALARP summary report (Ref. [38]) presents summarised justifications for several key design decisions of relevance to chemistry, including the decision to operate without boron in the primary circuit during normal operations, the use of potassium hydroxide as the primary circuit alkalising agent and the emergency boron injection system.
   1. Basis of assessment: requesting party’s documentation
8. The principal documents that have formed the basis of my chemistry assessment of the E3S case are:

* ‘E3S Chapter 20: Chemistry’ (ref. [15]) which is the top-level safety case document that presents an overarching summary of the chemistry claims, arguments and evidence for the Rolls-Royce SMR design.
* Water chemistry specification tables relating to the reactor island (ref. [39]) and the turbine island (ref. [40]).
* Documents presenting the sub-claims and arguments relating to the following aspects of the primary circuit chemistry:
  + Minimisation of radioactivity (ref. [41])
  + Minimisation of corrosion of structural materials (ref. [42])
  + Minimisation of fuel cladding corrosion (ref. [43])
  + Method of monitoring and control (ref. [44])
* Documents presenting the sub-claims and arguments relating to the following aspects of the secondary circuit chemistry:
  + Minimisation of corrosion of structural materials (ref. [45])
  + Method of monitoring and control (ref. [46])
* A report presenting the RP’s strategy for evaluating the chemistry effects considered in its fault and accident analyses (ref. [37]).
* The following documents relating to the derivation of the normal operation source term:
  + Normal Operation Source Term Strategy Report (ref. [47])
  + Normal Operation Source Term Radionuclide Selection Report (ref. [48])
* The following submissions relating to materials selection and materials degradation:
  + Ageing Management Plan (ref. [49])

# ONR assessment

* 1. Assessment strategy

1. My assessment focussed on a number of main themes of relevance to chemistry control. These were protection of the structural materials, maintaining fuel integrity and performance, minimisation of out of core radiation fields and minimisation of releases during fault and accident conditions.
2. I chose to target for assessment those areas where I considered that justification and scrutiny of the design may be needed due to factors such as novelty, as well as those which I judged to be the most safety significant in the context of the design and safety case. Hence I have focused much of my effort in Step 2 on the primary circuit chemistry. This targeting approach supports my overall Step 2 assessment objective of evaluating the design against regulatory expectations to identify any fundamental safety shortfalls that could prevent ONR permissioning the construction of a power station based on the design.
3. The aspects of the Rolls-Royce SMR safety case that I focussed my assessment on were set out in my assessment plan, produced prior to the start of Step 2 (ref. [23]).
   1. Assessment
      1. Primary circuit chemistry
4. SAP ECH.1 describes ONR’s expectation that safety cases should identify and analyse how chemistry can impact safety in normal operations and fault conditions, with demonstration as to how chemistry is controlled. With this in mind, during Step 2 I sampled the safety case documentation that describes key aspects of the primary circuit chemistry regime. This included whether the pH and impurity control requirements, along with the various chemical additions, are appropriate to be able to control corrosion. Additionally, I considered the impact of the chemistry choices on the radioactivity produced and transported in the primary circuit, and on fuel cladding corrosion and fuel deposits.

#### Justification for the chemistry choices

1. As described in section 3, the Rolls-Royce SMR design adopts a primary circuit operating chemistry regime that uses potassium hydroxide for pH control and does not use soluble boron for reactivity control (ref. [39]). The RP’s decision to adopt this primary circuit chemistry has a range of implications. The effect on power excursion and relevant acceptance criteria in reactivity faults is within the scope of the Fault Studies assessment (ref. [50]), and the impacts on the design of the core are within the scope of the Fuel and Core assessment (ref. [51]). The safety justification for the primary circuit chemistry and the impacts of this operating chemistry choice on the generation, transport and behaviour of radioactivity are within the scope of my assessment and are recorded here.
2. At the top level, E3S chapter 20 claims that the Rolls-Royce SMR chemistry regime and development of the chemistry systems design, reduces risks ALARP. Further sub-claims state that the pH, redox potential and concentration of impurities in the reactor coolant are controlled in order to reduce corrosion SFAIRP. The main primary water chemistry submissions (refs. [42], [43], [44]) begin to set out the arguments and evidence for these claims, and describe the following chemistry control measures:

* pH control
* redox control
* impurity control
* zinc addition

1. The RP has chosen an expected normal operating pHT of 7.4, achieved through dosing potassium hydroxide into the primary coolant. Since the Rolls-Royce SMR design does not operate with addition of boric acid to the primary coolant, the maximum achievable pH is not limited by the need to coordinate the pH raiser with large concentrations of boric acid at the beginning of a cycle. Therefore, a constant pHT of 7.4 across the cycle should be achievable and is claimed to increase the stability of primary circuit surface oxides and hence minimise corrosion rates. A pHT of greater than 7.4 may be feasible if a yet to be defined fuel vendor imposed limit on maximum potassium concentration (to avoid accelerated fuel cladding corrosion) allows. The RP notes that the benefits and detriments of implementing a pHT greater than 7.4 will be considered and reported during Step 3 of GDA (ref. [42]).
2. Whilst the RP has presented literature data which gives confidence that the corrosion behaviour of wetted primary circuit materials in potassium hydroxide and boric acid is not significantly different to that in lithium hydroxide and boric acid at representative pH, as the design operates without boric acid, further justification is required to substantiate the claims on pH. The RP has initiated a laboratory test programme in order to provide additional data in a potassium hydroxide boron-free chemistry, since no OPEX from plants operating with this chemistry is available to the RP.
3. The RP’s laboratory test programme aims to demonstrate that the selected potassium hydroxide boron-free chemistry regime presents no disadvantages over a lithium boric acid chemistry in terms of the impact on the corrosion of the key primary circuit materials, and to use this to demonstrate the relevance of the large body of OPEX from plants operating with lithium/boric acid chemistry to the Rolls-Royce SMR design. Whilst the timescales of the test programme are such that the results, and therefore key evidence in support of many of the primary circuit chemistry claims, will not be available until Step 3 of the GDA, I consider the approach to be broadly reasonable.
4. Control of redox potential in the primary circuit is achieved through hydrogen injection, to an expected concentration of 15 to 50 cm3 kg-1 and a lower limit of 5 cm3 kg-1, in order to supress the radiolysis of water and any resultant corrosive environment during power operation (ref. [39]). Optimisation of the target hydrogen concentration range is discussed in the primary circuit corrosion minimisation submission (ref. [42]), and a range of literature data is presented alongside some OPEX from PWRs operating with lithium-boron chemistry. Whilst the upper expected value is in line with international practices to minimise the risk of fuel cladding embrittlement, the lower end of the expected range and the lower limit are lower than most international guidelines. Further evidence is required in Step 3 to support the proposed hydrogen concentration range for the Rolls-Royce SMR and to justify that this operating practice reduces risks SFAIRP.
5. Primary circuit impurity limits (for chloride, fluoride, sulfate and oxygen) selected for the Rolls-Royce SMR are in line with international guidelines for PWRs (refs. [39] [52]) and are claimed to reduce corrosion SFAIRP. A range of literature data is presented to explain the effect of such impurities on SCC and other relevant corrosion mechanisms and to begin to justify the selected limits. However the key evidence supporting this justification in the Rolls-Royce SMR chemistry will be presented in Step 3, from the output of the RP’s laboratory test programme.
6. The RP has chosen to inject zinc into the primary coolant during normal operation at an expected concentration of 5 to 15 ppb. The RP makes specific claims on zinc addition to reduce dose rates, however it also foresees a beneficial effect for corrosion mitigation. A range of literature data and some PWR plant data is presented in support of these claims (refs. [41] [42]). Some limited laboratory testing with zinc in VVER chemistries is also presented, indicating that the effect of zinc is similar in potassium hydroxide as in lithium hydroxide; the RP intends to produce laboratory test data in Step 3 of GDA to support this argument. As noted in section 1.2, the RP’s approach to commissioning chemistry will be reported in Step 3 GDA submissions, however the RP presents an initial review of OPEX from other PWRs which have injected zinc during hot functional testing and states the expectation that the Rolls-Royce SMR will inject zinc during this phase of commissioning (ref. [42]). Whilst in general I consider the addition of zinc to be RGP for a new PWR, further information is required during Step 3 to demonstrate that the effects of zinc in the Rolls-Royce SMR design and chemistry are understood and that the target concentration is appropriate.
7. Whilst the RP presented an assumption that reactor coolant water chemistry will be changed from alkali reducing operating conditions to a neutral oxygenated chemistry prior to the Reactor Pressure Vessel (RPV) head lift (and vice versa on the following return to service during start-up), no arguments or initial justification to underpin this start-up and shutdown chemistry were provided during Step 2. Shutdown chemistry choice, in particular, is a fundamentally important aspect of the chemistry regime that will have significant impacts, including on the transport and accumulation of radioactivity in the Rolls-Royce SMR design. The RP’s current assumption for the Rolls-Royce SMR shutdown chemistry is a novel approach when compared to current established practices in operating PWRs. Insufficient information was provided by the RP during Step 2 to enable me to form a judgement on the feasibility and implications of the approach. I expect the RP to provide a robust justification for the chosen start-up and shutdown chemistry during GDA. Hence this is a residual matter on which I will seek further information early in Step 3.

#### Control of the chemistry

1. SAP ECH.3 describes ONR’s expectations regarding how, once the chemistry based operating rules are derived from the safety case, adequate provisions should be in place to ensure the plant is designed and can be operated within the safe operating envelope defined in the safety case.
2. The RP makes two key claims in this regard, that SSCs are provided within the SMR design in order to monitor and control chemistry, and that the CPS design minimises the accumulation of radionuclides in the reactor coolant SFAIRP (ref. [44]).
3. A continuous flow of primary coolant is circulated through the CPS in normal operation to purify the coolant in order to meet the specified chemistry limits (at least 9% of the total primary coolant volume is circulated through the CPS each hour) (ref. [53]). The CPS contains three ion exchange columns; two columns are in parallel and contain mixed bed resin with the cation component in the potassium form, to prevent the removal of potassium from the primary coolant. The third is downstream of the mixed beds and contains fission product selective resin, selected for clean-up in the event of a fuel cladding failure. Initial information is provided in the System Outline Description on the sizing assumptions and intended operation of the ion exchange columns (ref. [53]), however further information is needed in Step 3 to provide assurance that the equipment is suitable to meet the stated chemistry specifications and to minimise radioactivity in the coolant SFAIRP.
4. A Chemistry Control System (CCS) is provided to control reactor primary coolant chemistry through control of primary circuit oxygen levels, pH and zinc (ref. [54]). The system is formed of three dosing lines that supply chemicals to the return line of the CPS, which then returns the dosed primary coolant to the primary circuit. As noted in 4.2.1.1, hydrogen addition is required in power operation to suppress water radiolysis and reduce corrosion. A hydrogen dosing line injects pressurised hydrogen into the CPS, where it is dissolved prior to reaching the primary circuit. The zinc dosing line pumps zinc acetate solution from the zinc addition tank into the CPS. The chemical dosing line, pumps a range of different chemicals individually depending on the stage in the operating cycle (potassium hydroxide, hydrogen peroxide or hydrazine) from the chemical addition tank, into the CPS. Some high level information is provided in the System Design Description on the sizing of the tanks and the dosing rates (ref. [54]), however further information is needed in Step 3 to provide assurance that the equipment is suitable to meet the stated chemistry specifications and can deliver the functions safely.
5. Due to the adoption of a primary circuit operating chemistry regime that does not use soluble boron for reactivity control, I note that aspects of the chemistry control in the Rolls-Royce SMR are less complex than a PWR operating with a typical chemistry regime. For example, the need for systems to store and control the make-up of boric acid solutions in normal operation is removed, and the risk of boric acid corrosion from leaks in such systems is mitigated. Faults associated with the addition of boric acid of an incorrect concentration or enrichment to the primary coolant during normal operation are also removed by the selected operating chemistry.
6. Injection of soluble boron is claimed as a secondary means of reactivity control in some fault scenarios, however (ref. [55]). The category B alternative shutdown function is delivered via the Emergency Boron Injection System (EBIS) and the High Pressure Injection System (HPIS). The EBIS stores enriched potassium tetraborate which is supplied to the RPV via the HPIS and to the refuelling pool when demanded by the alternative shutdown function (ref. [56]). A boron tank sizing calculation is presented which appears conservative, however information on the monitoring and control of boron enrichment and concentration in the boron storage tank was not available. Clearly the control of boron enrichment and concentration is fundamentally important to ensuring that the function can be delivered; I will follow this aspect up as part of my Step 3 assessment.
7. The RP has identified relevant species which should be controlled in the primary circuit, and has provided some information about the means with which these will be controlled, and that the purification and dosing systems will be capable of delivering the stated chemistry regime. Whilst further information to justify the adequacy of these systems in the Rolls-Royce SMR chemistry and conditions is required in Step 3 of GDA, the general approach is reasonable and in line with practices at other PWR plants.

#### Impact on the generation, transport and behaviour of radioactivity

1. In line with ONR SAPs EHT.4 and EHT.5, the coolant within heat transport systems should minimise the potential for radioactivity accumulation or transport within the plant.
2. Further to this, IAEA SSG-13 notes that the primary water chemistry programme applied should effectively control and minimize the buildup of radioactive material from the transport and accumulation of fission products and activated corrosion products on the internal surfaces of the systems (ref. [34]).
3. The RP makes a number of claims on the control of chemistry for the minimisation of radioactivity. The first of these is that radioactivity in the Rolls-Royce SMR is minimised SFAIRP to minimise worker and public dose. This is underpinned by several sub-claims:

* Generation of radionuclides in the reactor coolant is minimised SFAIRP.
  + The reactor coolant chemistry is optimised to minimise general corrosion rates of structural materials SFAIRP.
  + The reactor coolant chemistry is optimised to minimise fuel cladding corrosion SFAIRP.
  + The chemical quality of make-up water and chemical additives are controlled to reduce radioactivity SFAIRP.
* Deposition of radionuclides in the primary circuit is minimised SFAIRP.
  + Zinc is injected into the reactor coolant to minimise deposition of radiocobalts on out of core surfaces SFAIRP.
  + The reactor coolant hydrogen concentration is optimised to reduce deposition of non-active corrosion products on fuel surfaces SFAIRP.
  + The reactor coolant pH is optimised to reduce deposition of non-active corrosion products on fuel surfaces SFAIRP.
* Accumulation of radionuclides in the reactor coolant is minimised SFAIRP.
  + The CPS design minimises accumulation of radionuclides in the reactor coolant SFAIRP.

1. The RP describes how the primary circuit chemistry of the Rolls-Royce SMR has been designed in order to minimise the generation of corrosion products which can become activated and collect around the primary circuit (ref. [41]). A target pHT value of 7.4 is set to reduce the impact on radioactivity caused by general corrosion, hydrogen is added to the primary circuit to maintain the reducing environment to minimise corrosion of structural materials, and zinc injection will be applied which is also likely to reduce the corrosion rate and will limit the deposition of radioactive cobalt on primary circuit surfaces. Whilst I consider that appropriate chemistry controls have been identified to minimise the generation of radioactivity in the primary circuit, as noted in section 4.2.1.1, further evidence is required in Step 3 to support the proposed operating envelope for the specific Rolls-Royce SMR design. Key evidence for this is not expected to be presented until Step 3 of the GDA, from the output of the RP’s laboratory test programme which considers corrosion rates in the selected potassium hydroxide chemistry.
2. I note that the choice of operating chemistry in the Rolls-Royce SMR, which does not include the use of soluble boron and lithium, is likely to have a beneficial effect in terms of the amount of tritium produced during normal operation when compared with a PWR operating with lithium-boron chemistry. Whilst initial evidence is presented in support of this, a detailed calculation of the expected tritium will be produced by the RP as part of the derivation of the normal operation source term in Step 3 of the GDA. I note however that due to the use of potassium hydroxide for pH control, potassium-40 and -42 will be produced in the primary circuit and will contribute to operator dose. In response to Regulatory Query 01210 (RQ-01210), the RP noted that as the design is boron-free the number of moles of potassium in the reactor coolant is minimised (since there is no requirement to neutralise boric acid with large amounts of potassium) (ref. [57]). Additionally, the RP presents literature data which indicates that the use of potassium hydroxide will not significantly increase dose rates compared to use of lithium hydroxide, adding that design specific calculations to determine the contribution to operator dose from potassium for the Rolls-Royce SMR will be presented in Step 3.
3. Whilst I consider that appropriate chemistry controls have been identified to minimise the generation and transport of radioactivity in the primary circuit, further evidence is required in Step 3 to support the proposed operating ranges for the specific Rolls-Royce SMR design and its potassium chemistry. In particular on shutdown chemistry, insufficient detail has been presented to form a judgement on the adequacy of the information with respect to radioactivity minimisation. Additionally, (and as described in more detail later in section 4.2.1.4) the capability to perform ultrasonic fuel cleaning is included within the Rolls-Royce SMR design, however no further information was provided on how and when the procedure is expected to be carried out and hence any impact on radioactivity transport and minimisation. These are residual matters on which I will seek further information in Step 3.
4. There are additional aspects of relevance to the minimisation of radioactivity that are wider than the direct influence of the chemistry regime, such as the optimisation of cobalt containing hard facings and of trace cobalt levels in bulk materials, and the application of surface finishes to primary circuit materials. In these areas the safety case and underlying evidence will need to be generated across multiple discipline areas. I was unable to locate these areas of the case and any relevant claims from E3S chapter 20 and hence raised RQ-01284 to seek clarification. The RQ response explained that the cobalt inventory will be captured under the chapter 12 claim that the Rolls-Royce SMR source term is minimised (ref. [10]), and requirements concerning material selection and surface finish will be included in chapter 20 (ref. [57]). A new supporting report titled Minimisation of Radioactivity will be produced in Step 3 to support these claims, and the RP intends to perform a consolidation of the claims and arguments related to the minimisation of radioactivity across the E3S case prior to the start of Step 3 of GDA (ref. [57]). Whilst the RQ response provided some confidence that these multidiscipline aspects are being considered, I judge that the safety case in these areas is less well developed than the rest of the chemistry case at present. I will follow up this aspect of the overall demonstration that radioactivity is minimised as part of my Step 3 assessment.

#### Fuel cladding corrosion and fuel deposits

1. NS-TAST-GD-088 (ref. [30]) notes that a suitably considered chemistry programme should preserve the integrity of the fuel and limit the formation of deposits (crud) which could contribute to failures or limit the degradation rate to acceptable levels. During Step 2 of the GDA I sampled a submission on the minimisation of fuel cladding corrosion in this regard (ref. [43]).
2. The RP claims that the Rolls-Royce SMR chemistry regime has been optimised in order to reduce the risk of fuel cladding corrosion SFAIRP:

* Corrosion product deposition on fuel cladding is minimised SFAIRP;
* The reactor coolant pH is controlled through additions of potassium hydroxide, reducing the risk of fuel cladding corrosion SFAIRP;
* The redox potential in the reactor coolant is controlled in order to reduce fuel cladding corrosion SFAIRP; and
* The concentration of impurities in the reactor coolant and spent fuel pool is controlled in order to reduce fuel cladding degradation SFAIRP.

1. Due to its boron-free chemistry regime, the risk of Crud Induced Power Shift (CIPS) is removed in the Rolls-Royce SMR design. However, Crud Induced Localised Corrosion (CILC), where deposits on the fuel cladding surface can lead to enhanced cladding corrosion through temperature increase and accumulation of chemical species, is possible. In line with NS-TAST-GD-088, I expect the generation and accumulation of fuel deposits for a modern PWR design to be minimised SFAIRP, and for a robust quantification, characterisation and justification to be made during GDA of the fuel deposits expected in order to understand the risk of CILC occurring.
2. As described earlier in section 4.2.1, the expected pH range has been selected to minimise corrosion of primary circuit materials, which can lead to the formation of deposits on the fuel cladding surface and subsequent CILC. The control of pH is achieved with the addition of potassium hydroxide and a balance must be struck between achieving a high pH to prevent corrosion of primary circuit materials, and controlling the concentration of potassium hydroxide to avoid an environment that is aggressive toward the zirconium cladding material. The RP notes that a fuel vendor limit for potassium hydroxide has not yet been determined (ref. [43]). The RP presents literature data in a potassium hydroxide and boric acid chemistry which indicates that potassium hydroxide performs better than lithium hydroxide from the perspective of reducing fuel cladding corrosion. Further work is ongoing through the RP’s laboratory test programme to demonstrate this in a potassium chemistry without boron.
3. Controls on primary circuit oxygen concentration and on hydrogen addition to minimise fuel cladding corrosion are described, and a range of literature data and plant OPEX is also presented to support the expected operating ranges for relevant impurities, including silica and halides. Relevant species have been identified which should be controlled in the primary circuit in support of fuel integrity, and the operating ranges set out are in line with international guidance. However as noted earlier in section 4.2.1, further evidence will be required in Step 3 to support the proposed operating ranges for the specific Rolls-Royce SMR design and operating chemistry environment.
4. As described above, the RP intends to inject zinc into the primary circuit during normal operations to minimise radiation doses to operators. Zinc, in combination with silica, which may be present as an impurity, can concentrate in fuel deposits leading to reduced deposit porosity and increases in clad temperature which can enhance clad corrosion. Since zinc is more soluble in the presence of boric acid, this effect may be greater in the selected boron-free operating chemistry. Further information is required in Step 3 to understand the impact of this and to justify that the selected zinc concentration reduces the risk of fuel cladding corrosion SFAIRP.
5. The RP notes in the top-level chemistry submission that it expects the fuel deposit inventory to be relatively small in the Rolls-Royce SMR design, due to the materials choices and chemistry regime. To evidence this, it further explains in the source term strategy report (ref. [47]) that an activity transport model will be used to quantify the mass and composition of fuel deposits by simulating boiling based on a sub-cooled nucleate boiling rate derived using the Versatile Internals and Component Program for Reactors (VIPRE) code (a reactor core thermal-hydraulics analysis code). The results of this deposits estimate are expected to be submitted in Step 3 of GDA and the approach appears to meet the expectations set out in NS-TAST-GD-088.
6. The capability to perform ultrasonic fuel cleaning is included within the Rolls-Royce SMR design. However the response to RQ-01108 confirmed that no safety case claims are currently made on the use of fuel cleaning (ref. [57]) and no further information was provided on how and when the procedure is expected to be carried out. The RP notes in the top-level chemistry submission (ref. [15]) that since a number of factors affecting the fuel deposit inventory have not yet been finalised, such as the shutdown chemistry and the dosed zinc concentration, it is not currently known whether there is a need to perform fuel cleaning. A decision record which presents the rationale for the selected fuel cleaning technology was also submitted (ref. [58]), and presents a conflicting view, that complete ultrasonic cleaning of all partially spent assemblies which are returning to the RPV for the next cycle is required at each shutdown. Regardless, insufficient detail has been presented during Step 2 to understand the safety claims on the system and to form a judgement on whether its use reduces risks SFAIRP. This is a residual matter that I will follow up in Step 3 of the GDA.

#### Conclusion

1. Based on my sample, I judge that the selected chemistry regime generally follows RGP where it is available, and that the RP has identified appropriate species that should be controlled. The chemistry implications of adopting a boron-free potassium hydroxide primary circuit chemistry are well documented in the E3S case and initial evidence for these is presented. Further evidence is required in Step 3 to support the proposed operating ranges for the Rolls-Royce SMR and to justify that these operating practices reduce risks including dose to operators SFAIRP, however. Whilst the key aspects of this substantiation are reliant on the results of a laboratory test programme which is not expected to yield results until Step 3 of GDA, based on the initial evidence presented I have confidence that the RP will be able to further develop the necessary evidence to support this aspect of its E3S case.
2. On shutdown chemistry and fuel cleaning, insufficient detail has been presented to form a judgement on the adequacy of the information and I will seek further information in Step 3 on these residual matters.
   * 1. Secondary circuit chemistry
3. Secondary water chemistry control in a PWR is important in minimising corrosion damage and performance losses for all secondary system components and therefore to ensuring the safety, reliability and performance of the secondary systems. To achieve this objective, the water chemistry must be compatible with the many diverse systems that make up the secondary circuit.
4. The RP’s main claim on the secondary circuit chemistry of the Rolls-Royce SMR is that it is controlled in order to reduce corrosion in the water and steam system and subsequent transport of corrosion products into the steam generators, SFAIRP. The secondary chemistry regime consists of High-All Volatile Treatment (H-AVT) with ammonia for pH control, and addition of hydrazine to scavenge oxygen (Ref. [40]). Whilst the choice of alkaline agent has not yet been adequately justified with supporting evidence, the H-AVT regime is commonly encountered worldwide and at this stage of the assessment I consider this to be a reasonable approach that is consistent with the RGP described in SSG-13 (ref. [34]) and NS-TAST-GD-088 (ref. [30]). The RP states in its submission on minimisation of corrosion in the secondary circuit (Ref. [45]) that a change of alkaline agent, from ammonia to a mixed ammonia-ethanolamine regime in order to achieve better partitioning of alkalising agent into the condensate and a more consistently high pH, is being considered. I judge this to be an appropriate potential improvement to the secondary circuit chemistry choice for the RP to consider, and I will follow this aspect up in my Step 3 assessment.
5. Secondary circuit impurity control is maintained with the use of the SGPS during operations, along with hydrazine addition during start-up. The SGPS provides the capability for continuous blowdown of up to 1% of the main steam flow rate from the three steam generators, which the RP considers sufficient to maintain the secondary chemistry within specified limits. During normal operation, a single mixed bed ion exchange column will be aligned to remove ionic contaminants from the blowdown stream. A second column will remain on standby, for use during resin replacement in the duty column. At present, the sizing of the system is based on scaling of existing plant data with respect to blowdown flow rate. Whilst I judge the approach to impurity control to be appropriate and in line with common practice for PWRs, further development of the sizing of the system, including a demonstration that the chemistry specifications can be delivered by the design, is needed; I will follow this aspect up in my Step 3 assessment.
6. Additionally, a mobile condensate polishing system is described in the secondary circuit method of monitoring and control submission (ref. [46]), for use during start-up and in the event of a condenser leak. However, I note that the condensate polishing system is not included in the current design reference point (DRP) (ref. [59]); I will seek clarification of the claims on this system and its intended use as part of my Step 3 assessment.
7. A chloride ingress protection system, consisting of an alarm and manually operated isolation valve trip based on direct conductivity measurements, is claimed to provide protection against a condenser tube leak. The trip will close condensate and main feed valves and revert to auxiliary feedwater for the steam generators. I raised RQ-01155 to understand the timescales on which operator initiation of the system may be required in the event of a condenser leak. In response, the RP noted that the method of initiation of the chloride protection system during each action level will be subject to Allocation of Function assessment, led by Human Factors Engineers, with input from the chemistry team (ref. [57]). I will follow up on this matter and the relevant justifications during my Step 3 assessment.
8. The secondary circuit chemistry information that has been submitted is consistent with UK RGP and should enable the RP to further develop the generic Rolls-Royce SMR design and associated E3S case evidence.
   * 1. Materials selection
9. In line with SAP EAD.2, the effects of the chemical environment on materials properties, materials ageing and degradation processes should be considered and adequate margins should exist throughout the life of a facility to allow for these effects. For Step 2, I sought evidence that appropriate processes are in place to ensure that the requirements placed upon and expectations made of the operating chemistry are suitably considered when materials selection decisions are made.
10. Structural Integrity colleagues took the lead on assessing the case for the integrity of metallic components and structures, and therefore carried out a more in depth assessment of the RP’s materials selection methodology (ref. [60]). My assessment focussed on the consideration of the effects of the operating chemistry on susceptibility to material degradation mechanisms within the methodology, including in instances where integrity may not be threatened but corrosion is still important in terms of the impact on corrosion product and radioactivity transport.
11. In response to RQ-01108 on how the RP ensures that the chemistry environment is appropriately considered in the process of selecting a material (ref. [57]), the RP refers to the structured design optioneering process C3.2.2-2 (ref. [61]), which sits under process C3.2.1 for managing engineering activities (ref. [62]). I reviewed the two processes and judged that they present a logical decision making process that gives appropriate consideration to OPEX and RGP and to documented requirements. However, the methodology presented is a generic decision making process, and therefore lacks details of factors that I would expect to form part of materials selection decision making, such as explicit prompts for the consideration of particular degradation mechanisms and of the chemical environment.
12. The RQ response provides some further detail, noting that baseline water chemistry specifications have been set in support of the design development, including materials optioneering. These specifications are a specific input assumption to materials selection decisions and are communicated via the RP’s requirements management tool. Additionally, the RP’s gated review process for the design of SSCs mandates the involvement of key stakeholders. The RP notes that the chemistry team will be included as a stakeholder, if required, for a specific materials selection scenario. The output of the process is a materials selection decision record; examples of decision records which demonstrate chemistry involvement are not expected to be submitted for assessment until Step 3 of the GDA, since due to limited design maturity many materials selection decisions are yet to be made.
13. There is a key relationship between materials integrity and operating chemistry control and it is my expectation that control of chemistry should supplement materials selection, rather than materials choices resulting in significant demands on chemistry control; I judge that this consideration is appropriately reflected in the decision making process, albeit at a high level and with a dependence on the input of the chemistry team being sought when appropriate to do so. I will seek evidence of this being achieved as part of my Step 3 assessment.
14. To conclude, the RP has developed appropriate approaches which allow for consideration of the effects of and requirements upon the chemistry regime in making suitably justified materials selection decisions.

### Normal operation source term

1. The source term can be defined as the types, quantities and physical and chemical forms of the radionuclides present in a nuclear facility that have the potential to give rise to exposure to radiation, radioactive waste or discharges to the environment. The derivation of the radioactive source term is a fundamental part of understanding and therefore being able to control the hazards associated with any nuclear facility. ONR expects that the RP is able to demonstrate and justify that this source term is appropriate to be used as the basis for the safety case. Use of the normal operation source term, for example in dose calculations and in waste categorisation, is out of the scope of my assessment and is covered by the relevant discipline assessment (ref. [63], [64]).
2. I reviewed the Normal Operation Source Term Strategy Report (ref. [47]) which sets out the strategy for the derivation of the normal operation source term for the Rolls-Royce SMR, defining the scope of the source term and the RP’s principles for deriving and justifying it. The primary source term will consider the formation of radionuclides in the primary coolant in the reactor core and include fission products, corrosion products, activation products and actinides. The primary source term will then form the basis for other source terms, including the fuel deposits source term and the secondary system source term. Best estimate, design basis and cycle average values for each of the radionuclide groups will be derived.
3. The RP sets out a hierarchy of data sources which it will use to derive and justify the source term, with OPEX from analogous plants being prioritised over computer codes/models and calculation from first principles. The RP notes however that the approach taken will vary by radionuclide due to the availability of plant data (many more radionuclides are commonly included in a source term than are routinely measured on plant) and differences in the chemistry meaning that plant data is not available for all radionuclides. Information on how the RP will select OPEX and demonstrate its relevance to the design was not available in Step 2 of the GDA (except at the broad principles level); I will seek to review the RP’s process for OPEX selection during Step 3.
4. I also reviewed the Radionuclide Selection Report (ref. [48]) which provides the rationale and technical basis for why radionuclides have been selected for inclusion in the normal operation source term. An initial radionuclide list was produced from an analysis of international standards for source term development, including ANSI/ANS 18.1 (ref. [65]), alongside source term datasets from similar PWR designs. Additional radionuclides specific to the Rolls-Royce SMR design and chemistry, including potassium-40 and -42 were added. The radionuclide list was then screened based on number of appearances in the standards and datasets and then further sifted against a series of criteria relating to the end uses of the source term. I consider that the approach to radionuclide selection follows a logical process that appropriately considers RGP as well as the relevant design and operational differences applicable to the Rolls-Royce SMR.
5. Based on my sample, I am content with the high-level strategy for developing and justifying the source term and with the list of selected radionuclides. Further information on the detailed methodologies used for deriving the different parts of the source term will be required in Step 3. Whilst the OPEX-based source term is being derived, an interim dataset, based on the methodology outlined in ANSI/ANS 18.1, has been produced by the RP in order to facilitate initial end user analysis and to progress the design. These analyses will need to be updated as the OPEX-based source term is derived and justified.
6. In summary, the strategy for developing the normal operation source term is consistent with UK RGP and should enable the RP to further develop the generic Rolls-Royce SMR design and associated E3S case evidence.

### Accident chemistry

1. In line with SAP ECH.1 (ref. [19]) the safety case should, by applying a systematic process, address all chemistry effects important to safety. NS-TAST-GD-089 (ref. [31]) further explains that the scope of chemistry assessment is broader than just considering normal operations. Many approaches to accident analyses can make assumptions and/or specific claims on the relative importance of chemical phenomena in justifying acceptable levels of safety. These assumptions and/or claims should be appropriately justified in the safety case.
2. My assessment in this area focused on the RP’s demonstration that the risks associated with the three main accident topics (fission product chemistry, combustible gas chemistry, and core melt and in-vessel retention) will be appropriately modelled and adequately included in the safety case. The RP initially produced an accident chemistry strategy report that covered only the methodology for analysing the fission product chemistry aspects. This was redrafted later in Step 2 (ref. [37]) and now provides a suitable strategy to address all three of the main topics, describing how the key chemistry assumptions and/or claims which have a nuclear safety significance will be evaluated. The strategy also describes a reasonable claims structure relating to accident chemistry, and a strategy for how the safety case will be developed to present suitable underlying arguments and evidence.
3. On the basis of my sample of the RP’s accident chemistry strategy, I consider that the accident chemistry topic is developing satisfactorily, and that there are no fundamental gaps in the strategy. The analysis approaches identified by the RP for the various scenarios are likely to be reasonable from a chemistry perspective, subject to further development and justification. This area will be the subject of more detailed assessment in Step 3 of GDA.
4. IAEA SSG-13 notes that appropriate water chemistry control should be applied to minimise the risk and consequences of a loss of coolant accident resulting in the release of iodine radionuclides to the containment building. NS-TAST-GD-089 (ref. [31]) also refers to purposeful control (buffering) of the pH of in-containment water sources to mitigate the long-term release of iodine during some accident scenarios.
5. At the current DRP (DRP1), the Rolls-Royce SMR design does not include a means to purposefully control the pH of in-containment water sumps. In response to a RQ that I raised to understand the basis for this decision, the RP stated that additional analysis was required to support optioneering at DRP1, and therefore a decision on the inclusion or exclusion of engineered means to control pH could not be made at this stage (ref. [57]). The RP further explains that calculations are now in progress to determine the in-containment water pH and to inform whether a pH control system is required in the Rolls-Royce SMR design. Sensitivity analysis will be performed as part of this work, recognising uncertainties around dose rates resulting from accident scenarios, as well as source materials. The RP also noted that it considers the impact of including pH control in a future design iteration to be low risk.
6. Whilst I accept that the means to purposefully control the pH of in-containment water sumps can be a relatively simple system which could be straightforward to backfit to the design, I consider control of the pH of in-containment water sources to be established practice, and therefore RGP, for a PWR. I therefore expect a robust justification to be provided during GDA to support the RP’s position if it is to remain a position in which no purposeful pH control provision is included in the design. This is a residual matter that I will return to during my Step 3 assessment.
7. In summary, the information that has been submitted on the strategy for developing the accident chemistry aspects of the safety case is consistent with UK RGP and should enable the RP to further develop the generic Rolls-Royce SMR design and associated E3S case evidence. In respect to sump pH control, I have identified potential shortfalls against UK RGP and I will follow up in Step 3.

### Chemistry sampling and monitoring

1. Representative sampling and analysis carried out at an appropriate frequency is an important factor in the control of chemistry (and radiochemistry) for safety. SAP ECH.4, along with SSG-13 (ref. [34]), sets an expectation that adequate provisions are in place in the design to achieve this.
2. The RP makes a sub-claim under E3S chapter 20 (20.4.1) that sampling and monitoring systems are designed to provide representative data on the concentrations of chemical and radiochemical species within plant systems. Various high-level design considerations aimed at ensuring representative sampling are set out in the method of monitoring and control submissions for the primary (ref. [44]) and secondary (ref. [46]) circuit sampling systems, including minimisation of sample line length and ensuring appropriate flow rates through the sampling lines. Whilst I consider such measures to be in line with RGP for the design of such sampling systems (as described in ref. [31] and ref. [34]), I judge it necessary to sample evidence that the systems as designed can deliver the necessary information to control the chemistry; I will follow this aspect up as part of my Step 3 assessment.
3. A range of sampling measures aimed at ensuring the safety of the operator are also discussed, such as activity monitoring at the primary system sampling headers to detect primary circuit activity increase (ref. [44]), although I note that, due to the maturity of the system design, shielding calculations for the NSS were not yet available. I judge such measures to be appropriate fundamental considerations towards the delivery of safe sampling operations.
4. During Step 2, information was not available on the design and intended operation of the post-accident sampling capability of the NSS, nor on the intended sampling frequencies of chemistry parameters during normal operation and whether the design is capable of delivering these; I will follow these aspects up as part of my Step 3 assessment.
5. Additionally, limited information was available on the specific radiochemical parameters that the RP intends to monitor, for example to detect any primary to secondary steam generator leakage and to provide capability for the detection of failed fuel (ref. [39]). I will seek further information in this area as part of my Step 3 assessment.
6. From my sample, it is clear that the RP understands the importance of achieving representative chemistry sampling in order to generate the information required to appropriately control chemistry parameters that are important to safety. In addition, the information that has been submitted on chemistry sampling and monitoring is consistent with UK RGP and should enable the RP to further develop the generic Rolls-Royce SMR design and associated E3S case evidence. In respect to sampling and monitoring of radiochemical species important to safety, further information is required in Step 3 of the GDA.

### Reactor Island auxiliary system chemistry

1. I chose to sample the RP’s strategy for the control of SFP chemistry, since this is a key factor in preventing cladding corrosion of new and used fuel and in the minimisation of the spread of radioactivity arising from any failed fuel in the SFP.
2. The RP claims that the concentration of impurities are controlled in order to reduce corrosion SFAIRP, and further claims that the FPPS design minimises accumulation of radionuclides in the SFP SFAIRP (ref. [15]).
3. The SFP chemistry regime is similar to that of the primary circuit, in that it consists of potassium hydroxide addition for pH control, no soluble boron and minimisation of impurities (ref. [39]). E3S chapter 20 notes that no limits have been set on pH in the SFP since the shutdown chemistry is yet to be decided. Chloride, fluoride and sulfate are controlled in line with levels at similar plants to minimise corrosion of fuel assemblies, and diagnostic parameters are set to monitor turbidity and other impurities such as silica and suspended solids. Total activity will be controlled, however no limit is set at this stage. Whilst further work is required to justify limits and operating ranges (and to set these where currently missing), I judge that in general the RP has identified appropriate species to control in the SFP.
4. The generic design is such that a continuous flow of coolant is circulated through the FPPS in normal operation to purify the coolant and maintain the coolant activity within specified limits; these are specified as category C functional requirements. The FPPS consists of two purification trains which each contain a single mixed bed ion exchange column and a back washable filter. The flow rate with both trains in operation is such that the entire volume of the SFP is circulated twice through the purification equipment every 24 hours with both trains active. A single purification train will normally be online at any given time, with the capability to isolate the standby train for maintenance and resin replacement. The anion resin will be in the hydroxide form and the cation component in the potassium form to ensure that potassium is not removed from the coolant.
5. Whilst at this stage, detailed sizing of the ion exchange columns had not been performed, and evidence for the impact of the operating chemistry on the effectiveness of the clean-up system was not yet available, I am satisfied that the fundamental approach to purification of the SFP coolant is suitable and consistent with practices at similar plants.
6. I judge that the information that has been submitted on reactor island auxiliary system chemistry is consistent with UK RGP and should enable the RP to further develop the generic Rolls-Royce SMR design and associated E3S case evidence.
   * 1. Chemistry safety case
7. Chemistry SAP ECH.1 (ref. [19]) highlights ONR’s expectation that safety cases should identify and analyse how chemistry can impact safety in normal operations and fault conditions, with demonstration as to how chemistry is controlled. The initial step, of stating clearly the claims that are being made on chemistry for nuclear safety, is a particularly important step in developing the safety case and hence was the focus of my assessment of this area in Step 2 of the GDA. In addition, I considered the adequacy of the way in which the chemistry aspects of the case are structured, how the various chemistry documents support the E3S chemistry chapter, and the links between documents required to develop the case.
8. The structure of the safety chapters of the E3S case for the Rolls-Royce SMR design is broadly aligned to IAEA SSG-61 (ref. [35]), with the addition of further chapters aimed at directly addressing UK regulatory expectations. One of the additional chapters is “Chapter 20: Chemistry” and there are other additional chapters of relevance here, covering Structural Integrity and ALARP. In the UK context, it is considered to be RGP for new facilities to dedicate a specific section of the safety case to deal exclusively with reactor chemistry, and to provide links from that section to other relevant areas of the safety case where chemistry has an impact (ref. [30]). From a review of the E3S case structure for the Rolls-Royce SMR, I am broadly content that the case appropriately prioritises chemistry and that the structure provides for the recognition of the importance of chemistry to safety in line with this RGP. At the chapter level, I consider that the E3S case also provides appropriate links between chemistry information and the key chapters where chemistry interacts.
9. At the chapter level, I judge that the chemistry safety case identifies the areas that I would expect to see feature as part of a complete case, and it therefore has sufficient breadth; further development of the detailed evidence underpinning these areas (the depth) will be required as the case progresses. In most cases, appropriate claims and arguments are set out in the chemistry documentation where there is a safety impact. As noted in 4.2.1.3 for some claims, such as the minimisation of radioactivity, where the underlying evidence will be generated across multiple discipline areas, the safety case is less well defined. Further evidence is needed to demonstrate that these aspects of the case are being developed appropriately across disciplines. I will follow this up as part of my Step 3 assessment.
10. SAP SC.5 sets out the expectation that areas of uncertainty and optimism are identified in the safety case, and that a balanced view of the level of knowledge, understanding and resultant risk is presented. In the key areas of the chemistry case that deal with the novel aspects of the primary circuit chemistry, the RP acknowledges the lack of direct OPEX for the chosen chemistry regime to support safety case justifications relating to materials and fuel cladding integrity. As described in section 4.2.1.1, the RP has therefore presented a credible plan to generate additional data from laboratory testing, which it considers will demonstrate the relevance of the large body of OPEX from plants operating with lithium/boric acid chemistry to the Rolls-Royce SMR design. For this important aspect of the case, I judge that a balanced view is presented which identifies the further work needed to support the claims made and therefore I consider that the expectation in the SAP is met.
11. From my sample, I judge that the recently issued version 2 of the E3S case aligns with the information that I have assessed during Step 2. In general I consider that the current DRP (DRP1) aligns with the information that I have assessed, except for the condensate polishing system which, as noted earlier in my assessment, is not included in the current DRP. To conclude, the scope and structure of the chemistry safety case meet my expectations for this stage of the project, are consistent with UK RGP, and should enable the RP to further develop the E3S case evidence as it relates to chemistry.
    * 1. ALARP
12. Chemistry SAP ECH.2 (ref. [19]) outlines ONR’s expectations in circumstances where a change to one chemistry parameter to improve safety can be to the detriment of another hazard. The most appropriate chemistry regime will be a holistic balance between all of the safety aims, with due priority given to those which are the most relevant, likely to occur, and have the potential to lead to the largest consequences. The SAP expects an ALARP demonstration to be made, proportionate to the level of risk and hazard, where there are a number of chemistry options available. NS-TAST-GD-005 provides further guidance on what is expected of an ALARP demonstration (ref. [32]).
13. E3S chapter 20 contains a summary of the ALARP demonstration for chemistry which recognises the need to strike an appropriate balance between competing safety aims when developing the Rolls-Royce SMR chemistry regime. The chapter is supported by a number of underlying reports which discuss why chemistry parameters have been set on an individual topic basis and seek to justify the limits (refs. [41] [42] [43] [45]). At this stage, and subject to the provision of suitable additional evidence later in GDA, I consider that an appropriate balance between safety aims is achieved in the chosen chemistry regime. The justification for this is described in the safety case to an extent commensurate with that expected at this stage of GDA, and is in line with NS-TAST-GD-051 (ref. [33]), which explains that a safety case should explicitly set out the argument for why risks are ALARP.
14. E3S chapter 20 also refers out to a number of decision records which discuss the detailed evaluation of options for key chemistry decisions, including the selection of potassium hydroxide as the alkalising agent and the decision not to use soluble boron for reactivity control (refs. [66] and [38]). The optioneering performed so far has focussed on the most novel and safety significant aspects of the chemistry case, which I consider to be an appropriate approach.
15. Whilst at this stage the ALARP demonstration for chemistry is still developing, I am satisfied that the approach meets RGP and should enable the RP to further develop the E3S case evidence as it relates to chemistry.

# Conclusions

* 1. Conclusions

1. This report presents the Step 2 chemistry assessment for the GDA of the Rolls-Royce SMR design. The focus of my assessment in this step was towards the fundamental adequacy of the design and safety case. I have assessed the Tier 1 E3S chapters and relevant supporting documentation provided by Rolls-Royce SMR Limited to form my judgements. I targeted my assessment, in accordance with my assessment plan (ref. [23]), at the content of most relevance to chemistry against the expectations of ONR’s SAPs, TAGs and other guidance which ONR regards as RGP.
2. Based upon my assessment, I have concluded the following:

* In general, the scope, structure and content of the E3S case meet my expectations for this stage of GDA from a chemistry perspective. Further work will need to be undertaken in Step 3 of GDA by the RP to develop the underlying evidence supporting the chemistry claims and arguments.
* The major chemistry parameters, which would be expected to form part of the plant operating rules, have in most cases been defined. Further work will need to be undertaken in Step 3 of GDA by the RP to develop the justification for the normal operating envelope and associated limits.
* The chemistry implications of adopting a boron-free potassium hydroxide primary circuit and SFP chemistry are well documented in the E3S submissions, except for those aspects relating to shutdown chemistry. Relevant benefits, including a reduction in tritium production, are identified and initial evidence for these is presented. However, further justification is required to substantiate a number of related claims. Whilst key aspects of this substantiation are reliant on the results of a laboratory test programme which is not expected to yield results until Step 3 of GDA, based on the initial evidence presented I have confidence, at this stage, that the RP will be able to further develop the necessary evidence to support this important aspect of the E3S case. Insufficient information was provided by the RP during Step 2 to enable me to form a judgement on the feasibility and implications of the shutdown chemistry approach; this is a residual matter on which I will seek further information early in Step 3.
* Whilst I consider that appropriate chemistry controls have been identified to minimise the generation and transport of radioactivity in the primary circuit, further evidence is required in Step 3 to support the proposed operating ranges for the specific Rolls-Royce SMR design; Further to this, on shutdown chemistry and fuel cleaning, insufficient detail has been presented to form a judgement on the adequacy of the information; these are residual matters on which I will seek further information in Step 3.
* A suitable strategy has been developed by the RP through which it will seek to demonstrate that the effects of chemistry during fault and accident conditions are understood and that risks are reduced SFAIRP. A robust justification will need to be provided during Step 3 to support the RP’s current position that no purposeful sump pH control provision is included in the design, however. This is a residual matter that I will follow up in Step 3.

1. Overall, based on my assessment to date, and subject to the provision and assessment of suitable and sufficient supporting evidence, I have not identified any fundamental safety shortfalls that could prevent ONR permissioning the construction of a power station based on the generic Rolls-Royce SMR design.
   1. Recommendations
2. My recommendations are as follows:

* Recommendation 1: ONR should consider the outcomes from my assessment as part of the decision to progress to Step 3 of GDA for the generic Rolls-Royce SMR design.

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# Appendix 1 – Relevant SAPs considered during the assessment

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| SAP No. | SAP Title |
| ECH.1 | Engineering principles: chemistry – Safety cases |
| ECH.2 | Engineering principles: chemistry – Resolution of conflicting chemical effects |
| ECH.3 | Engineering principles: chemistry – Control of chemistry |
| ECH.4 | Engineering principles: chemistry – Monitoring, sampling and analysis |
| EHT.4 | Engineering principles: heat transport systems – Failure of heat transport system |
| EHT.5 | Engineering principles: heat transport systems – Minimisation of radiological doses |
| EAD.2 | Engineering principles: ageing and degradation – Lifetime margins |
| SC.5 | The regulatory assessment of safety cases – Optimism, uncertainty and conservatism |