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## 21.1 List of Abbreviations and Acronyms

ABWR	Advanced Boiling Water Reactor
ALARP	As Low As Reasonably Practicable
ADG	Feedwater Deaerating Tank and Gas Stripper System [FDTGSS]
AP1000	Advanced Passive pressurised water reactor
APG	Steam Generator Blowdown System [SGBS]
ASTEC	Accident Source Term Evaluation Code
ATE	Condensate Polishing System [CPS]
AVT	All Volatile Treatment
BAT	Best Available Techniques
BOC	Beginning of Cycle
CDM	Construction (Design and Management)
CEX	Condensate Extraction System [CES]
CFD	Computational Fluid Dynamics
CGN	China General Nuclear Power Corporation
CIPS	Crud Induced Power Shifts
CPR1000	Chinese Pressurised Reactor
CRDM	Control Rod Drive Mechanism
CRUD	Chalk River Unidentified Deposit
DBC	Design Basis Condition
DDT	Deflagration-Detonation-Translation
DEC	Design Extension Condition
DEC-A	Design Extension Condition A
DEC-B	Design Extension Condition B
DEL	Safety Chilled Water System [SCWS]
DER	Operational Chilled Water System [OCWS]
EPR	European Pressurised Reactor

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DWN	Nuclear Auxiliary Building Ventilation System [NABVS]
EBA	Enriched Boric Acid
EHR	Containment Heat Removal System [CHRS]
EUF	Containment Filtration and Exhaust System [CFES]
EUH	Containment Combustible Gas Control System [CCGCS]
FAC	Flow-Accelerated Corrosion
GDA	Generic Design Assessment
HFT	Hot Functional Test
HPR1000 (FCG3)	Hua-long Pressurised Reactor under Construction at Fangchenggang nuclear power plant unit 3
IAEA	International Atomic Energy Agency
IGA	Intergranular Attack
IRWST	In-containment Refuelling Water Storage Tank
IVR	In-Vessel Retention
KRH	Nuclear Island Hydrogen Detection System [HDS]
LHSI	Low Head Safety Injection
LOCA	Loss of Coolant Accident
MCL	Main Coolant Line
MSR	Moisture Separator Reheater
NI	Nuclear Island
OPEX	Operation Experience
PAR	Passive Autocatalytic Recombiner
PCER	Pre-Construction Environment Report
PCSR	Pre-Construction Safety Report
PTR	Fuel Pool Cooling and Treatment System [FPCTS]
PWR	Pressurised Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
PZR	Pressuriser

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RBS	Emergency Boration System [EBS]
RCCA	Rod Cluster Control Assembly
RCC-M	Design and Construction Rules for Mechanical Components of PWR Nuclear Islands
RCP	Reactor Coolant System [RCS]
RCV	Chemical and Volume Control System [CVCS]
REA	Reactor Boron and Water Makeup System [RBWMS]
REN	Nuclear Sampling System [NSS]
RGP	Relevant Good Practice
RHR	Residual Heat Removal
RIS	Safety Injection System [SIS]
RPE	Nuclear Island Vent and Drain System [VDS]
RPV	Reactor Pressure Vessel
RRI	Component Cooling Water System [CCWS]
RVI	Reactor Vessel Internals
SAP	Safety Assessment Principle (UK)
SCC	Stress Corrosion Cracking
SED	NI Demineralised Water Distribution System [DWDS(NI)]
SER	CI Demineralised Water Distribution System [DWDS(CI)]
SFC	Single Failure Criteria
SFP	Spent Fuel Pool
SG	Steam Generator
SIH	NI Chemical Reagents Distribution System [CDS]
SIR	Chemical Reagents Injection System [CRIS]
SIT	Feedwater Chemical Sampling System [FCSS]
SSC	Systems, Structures and Components
TAG	Technical Assessment Guide (UK)
TEG	Gaseous Waste Treatment System [GWTS]

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TEP	Coolant Storage and Treatment System [CSTS]
TEU	Liquid Waste Treatment System [LWTS]
TSP	Tri-Sodium Phosphate
UK HPR1000	UK version of the Hua-long Pressurised Reactor
VCT	Volume Control Tank
WENRA	Western European Nuclear Regulators Association
WANO	World Association of Nuclear Operation

System codes (XXX) and system abbreviations (YYY) are provided for completeness in the format (XXX [YYY]), e.g. Extra Cooling System (ECS [ECS]).

## 21.2 Introduction

The purpose of this Pre-Construction Safety Report (PCSR) Chapter 21 is to demonstrate that the design of reactor chemistry is substantiated according to the *General Safety Requirement*, Reference [1], This chapter also provides support to the production of the safety case for the UK version of the Hua-long Pressurised Reactor (UK HPR1000), which is developed based on the reference plant of Hua-long Pressurised Reactor under Construction at Fangchenggang nuclear power plant unit 3 (HPR1000 (FCG3)).

The present safety case of the reactor chemistry is produced based on the design reference version 2.1, as described in the UK HPR1000 Design Reference Report, Reference [2] (Rev E). The safety assessment results are documented in this chapter and corresponding safety assessment reports.

### a) Scope

According to the Generic Design Assessment (GDA) scope document, Reference [3], the scope of the reactor chemistry covers the following aspects:

- 1) Demonstration and justification of the effects of the coolant chemistry on:
  - Reactivity control;
  - Pressure boundary integrity;
  - Fuel and core component integrity;
  - Out of core radiation fields;
  - Waste generation;
  - Fuel crud accumulation;
  - Principles applicable to commissioning and cleaning of the plant.



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- 2) Chemistry effects on Design Basis Condition (DBC) and Design Extension Condition (DEC), including:
  - Physic-chemical phenomena in the analysis of accident source terms;
  - Combustible gas control;
  - Impact of In-Vessel Retention (IVR).
- 3) Definition of the UK HPR1000 chemistry regime for primary, secondary and auxiliary water systems important to safety, which will be focused on:
  - The limits and conditions will be demonstrated in the supporting documents;
  - Risks are minimised As Low As Reasonably Practicable (ALARP) overall considering the balance with other areas.
- 4) Substantiation of chemistry related systems, detailed information in the supporting documents, including:
  - Chemistry monitoring and sampling systems;
  - Chemistry control systems for maintaining chemistry and radiochemistry parameters within the defined limits and conditions.
- 5) Exclusion for GDA chemistry scope, including:
  - Detailed specification and action levels for all of control parameters;
  - Detailed system design of zinc injection;
  - Chemicals management.

b) Approach

The chemistry objectives for the UK HPR1000 are derived from the fundamental functions described in Reference [1]. Chapter 21 is demonstrated under three aspects: primary system, secondary system, and auxiliary systems. The essential safety requirements of the chemistry limits and conditions in each system are identified, and chemistry provisions are demonstrated as the function requirements of the various mechanical systems. The design and operation requirements to the main chemistry functions are discussed in each case to demonstrate that function requirements are substantiated with evidence to justify arguments that the safety functions of the chemistry have been met during all operating modes. Sampling and monitoring are used to provide the information for the chemistry systems to deliver the requirements.

The chemical aspects of accident scenarios, the potential hazards and mitigation measures are included in the specific sub-chapter to present how the chemistry strategy in such situations supports the overall safety claims of the plant.

In summary, the safety case with its supporting documents demonstrates that the

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UK HPR1000 reactor chemistry design reduces risks ALARP.

c) Definition

The chemical or radiochemical parameter is an indicator which enables to characterise the chemical or radiochemical state of the fluid in relevant system during the different operating phases. According to the PCSR Sub-chapter 31.5.2, two categories of parameters are used:

- 1) Control parameters: the parameters which play an important role in material integrity or fuel integrity, and require strict control;
- 2) Diagnostic parameters: the parameters which may affect radiation field build-up, corrosion of system materials, or fuel performance, and assist the chemistry staff in interpreting chemistry variations.

Safety case focuses on the control parameters associated with the chemical and radiochemical values including:

- 1) Hard limits (outermost limits) corresponding to control parameters, which are used as inputs or as initial conditions in fault studies;
- 2) Operating window (expected range) corresponding to control parameters, which are used as inputs into the design process.

### 21.2.1 Chapter Route Map

The ***Fundamental Objective*** of UK HPR1000 is: *The Generic UK HPR1000 could be constructed, operated, and decommissioned in the UK on a site bounded by the generic site envelope in a way that is safe, secure and that protects people and the environment.*

To underpin this objective, five high level claims and a number of level 2 claims are developed and presented in Chapter 1. Chapter 21 supports the ***Claim 3.3*** derived from the high level ***Claim 3***.

***Claim 3: Nuclear safety***

*The design and intended construction and operation of the UK HPR1000 will protect the workers and the public by providing multiple levels of defence to fulfil the fundamental safety functions, reducing the nuclear safety risks to a level that is ALARP.*

***Claim 3.3:*** *The design of the processes and systems has been substantiated and the safety aspects of operation and management have been substantiated.*

***Claim 3.3.10:*** *The chemistry aspects of the plant design have been developed to reduce the nuclear safety risk ALARP.*

To support ***Claim 3.3.10***, the following sub-claims for Chapter 21 have been

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developed based on the risks management process:

*Sub-claim 3.3.10.SC21.1: The requirements for chemistry important to nuclear safety have been derived in all operating modes and fault conditions.*

*Sub-claim 3.3.10.SC21.2: The design is substantiated against the requirements for chemistry important to nuclear safety in all operating modes and fault conditions.*

*Sub-claim 3.3.10.SC21.3: The design for chemistry regimes minimises the negative impact of radiation and chemicals on workers, public, plant and environment to levels that are ALARP in all operating modes and fault conditions.*

*Sub-claim 3.3.10.SC21.4: The ageing effects of the chemistry related systems important to nuclear safety have been addressed by selection of an optimum chemistry regime.*

According to the ONR Technical Assessment Guide (TAG), Reference [4], the trail from safety claims through arguments to evidences shall be clearly set out in the safety case. Chapter 21 is not produced in the form of a strict Claim-Argument-Evidence structure. However, a Route Map intending to set out a "direction of moving forward" for Chapter 21 is identified and presented in Appendix 21A, and it is still in the development during the whole GDA.

### 21.2.2 Chapter Structure

The structure of Chapter 21 is shown in T-21.2-1.

T-21.2-1 Structure of Chapter 21

Sub-chapter	Title	Content Introduction
21.1	List of Abbreviations and Acronyms	List of the abbreviations, acronyms that are used in Chapter 21.
21.2	Introduction	General introduction of chapter structure, scope, interfaces with other topics, and claims development.
21.3	Applicable Codes and Standards	Codes and guidelines used for chemistry.
21.4	Primary Water Chemistry and Associated Systems	<ul style="list-style-type: none"> <li>The technical basis for the chemistry regime, including material selection and circuit description;</li> </ul>
21.5	Secondary Water Chemistry and Associated Systems	<ul style="list-style-type: none"> <li>Chemistry control method, including the chemistry regimes and provisions;</li> <li>Substantiation of systems, including the</li> </ul>

<b>Sub-chapter</b>	<b>Title</b>	<b>Content Introduction</b>
21.6	Auxiliary Water Chemistry and Associated Systems	function, design and operation requirement.
21.7	Accident Chemistry and Associated Systems	Three parts related to accident chemistry as below: <ul style="list-style-type: none"> <li>• Fission product control;</li> <li>• Combustible gas control;</li> <li>• Core melt and corium retention.</li> </ul>
21.8	Sampling and Monitoring	<ul style="list-style-type: none"> <li>• The sampling arrangement and control parameters;</li> <li>• Justify that Nuclear Sampling System (REN [NSS]) and Feedwater Chemical Sampling System (SIT [FCSS]) can monitor the control parameters to ensure safety operation of the systems.</li> </ul>
21.9	ALARP Assessment	Provides the Relevant Good Practice (RGP), e.g. International Atomic Energy Agency (IAEA) safety guide and Operation Experience (OPEX) to support the ALARP case.
21.10	Concluding Remarks	
21.11	References	

### 21.2.3 Interfaces with other Chapters

Chapter 21 directly interfaces with other relevant PCSR Chapters. These chapters, and a description of the interfaces with Chapter 21 are presented in T-21.2-2.

#### T-21.2-2 Interfaces between Chapter 21 and Other Chapters

<b>Chapter</b>	<b>Interface</b>
Chapter 1 Introduction	Chapter 1 provides the fundamental objective, Level 1 Claims and Level 2 Claims. Chapter 21 provides chapter claims, arguments to support relevant claims that are addressed in Chapter 1.
Chapter 4	Chapter 4 provides selection principles of applicable codes

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<b>Chapter</b>	<b>Interface</b>
General Safety and Design Principles	and design principles. Chapter 21 provides codes and guidelines applied in chemistry.
Chapter 5 Reactor Core	Chapter 5 provides design requirements for the fuel and core, and the concentration of boron with fuel burnup. Chapter 21 provides the chemistry regime for the integrity of fuel cladding.
Chapter 6 Reactor Coolant System	Chapter 6 provides system design parameters of the primary coolant. Chapter 21 provides the water chemistry limits for the primary coolant.
Chapter 7 Safety Systems	Chapter 7, 10 and 11 present system design information. Chapter 21 provides information on the chemistry control and sampling requirement supported by the related systems.
Chapter 10 Auxiliary Systems	
Chapter 11 Steam and Power Conversion System	
Chapter 12 Design Basis Condition Analysis	Chapter 12 and its supporting documents provide accident analysis of DBC events, including chemical effects on fission product control, combustible gases control. Chapter 21 contains a description of the chemical effects that relate to DBC events.
Chapter 13 Design Extension Conditions and Severe Accident Analysis	Chapter 13 and its supporting documents provide accident analysis of Design Extension Condition A (DEC-A) and Design Extension Condition B (DEC-B) events, including chemical effects on fission product control, combustible gases control, core melt and retention. Chapter 21 contains a description of the chemical effects that relate to DEC-A and DEC-B events.
Chapter 17 Structural Integrity	Chapter 17 provides the constructive materials selection and degradation demonstration. Chapter 21 presents the chemistry effects on the assessment of ageing and degradation of materials.

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<b>Chapter</b>	<b>Interface</b>
Chapter 22 Radiological Protection	Chapter 22 provides the definition of radioactive sources for the UK HPR1000 and covers the various source terms present during normal operation. Chapter 21 provides optimum reactor chemistry controls to minimise the source term.
Chapter 23 Radioactive Waste Management	Chapter 23 provides the detailed treatment process and the strategy for the management of radioactive waste, and Chapter 24 provides the decommissioning strategy.
Chapter 24 Decommissioning	Chapter 21 provides optimum reactor chemistry controls to minimise the source term, which is beneficial for the treatment systems and decommissioning.
Chapter 25 Conventional Safety and Fire Safety	Chapter 25 provides the hazardous substances and explosive hazard management techniques and general prevention measures in the reactor chemistry area.
Chapter 28 Fuel Route and Storage	Chapter 28 covers the fuel cooling and the control of criticality during fuel handling and storage operations. The water quality of coolant in the reactor pool and spent fuel pool is included in Chapter 21.
Chapter 30 Commissioning	Chapter 21 provides the objectives for commissioning from the chemistry and material aspects. Chapter 30 provides the arrangements and requirements for commissioning according to these objectives.
Chapter 31 Operational Management	Chapter 21 provides the chemistry limits. Chapter 31 provides the arrangements for chemistry specification identified from reactor chemistry.
Chapter 33 ALARP Evaluation	Chapter 21 demonstrates that the chemistry aspects of the plant design have been optimised to reduce risks ALARP, which supports the overall ALARP demonstration addressed in Chapter 33.

### **21.3 Applicable Codes and Standards**

The codes and standards applied to reactor chemistry comply with the Chinese and the UK requirements of applicable laws (acts), regulations and other statutory instruments as described in the *General Principles for Application of Laws, Regulations, Codes and Standards*, Reference [5]. The codes and standards used for the design and assessment of the UK HPR1000 are adopted following the selection principles and the

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selection process described in Chapter 4, which considers the scope of application, degree of familiarity, application in practical engineering and relationship with the reference plant. After the selection process and the suitability analysis, the applicable codes and standards can be adopted, and their applicability and adequacy can be ensured. The list is provided in the T-21.3-1.

The design of the reactor chemistry for the UK HPR1000 is developed based on the reference plant for the HPR1000 (FCG3), in accordance with international standards, consideration for UK expectations and taking into account continuous feedback from the Chinese Pressurised Reactor (CPR1000) and other Pressurised Water Reactor (PWR) units worldwide.

The topic of reactor chemistry implements the following requirements to all aspects of the design and processes:

a) UK Acts and Regulations:

- 1) *The Health and Safety at Work etc. Act 1974*, Reference [6];
- 2) *The Construction (Design and Management) (CDM) Regulations 2015*, Reference [7];
- 3) *The Management of Health and Safety at Work Regulations 1999*, Reference [8];
- 4) *The Ionising Radiations Regulations 1999 (IRRs), 1999 No.3232*, Reference [9];

The design of the UK HPR1000 shall ensure that foreseeable conventional health and safety risks to the workers and the public are identified. The risk assessment shall take into account conventional health and safety in the design of the UK HPR1000 and the design provisions shall be developed to reduce and control risks ALARP.

The conventional health and safety risks are analysed in the design of chemistry related systems. The information on these risks is recorded in the conventional health and safety design risk registers, which are regarded as live documents and will be continually developed throughout the lifetime of the design.

- b) Considering the *Safety Assessment Principle (SAP)* and TAGs for *Chemistry of operating civil nuclear reactor (NS-TAST-GD-088)* and for *Chemistry Assessment (NS-TAST-GD-089)*, Reference [10], [11] and [12] respectively.
- c) Complying with the IAEA safety standards (relevant items are listed in T-21.3-1. The chemistry objectives are:
  - 1) Reactivity control by the neutron poisoning from boron;
  - 2) Integrity of fuel cladding and Systems, Structures and Components (SSC);

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- 3) Minimisation of radioactive waste generation and radiological doses to workers and the public.
- d) Consider some chemistry related issues of Western European Nuclear Regulators Association (WENRA), Reference [13], such as design basis envelope, operational limits and conditions, ageing management, accidents, radiation protection and waste management.
- e) Incorporate OPEX from international association including IAEA, World Association of Nuclear Operation (WANO) and based on learning from previous Generic Design Assessment (GDA), including European Pressurised Reactor (EPR), Advanced Passive pressurised water reactor (AP1000), and Advanced Boiling Water Reactor (ABWR).
- f) Analyse the codes and standards used in reference plant design.

According to the applicable analysis of the UK HPR1000 design, the suitability of codes and standards is demonstrated in the *Suitability Analysis of Codes and Standards*, Reference [14]. It is important to note that more up to date revisions may impact on the current design, and this will need to be considered in the nuclear site licensing phase.

T-21.3-1 Applicable Codes and Standards for Chapter 21

<b>Standards Number</b>	<b>Version</b>	<b>Title</b>	<b>Application for the UK HPR1000 Design</b>
IAEA Safety Standards, No. SSG-13	2011	<i>Chemistry Programme for Water Cooled Nuclear Power Plants, Specific Safety Guide</i> , Reference [15]	Adopted for chemistry programme
IAEA Safety Standards, No. SSR-2/1	2016	<i>Safety of Nuclear Power Plants: Design, Specific Safety Requirements</i> , Reference [16]	Adopted for safety assessment principles
IAEA Safety Standards, No. SSR-2/2	2016	<i>Safety of Nuclear Power Plants: Commissioning and Operation, Specific Safety Requirements</i> , Reference [17]	Adopted for commissioning and operation chemistry
IAEA Safety Standard, No. NS-G-1.9	2004	<i>Design of the Reactor Coolant and Associated Systems in Nuclear Power Plants</i> , Reference [18]	Adopted for chemistry related system design substantiate



<b>Standards Number</b>	<b>Version</b>	<b>Title</b>	<b>Application for the UK HPR1000 Design</b>
IAEA Safety Standards, No. NS-G-2.2	2005	<i>Operational Limits and Conditions and Operating Procedures for Nuclear Power Plants</i> , Reference [19]	Adopted for defining the operating limits for chemistry
IAEA Safety Standards, No. NS-G-1.12	2005	<i>Design of the Reactor Core for Nuclear Power Plants. Safety Guide</i> , Reference [20]	Adopted for enriched boric acid for reactivity control
PO&C	2013	<i>WANO Performance Objective And Criteria</i> , Reference [21]	Adopted for chemistry objective

## 21.4 Primary Water Chemistry and Associated Systems

To achieve the safety requirements claimed in Sub-chapter 21.2, a primary water chemistry control strategy aimed at maintaining chemistry regime in the primary circuit within specified ranges has been developed. This covers the primary circuit scope, material selection, chemistry regime, provision, and substantiation of associated systems.

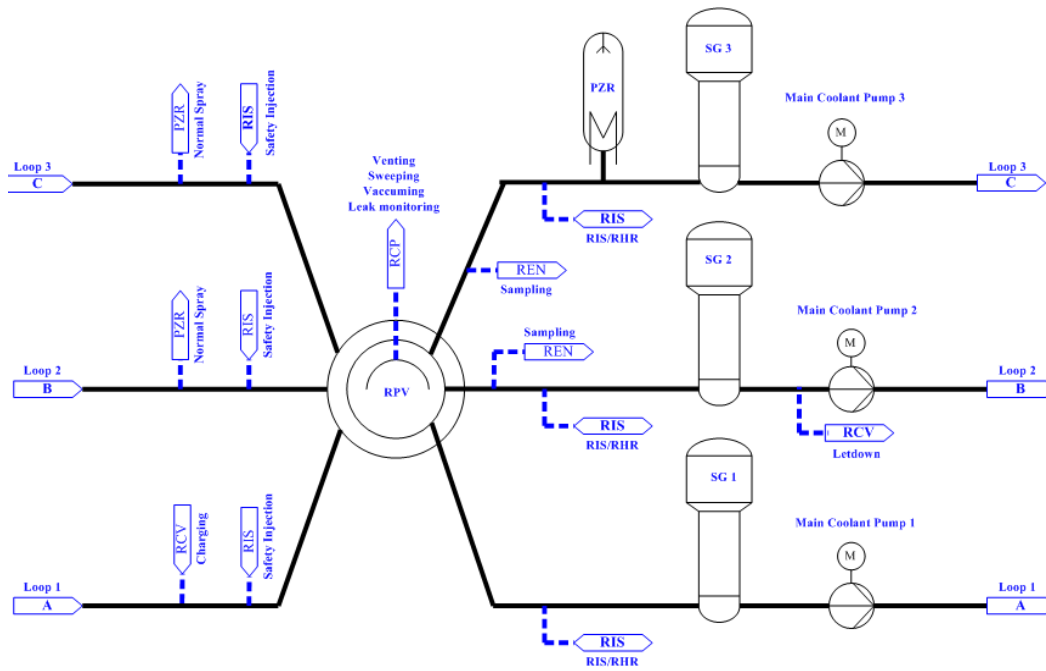
### 21.4.1 Description of Primary Circuit

The primary coolant of Reactor Coolant System (RCP [RCS]) is conditioned in order to control reactivity, limit corrosion and reduce the radioactivity in the primary circuit. The RCP [RCS] consists of the Reactor Pressure Vessel (RPV), Steam Generator (SG), Pressuriser (PZR), reactor coolant pump and Main Coolant Line (MCL). A simplified diagram of the main loops is shown in F-21.4-1. Further detailed information is described in the Sub-chapter 6.4.5.

According to the *Main Design Technical Parameters*, Reference [22], the basic design parameters of RCP [RCS] are shown in the T-21.4-1.

T-21.4-1 Basic Design Parameters of RCP [RCS]

<b>No.</b>	<b>Parameter</b>	<b>Unit</b>	<b>Values</b>
1	Design temperature	°C	343
2	RPV inlet temperature	°C	289.5
3	RPV outlet temperature	°C	324.5
4	RPV Coolant Average Temperature (100%FP)	°C	307
5	Average Refuelling Cycle Length	Months	18



F-21.4-1 Simplified Diagram of RCP [RCS] Main Loops

### 21.4.2 Material Selection

Material selection of the fuel cladding and other SSC of primary circuit are commensurate with the *Sub-claim 3.3.10.SC21.3* in terms of the following two main design objectives:

- The corrosion leading to degradation of fuel cladding and other SSC of primary circuit shall be controlled by chemistry regime in all operating modes and fault conditions;
- Radioactive inventory and release shall be controlled by chemistry regime and judicious material selection at source.

#### 21.4.2.1 Material Selection Principle

Material selection of the UK HPR1000 takes account of decades of experience in the design, construction, operation and decommissioning of relevant PWRs which mainly include CPR1000 (China), HPR1000 (FCG3) and other PWRs worldwide. The material selection of metallic SSC in the UK HPR1000 is based on the *Material Selection Methodology*, Reference [23].

Compatibility with the full range of reactor chemistry conditions over the plant design life is a key principle for material selection. This includes reducing elements in materials that can become activated and minimising the corrosion products.

A number of material selection reports for specific components have been established, including the RPV, SG, PZR, RVI and MCL. The material selection report for the

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reactor coolant pump, as well as other representative lower class SSC will be issued in step 4.

#### 21.4.2.2 Minimising Activated Elements

In the UK HPR1000, all elements in the materials contacting with the reactor coolant are evaluated from the activity minimisation point of view, and some elements which have significant contribution to the radioactive dose rate needs to be strictly controlled. According to the *Report of Radionuclide Selection during Normal Operation*, Reference [24], these elements mainly include cobalt, silver, antimony and nickel.

##### a) Cobalt element

###### 1) Cobalt content in metals

For materials in contact with the reactor coolant in the UK HPR1000, the cobalt content is controlled to levels that meet as a minimum the requirements of applicable codes and standards. In addition, the cobalt content of the material is required to be no more than those used in PWRs built by China General Nuclear Power Corporation (CGN), and will as a minimum be comparable to those used in other PWR plants worldwide either operating or in construction. For example:

- The cobalt content of stainless steel base metal in contact with the reactor coolant in the UK HPR1000 is no more than 0.10% ( $\text{Co} \leq 0.20\%$  in Design and Construction Rules for Mechanical Components of PWR Nuclear Islands (RCC-M)).
- Particularly, the cobalt content of the Reactor Pressure Vessel (RPV) internals in the high neutron flux region is no more than 0.06% ( $\text{Co} \leq 0.20\%$  in RCC-M).
- For stainless steel welding metal of corrosion resistance cladding and welds contacting reactor coolant, the cobalt content is no more than 0.050% ( $\text{Co} \leq 0.20\%$  in RCC-M).
- The cobalt content of nickel based alloy is no more than 0.06% ( $\text{Co} \leq 0.10\%$  in RCC-M).
- Particularly, for Alloy 690TT (Thermal Treated) of SG tubes, the cobalt content is no more than 0.015%.
- For nickel based alloy welding metal of claddings contacting reactor coolant, the cobalt content is less than or equal to 0.050% ( $\text{Co} \leq 0.20\%$  in RCC-M). For nickel based alloy buttering and welds, the cobalt content is less than 0.06% ( $\text{Co} \leq 0.20\%$  in RCC-M).

###### 2) Cobalt based alloys

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Cobalt based alloy (e.g. Stellite<sup>®</sup>), is a type of cobalt-chromium-tungsten alloy designed for wear resistance, which displays outstanding hardness and corrosion resistance. However, the application of cobalt based alloys in the UK HPR1000 is strictly limited to components where a material with sufficient hardness at high temperature, and high resistance on wear, erosion, flaking and corrosion during operation is required to ensure the safety requirements notably in terms of wear resistance throughout the service lifetime of those parts. Such components include wear resisting parts of the Control Rod Drive Mechanism (CRDM), Reactor Vessel Internals (RVI) and some valves. The application of cobalt based alloys in CRDM and RVI has already been reduced to level comparable to other designs. The detailed information is presented in the *Topic Report on Application of Cobalt Based Alloys in SSCs* Reference [25]. For valves, the detailed information is presented in the *Application Analysis of Cobalt based Alloy in Valves*, Reference [26].

b) Silver element

Silver is strictly limited in materials used in the UK HPR1000. In the reference plant of HPR1000 (FCG3), silver is only incorporated in the RPV seal gasket and the letdown heat exchanger in the Chemical and Volume Control System (RCV [CVCS]). But in the UK HPR1000, the structure of the heat exchanger in the RCV [CVCS] is improved with the elimination of silver coated seal gaskets.

Within the reactor, silver is also used in the absorber rods of the Rod Cluster Control Assembly (RCCA), Detailed information is described in the *HARMONI™ RCCA - Description, Functional Requirements and Materials Properties*, Reference [27].

c) Antimony element

In the UK HPR1000, antimony is not permitted in components within the primary circuit except in the secondary neutron sources. Detailed information is described in the *SCCA - Description, Functional Requirements and Materials Properties*, Reference [28].

d) Nickel element

The nickel element is a vital element of nickel based alloy and austenitic stainless steel used in SSC in contact with primary coolant. It is not possible to replace nickel with an alternative element for nickel based alloys and austenitic stainless steels used in the UK HPR1000. However, its release rate (corrosion rate) is very low due to these materials' corrosion-resistant characteristics and surface finishing, as well as controlled water chemistry regime.

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### 21.4.2.3 Corrosion Control

The materials of SSC of primary circuit in contact with reactor coolant are Alloy 690TT and austenitic stainless steels, which are proven materials, used successfully in existing PWRs, and are highly resistant to various types of corrosion under reactor chemistry conditions.

#### a) General corrosion

General corrosion causes uniform surface loss of the materials in the primary circuit. It can occur in high temperature and water condition. The influencing factors of general corrosion include material type, surface finish, temperature, pH and electrochemical potential.

In the UK HPR1000, the SSC in contact with the reactor coolant are either constructed from, or clad with austenitic stainless steels or nickel based alloy. Alloy 690TT is selected for SG tubes in the UK HPR1000. These materials exhibit excellent resistance to general corrosion and are capable of achieving low release rate of corrosion products under defined chemistry regime.

#### b) Localised corrosion

Special attention is paid to the main form of local corrosion in the UK HPR1000, notably for Stress Corrosion Cracking (SCC). SCC is a major concern for stainless steels and nickel base alloys as their corrosion resistance is provided by a thin oxide layer. SCC occurs when combinations of susceptible material, tensile stress and corrosive condition exist. Environmental factors influencing SCC include pH, electrochemical potential, hydrogen concentration, temperature and contaminant species (e.g. chlorides, fluorides and sulphates). Material selection is another determinant factor of SCC. In the UK HPR1000, the materials of the primary circuit are optimised to avoid abnormal sensitisation during construction, to eliminate or mitigate the SCC.

##### 1) Appropriate material selection and fabrication procedure control

In the UK HPR1000, Alloy 690TT and its welding metal is introduced to substitute Alloy 600 and its welding metal. It is widely accepted that Alloy 690TT is much more resistant to SCC compared with Alloy 600. The steam generator tube, which has the largest surface areas in the primary circuit, is made from Alloy 690TT. The thermal treatment applied to Alloy 690 is a heat treatment given to tubes in their final state to develop the desired grain-boundary carbide distribution with minimal chromium depletion, which increases its resistance against SCC. The detailed information is provided in the *Material Selection Report of SG*, Reference [29].

Stainless steel with sensitised grain boundary microstructure has high

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propensity toward SCC. In the UK HPR1000, the majority of stainless steels (including parent metal and weld metal) in contact with reactor coolant are ultra-low carbon content (no more than 0.035% in most case) according to RCC-M codes. These materials exhibit less susceptibility to sensitisation and excellent resistance against SCC.

Sensitised materials are not prohibited in primary circuit. Materials with high carbon content are restricted for upper support plate, low core plate, and fasteners in RVI to meet the structural strength and functional requirement of these components. The upper support plate and low core plate are subjected to intergranular corrosion test to prevent material sensitization. The fasteners are not subjected to welding activities, thus would not be sensitised during operation.

## 2) Residual tensile stress control

Residual tensile stress in material is another contributing factor of SCC. Studies have shown that residual tensile stress induced either by extensive cold work or by welding initiates SCC for both stainless steels and nickel base alloys. In the primary circuit of the UK HPR1000, cold work are minimised during manufacturing of SSC, cold work hardening material are only used in fasteners such as pins and screws.

In the UK HPR1000, the demonstrations of ageing and degradation for materials focus on the main equipment in the primary circuit, as well as representative equipment from nuclear auxiliary systems in contact with the reactor coolant. The material ageing and degradation demonstrations will fully cover significant ageing/degradation mechanisms of the whole plant throughout the service lifetime and will incorporate the understanding of international OPEX. In step 3, series of material ageing and degradation reports have been published, Reference [30], [31], [32], [33] and [34]. In step 4, the ageing and degradation report on reactor coolant pump as well as the main steam line will be issued, to demonstrate judicious material selection.

### 21.4.2.4 Surface Treatment

In the UK HPR1000, appropriate treatment is conducted to the surface of SSC in contact with the reactor coolant to improve material corrosion resistance. This reduces the generation of corrosion products and also the deposition of corrosion products and species in the reactor coolant, which in turn results in the reduction of the radiation dose rate. The main measures are:

- a) In the UK HPR1000, surface roughness of no more than Ra 6.3µm after manufacturing serves as the minimum requirement on surface roughness control for all SSC of the primary circuit in contact with the reactor coolant. The basis of 6.3µm is to minimise the generation/deposition of corrosion products, to reduce

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the imitation/propagation of surface cracking, and to guarantee the inspectability during Non-Destructive Testing. SSC with smoother surfaces are anticipated to be used in the design due to their improved corrosion resistance and their ability to minimise the generation and disposition of corrosion products. The stipulation of design requirements of surface roughness for SSC will also consider the practical manufacturing techniques.

- b) For MCL inner surface, the surface roughness is required to be no more than 3.2µm.
- c) The outside surface of the finished SG tubes (Alloy 690TT) is required to have a maximum surface roughness of Ra 1.0 micrometres. The inside surface of the finished tubes is required to have a maximum surface roughness of Ra 0.5 micrometres, which reduces the release rate of corrosion products.
- d) Electro-polishing is applied to the inner surface of SG channel head. The surface roughness of SG channel head is required to be Ra 0.63µm after electro-polishing. Electro-polishing applied to SG channel head would minimise deposition of corrosion products during operation, thus reduce the radioactivity of the channel head.
- e) The wrought stainless steel components are pickled and passivated during manufacturing to facilitate the formation of passive oxide.

Topic Report on Surface Treatment of SSC will be submitted in step 4, to demonstrate the surface treatment of SSC in contact with the coolant.

#### 21.4.2.5 Fuel cladding material

The fuel rod cladding is made of M5<sub>Framatome</sub> alloy, which is ternary alloy (ZrNbO). As cladding material, M5<sub>Framatome</sub> alloy is widely used in many nuclear power plants all over the world. Numerous inspections and measurements on fuel rods cladding confirmed the excellent operational behaviour of the M5<sub>Framatome</sub> cladding material with respect to waterside corrosion and hydrogen pickup, rod creep and growth up to very high burn-up. More detailed information will be presented in Operating Experience with AFA 3G<sup>TM</sup>AA Fuel Assemblies, Reference [35].

#### 21.4.2.6 Summary of material selection

The materials used in SSC in contact with the reactor coolant for the UK HPR1000 at this moment are shown in the T-21.4-2 and T-21.4-3.

At the end of step 4, Material Selection Summary Report, which summarises the outcome of all the material selection reports, ageing and degradation reports, will be issued.

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T-21.4-2 Main Base Metal in Contact with Reactor Coolant

<b>Equipment and Component</b>	<b>Type of Material</b>	<b>Chapter of Code</b>
RVI	Z2 CN 19-10 + N <sub>2</sub>	RCC-M M3301, M3302, M3304, M3306, M3307, M3310
	Z3 CN 18-10 + N <sub>2</sub>	RCC-M M3302
	Z2 CND 18-12+N <sub>2</sub> (cold hardening)	RCC-M M3308
	Z6 CND 17-12+N <sub>2</sub> (cold hardening)	RCC-M M 3308, M 5140
MCL	X2CrNi19-10+N <sub>2</sub>	RCC-M M3321
Reactor coolant pump	SA-336M GR.F6NM	ASME SA-336M
RPV	NC30Fe	RCC-M M4108
SG	UNS N06690	ASME SB-163
PZR	Z2 CND 18-12+N <sub>2</sub>	RCC-M M 3306, M 3301, M 3308
	Z2 CND 17-12	RCC-M M 3304, M 3307, M 3306
	Z2 CN 19-10 + N <sub>2</sub>	RCC-M M 3307

T-21.4-3 Main Filler Metal in Contact with Reactor Coolant

<b>Equipment and Component</b>	<b>Type of Material</b>	<b>Chapter of code</b>
Austenitic stainless steel overlay and butt weld	ER309L/ER308L	AWS A5.9/AWS A5.9+RCC-M S2910
	EQ309L/EQ308L	RCC-M S2970/ RCC-M S2960
	E309L/E308L	RCC-M S2930/RCC-M S2920
	E316L/ER316L	RCC-M S2925/ RCC-M S2915
Nickel based alloy overlay and butt weld	ENiCrFe-7	AWS A5.11+RCC-M S2986
	ERNiCrFe-7/7A	AWS A5.14+RCC-M S2981/ AWS A5.14
Cobalt based alloy hardfacing	ERCoCr-A	AWS A5.21+RCC-M S 8000, Gr 6



### 21.4.3 Chemistry Control

Chemistry control is required to help minimise the degradation risk of SSC associated with the primary coolant. The coolant at elevated temperatures and with chemical species is a potentially aggressive medium when in contact with structural materials. Chemical control of the primary coolant consists of managing chemical additives and minimising chemical impurities, in order to minimise the risks of loss of reactivity control by boron concentration, barrier integrity and limit radiation impacts, Reference [36].

The determination of chemistry control parameters is based on the control of reactivity and the maintenance of material integrity, fuel cladding integrity and radiation field control. The rationale of risk mitigation from the chemistry is shown in T-21.4-4. The *Topic Report on Power Operation Chemistry*, *Topic Report on Startup and Shutdown*, and *Topic Report on Commissioning Chemistry*, Reference [37], [38] and [39] provide the chemistry regime and provisions for the UK HPR1000.

T-21.4-4 Rational of Risk Mitigation from the Chemistry Control Measures

Risks	Chemistry Regime	Objective
Loss of adjusted measure for reactivity control Boron crystallisation risk Boron dilution risk	Boron concentration	To compensate the control of reactivity
Degradation of fuel cladding and performance caused by Chalk River Unidentified Deposit (CRUD)	pH control; Hydrogen and oxygen control; Impurity control; Zinc injection.	To maintain an alkaline reducing condition of the primary circuit for the benefit of minimising corrosion and controlling the behaviour of corrosion products
Degradation of SSC integrity		To limit the oxidising species from coolant radiolysis and maintain reducing conditions
Degradation of SG heat transfer performance		To reduce corrosion impurities into the coolant
Increasing production and transport of radioactivity	pH control; Impurity control; Hydrogen and oxygen control;	To limit the production and transportation of corrosion products to the core and subsequent activation and deposition

<b>Risks</b>	<b>Chemistry Regime</b>	<b>Objective</b>
	Zinc injection	

#### 21.4.3.1 Chemistry Regime

##### a) Boric acid

Boron is injected into the primary coolant of PWRs as a neutron absorber in order to assist in reactivity control. Boron is added and removed in the form of boric acid mixed with demineralised water to the required concentration. The concentration of boron is slowly adjusted in order to control relatively slow reactivity changes, principally to accommodate the effects of fuel burnup. Detailed information relating to how the boric acid solution is used as a chemical reactivity poison and how the operating range of the boron concentration is determined is provided in the Sub-chapter 5.5.2.

The effective neutron absorption component in boric acid is B-10, and the isotopic proportion of B-10 in natural boron is around 20 at%. The remaining 80 at% is B-11, which only has a small relative neutron cross section. Therefore, the enrichment of B-10 in the boric acid increases the neutron absorbing ability, relative to natural boric acid. The use of Enriched Boric Acid (EBA) does not permit an increase in B-10 (which is fixed for reactivity control) but permits a decrease in the total boron concentration.

There are a number of benefits for EBA application over boric acid including:

- 1) It allows a higher pH to be used throughout the cycle and decreases the boron concentration at the beginning of the cycle;
- 2) It allows a constant pH to be used throughout the cycle (once the xenon equilibrium has been achieved after the first few days) avoiding any effects induced by changing the pH;
- 3) The maximum lithium concentrations needed to maintain the high pH value at the start of cycle are lower, reducing the potential for corrosion of the zirconium alloy fuel cladding;
- 4) The volume of borated water that the Emergency Boration System (RBS [EBS]) needs to inject in the event of DBC 2-4 and DEC-A conditions is less compared with natural boric acid, avoiding the PZR overflowing.

EBA is applied and enrichment is selected for 35 at% in the HPR1000 (FCG3). However, selection of EBA is determined by many factors. All impacted factors on the selection of EBA will be demonstrated.

##### b) pH control

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The high constant pH is beneficial for the primary water chemistry conditions, as this leads to reduced corrosion product formation and subsequent activation and deposition. The determination of the  $\text{pH}_{300^\circ\text{C}}$  control strategy for the UK HPR1000 is demonstrated in the *Topic Report of pH Control in the Primary Circuit of UK HPR1000*, Reference [40].

#### 1) Operating $\text{pH}_{300^\circ\text{C}}$ effect

As pH varies with the temperature and boric acid within the primary coolant, this leads to challenges in maintaining the acid/alkaline condition under different conditions.

The primary coolant  $\text{pH}_{300^\circ\text{C}}$  strongly influences the corrosion processes which can affect the materials in the primary circuit and also the integrity of the fuel cladding. The  $\text{pH}_{300^\circ\text{C}}$  of the primary circuit can also impact on the CRUD and the subsequent transfer around the primary circuit. These activated corrosion products can deposit on out of core surfaces leading to an increase in radiation field.

To reduce the CRUD on fuel surfaces and to reduce the resulting out of core radiation field, an appropriate  $\text{pH}_{300^\circ\text{C}}$  control methodology is needed for the UK HPR1000 in order to achieve the following objectives:

- Minimise material corrosion and release;
- Minimise the transfer of corrosion products to the core;
- Minimise the deposition of corrosion products in the core.

#### 2) Lithium hydroxide

Lithium hydroxide (LiOH) has been selected for the pH conditioning of the primary coolant of the UK HPR1000. Other alkaline reagents such as ammonia, sodium and/or potassium hydroxide present some drawbacks when compared with lithium hydroxide, because they are not as thermally and radiolytically stable. In addition, sodium and potassium can be activated to Na-24 and K-42, respectively leading to an increase in the radioactivity of the RCP [RCS] and auxiliary systems.

Lithium hydroxide is known to accelerate the corrosion of zirconium alloys at temperatures around  $300^\circ\text{C}$  for excessive lithium concentration. Therefore, the lithium concentration is considered by fuel suppliers as a limiting factor in fuel design, and a maximum lithium concentration and time of exposure are specified with regard to first barrier integrity.

A drawback of using natural lithium is that in a neutron flux it can lead to the production of H-3 (tritium) caused by activation of the Li-6 isotope. Lithium

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that is enriched in Li-7 leads to the negligible production of tritium. LiOH enriched in Li-7 to 99.9% will be used for the UK HPR1000. The choice of injecting enriched lithium hydroxide is the result of a Best Available Techniques (BAT) assessment for optimising the tritium source term, demonstrated in the Pre-Construction Environment Report (PCER).

### 3) Operating window

To reduce the CRUD and to minimise out of core radiation fields, and to reduce the exposure time for fuel cladding at the maximum lithium concentration, the target  $\text{pH}_{300^\circ\text{C}}$  value is set at 7.2. This is consistent with available worldwide based on the following processes.

- Minimise material corrosion and release: the reduction of general corrosion and release corrosion rates of primary circuit surfaces;
- Minimise the corrosion product transfer to the core: the reduction of corrosion product solubility in the core inlet surfaces (low temperature around  $290^\circ\text{C}$ );
- Minimise the corrosion product deposition in the core: the reduction of the source term likely to be deposited in the core; the increase of corrosion product solubility in the core outlet surfaces (high temperature around  $325^\circ\text{C}$ ).

The lithium concentration has been limited to minimise the risk of fuel cladding corrosion. The maximum lithium concentration selected for the UK HPR1000 is subject to the following conditions:

- Ensure the realisation of a  $\text{pH}_{300^\circ\text{C}}$  control strategy aimed at limiting the radiation field and CRUD;
- Be in compliance with fuel cladding OPEX;
- Meet the requirements of the fuel supplier.

To ensure the implementation of the  $\text{pH}_{300^\circ\text{C}}$  control strategy, the UK HPR1000 will set the upper lithium concentration value of the operating window at 3.5 mg/kg.

Further information on the formation of CRUD and evaluation of deposition on the surface of fuel cladding for the UK HPR1000 is developed.

### c) Hydrogen control

#### 1) Control of oxidising species

In normal operation, water is decomposed by radiolysis which generates  $\text{H}_2\text{O}_2$  and  $\text{H}_2$  molecules along with  $\text{e}^-$ ,  $\text{H}^\cdot$  and  $\text{OH}^\cdot$  radicals. These species are

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highly reactive and can interact with each other to form  $O_2$  and  $O^{2-}$ . Further information on the radiolysis reactions is detailed in the *Topic Report on Hydrogen Concentration Control in the Primary Circuit*, Reference [41].

Even low concentrations of oxygen have a significant effect on the susceptibility of materials to SCC. Oxygen can also increase the corrosion rates in primary circuit materials, which can lead to an increase of CRUD in the primary circuit, and can lead to an increase in fuel cladding corrosion.

Hydrogen is added to the primary coolant to maintain a reducing condition which helps to suppress the radiolytic decomposition of water (oxygen source). Optimal dissolved hydrogen concentration control is an important approach in maintaining material integrity performance. Dissolved hydrogen scavenges oxygen and limit the generation of oxidising species from water radiolysis in the RCP [RCS], thus reducing material corrosion.

## 2) Effect of hydrogen

The presence of hydrogen suppresses the generation of oxygen in the primary coolant during power operation. Thus, it contributes to reducing general corrosion, Primary Water Stress Corrosion Cracking (PWSCC) and low temperature crack propagation of nickel alloys.

The presence of hydrogen affects the redox potential of the primary coolant with an impact on the corrosion product solubility that can lead to a reduction in the radiation field.

It is important to ensure that there is an excess of hydrogen in the reactor at all times. However, there is a need to control the upper value of hydrogen concentration to maintain the integrity of the first and second barriers in the medium and long term, as well as avoiding the risk of explosion.

## 3) Operating limit

In order to assist in the determination of an appropriate hydrogen concentration operating window for the UK HRP1000, consideration has been given to worldwide experience of PWR units operating under similar conditions and experience gained from the operation of the CPR1000 units.

The upper value of the hard limit of hydrogen concentration of  $50\text{cm}^3/\text{kg}$ , at the standard temperature and pressure (273.15K and 1atm), is determined according to the hazard protection. The lower value of the hard limit of  $10\text{cm}^3/\text{kg}$  is to improve material integrity and reduce the radiation field.

During normal operation, the hard limit of hydrogen concentration in the primary coolant for the UK HPR1000 is defined as  $10\text{cm}^3/\text{kg}$  ~  $50\text{cm}^3/\text{kg}$ , and will prevent primary and secondary barrier loss. The operating window for

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the hydrogen concentration in the primary coolant for the UK HPR1000 is to be set based on an assessment of OPEX. The upper value of hydrogen concentration during shutdown (before oxygenation) is set at 3cm<sup>3</sup>/kg which satisfies the safety requirement. There will be no negative effect at this concentration level.

d) Zinc

Based on worldwide research and practices, the use of zinc can be regarded as RGP for reducing dose rates in light water reactors by preventing the release of corrosion products into the primary coolant and the adsorption and incorporation of radio-cobalt's on out-of-core surface. The majority of plants inject zinc to reduce dose rate, although some cite the additional goal of mitigating PWSCC initiation. Zinc injection reduces general corrosion rates and consequently reduces corrosion products transport to the fuel, and as a result the quantity and activity of radioactive waste can be minimised and out of core radiation fields reduced.

Zinc injection has been successfully implemented at a number of PWR units, with a variety of reactor coolant system designs. Most units that have injected zinc for a significant period of time have reliable evidence of dose rate reductions. There are some differences in the long-term dose rate reduction between plants that have commenced zinc injection after a number of cycles. Primary water chemistry can be optimised with zinc injection:

- 1) To preserve the integrity of SSC important to safety;
- 2) To minimise out of core radiation fields.

The zinc injection minimises the risks of PWSCC in susceptible materials and reduces on-going corrosion in the primary circuit. Lower corrosion product release, in turn, reduces the risk of Crud Induced Power Shifts (CIPS), and also minimises plant dose rates.

According to worldwide OPEX of zinc application in PWRs, zinc is typically injected as depleted zinc acetate with Zn-64 <1 at% and with reduced content of impurities (according to specifications from the supplier).

It is noted that the elevated levels of zinc within the primary circuit may cause zinc silicate to deposit within CRUD on the core and increase fuel cladding corrosion due to the solubility limit of zinc. Thus, the concentration of zinc is controlled to maintain the benefits of the dose reduction, while limiting the potential for fuel cladding corrosion.

The justification for the incorporation of zinc addition into the UK HPR1000 design is based on RGP, particularly at similar PWR plants which have injected zinc from the beginning of plant life. Zinc injection has been found to be

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compatible with the UK HPR1000 design, as reported in the *Topic Report on Zinc Injection in the Primary Circuit of UK HPR1000*, Reference [42].

e) Impurities

Impurities that are focused on are those that cause corrosion to the boundary materials in the primary circuit of a PWR. The main risks caused by the presence of these impurities include challenging the integrity of the primary circuit structural materials and fuel cladding. These impurities mainly result from: the corrosion of structural materials, makeup water, chemical additives and filling decomposition.

1) Chloride, fluoride, sulphate and dissolved oxygen

SCC of stainless steel can be induced by chloride in the primary circuit of a PWR under high temperature and in aerobic conditions. Alloy 690TT has high resistance to chloride-induced stress corrosion.

In the primary circuit, fluoride can cause the corrosion of zirconium alloy, and the corrosion rate will increase with an increase in fluoride concentration. Fluoride and sulphate can also cause SCC of stainless steel.

Oxygen reacts with various materials to form corrosion products, including stainless steel at high temperatures, carbon steel at various temperatures and copper alloy in alkaline condition. The main hazards caused as a result of these corrosion products include: promoting the corrosion of fuel cladding, increasing the content of radioactive elements, and increasing the SCC risk of stainless steel. Even if there is a low concentration of dissolved oxygen in coolant, it will have a harmful effect on the Intergranular Attack (IGA) of the pipeline. Controlling the oxygen concentration is important since this can reduce the deposition and radioactivity on the fuel surface.

2) Calcium, magnesium, aluminium and silica

In the primary circuit, the presence of impurities such as calcium, magnesium and aluminium alone will not directly affect the corrosion of fuel cladding. These elements can form oxides and silicates, which have negative temperature coefficients (i.e., solubility decreases with increasing temperature), so they may preferentially deposit at the highest temperature of the coolant system (e.g. the surface of fuel cladding), which may aggravate the corrosion of fuel cladding.

Increasing the concentration of silica has an effect on the precipitation of aluminium and calcium. In case of such precipitation that results in densification of the fuel crud, fuel crud becomes an insulating layer with increased thermal resistance rather than having excellent heat transfer

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behaviour. This results in temperature increase at the fuel rod surfaces, which increases the cladding corrosion rate. Therefore, fuel vendor recommends for monitoring and controlling of silica concentrations within the specified limits when zinc injection applied.

Based on the OPEX gained from the CPR1000 units, the concentration of calcium, magnesium, aluminium and silica in RCP [RCS] is usually low, which is equivalent to international levels.

Further information on the consideration of impurities and the determination of concentration limits is provided in the *Topic Report on Impurity Control for the Operation*, Reference [43].

#### 21.4.3.2 Chemistry Provisions for Commissioning and Operation

The chemistry provisions for the commissioning and operation for the UK HPR1000 are based on the reference plant of HPR1000 (FCG3), which considers OPEX from similar PWRs operated by CGN in China.

##### a) Commissioning phase

The commissioning process is important for establishing stable oxide films in the plant and this may subsequently reduce general corrosion rates and plant radiation fields. Industry OPEX will be taken into account when developing the commissioning chemistry regime and the principles applicable to chemistry commissioning for the UK HPR1000. These are described in the *Topic Report on Commissioning Chemistry*, Reference [39].

The following phases have been implemented for the UK HPR1000:

- 1) The chemistry regime during Hot Functional Test (HFT) is optimised in order to passivate the surfaces of the SGs permitting reduction of the nickel (and resulting cobalt-58) source term;
- 2) Water quality control for the commissioning phase;
- 3) Consumables in accordance with requirements in RCC-M F6400 are applied on SSC in stages of commissioning to avoid contamination on clean-up surfaces of SSC and prevent corrosion before operation.

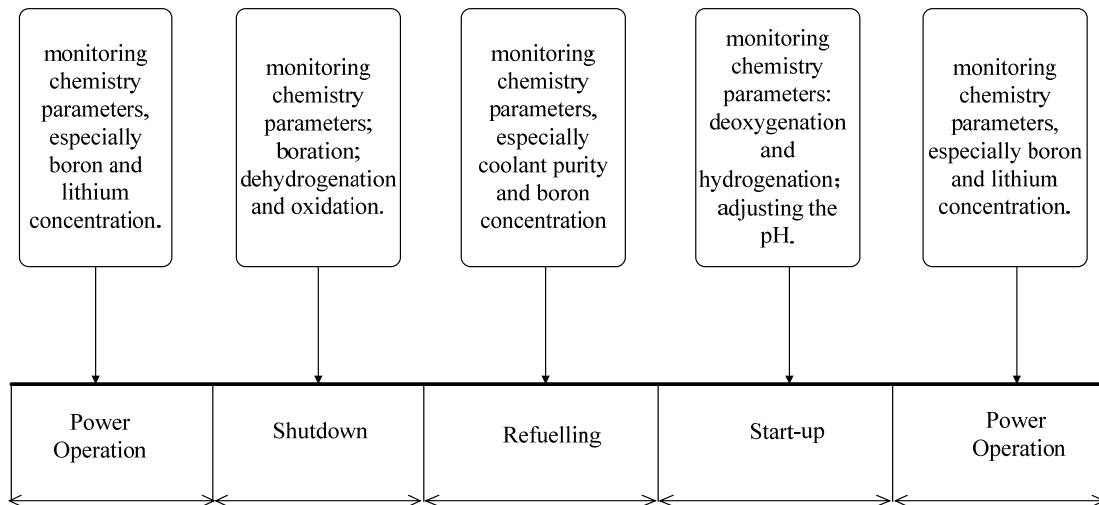
##### b) Operation phases

The normal operating phases of the primary circuit (RCP [RCS]) contain refuelling, startup, power operation and shutdown. The chemistry operation is from the reference plant which has been developed from the experience and feedback from PWRs of CGN. These chemistry operations are schematically shown in F-21.4-2.

Further information on the startup and shutdown chemistry approaches for the UK



HPR1000 is presented in the *Topic Report on Startup and Shutdown Chemistry*, and *Topic Report on Power Operation Chemistry*, Reference [37] and [38].



F-21.4-2 Chemical Operations for Different Operating Phases

### 1) Refuelling

In this phase, the RCP [RCS] is filled with coolant and connected to the reactor cavity and Spent Fuel Pool (SFP). The chemistry regimes are the same for the reactor cavity and as for the SFP. During this “open state”, the plant is highly vulnerable to impurity ingress, and operators need to focus on monitoring the chemistry parameters with significant attention to both coolant purity and boron concentration.

#### **Impurities control**

The provisions for impurities control are similar in the different phases of normal operation, startup and shutdown. Detailed substantiation is provided in Sub-chapter 21.4.4 and 21.6.4. The control of impurities in the primary coolant includes the following measures:

- Water quality of makeup water: the water quality of makeup water is ensured by the demineralised water supply at source;
- Impurities control of additives: the chemicals and fillings are controlled;
- Clean-up systems: the filters and demineralisers are used to remove the impurities, and the clean-up units are included the systems of RCV [CVCS], Fuel Pool Cooling and Treatment System (PTR [FPCTS]) and TEP [CSTS].

#### **Boron concentration**

The boron concentration during shutdown and refuelling should be adjusted to meet relevant sub-criticality limit. During normal operation, the boron

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concentration is adjusted to compensate the reactivity induced by power change or core burnup.

## 2) Startup

During this phase, chemistry operations are as follows:

- The boron concentration in RCP [RCS] is more than or equal to the boron concentration required for shutdown;
- Monitoring the chemistry parameters in RCP [RCS].(e.g. different requirements of sulphate, chloride and fluoride concentration at different temperatures);
- The chemistry regimes establishment phase begins. The chemical reagents are injected during this condition. For example, hydrazine is used to scavenge oxygen and lithium hydroxide is used to control pH value.

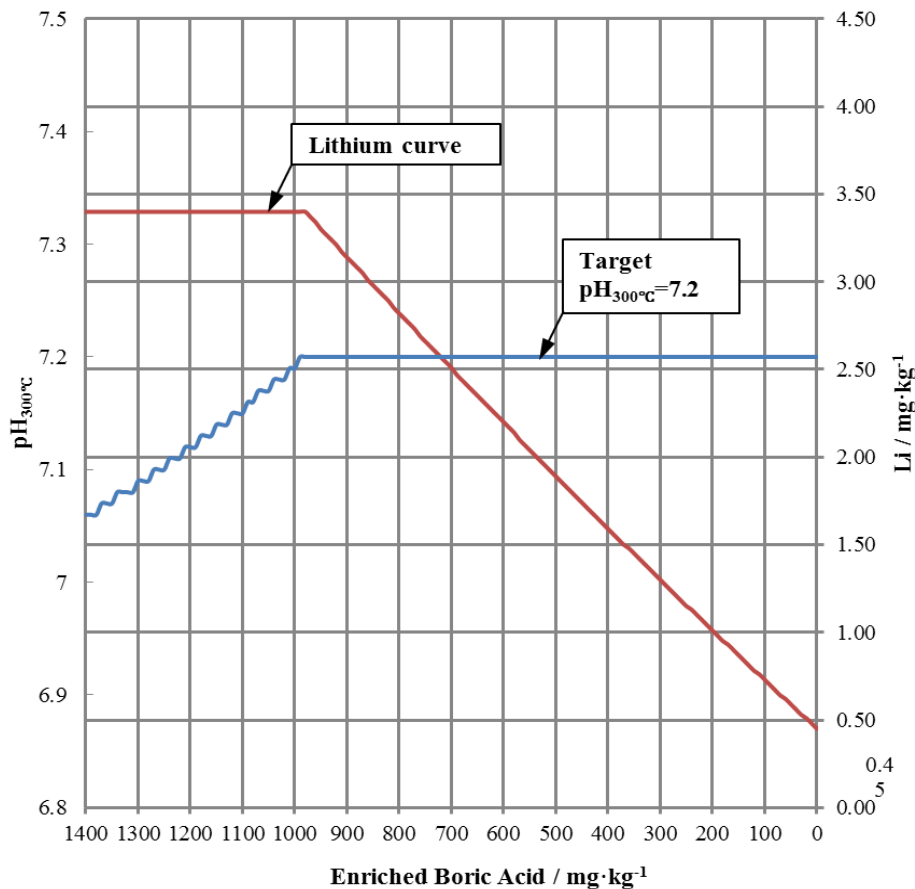
### **pH control**

- Based on the boron concentration at the Beginning of Cycle (BOC), the  $\text{pH}_{300^\circ\text{C}}$  control strategy for the UK HPR1000 primary coolant has been established by considering the maximum lithium concentration and the boron concentration at BOC. At BOC, the lithium concentration will be maintained at the upper value of the operating window.
- In order to maintain the stability of  $\text{pH}_{300^\circ\text{C}}$  during the whole cycle and prevent frequent fluctuations of the chemistry conditions in the primary circuit, the target  $\text{pH}_{300^\circ\text{C}}$  is achieved as soon as possible in the cycle. Boron-lithium curve along the fuel cycle of the UK HPR1000 is schematically shown in F-21.4 3.

### **Hydrogen control**

- During startup, mechanical removal of dissolved oxygen will be achieved through the degasification unit of the Coolant Storage and Treatment System (TEP [CSTS]) after the primary circuit has been refilled with primary coolant.
- Chemical removal of dissolved oxygen through hydrazine injection into the RCV [CVCS] is undertaken to maintain the dissolved oxygen content to below 0.1 mg/kg before  $\text{TRCP}=90^\circ\text{C}$ , in order to avoid any oxygen induced corrosion risk and hydrogen explosion risk after hydrogen injection starts.
- Hydrogen injection into the primary coolant is made through the hydrogenation station of RCV [CVCS] and hydrogen water chemistry

under NS/SG mode is established. The concentrations of hydrogen and oxygen in the primary coolant are continuously monitored by the REN [NSS].



#### F-21.4-3 Boron-lithium Curve along the Fuel Cycle of the UK HPR1000

### 3) Power operation

In this phase, operators monitor the chemistry parameters. The chemistry parameters are relatively stable except for boron and lithium concentration. The concentration of lithium is adjusted according to boron concentration to ensure the appropriate operational pH value.

#### **pH control**

With the decrease of boron concentration to compensate for fuel burnup, the pH<sub>300°C</sub> value gradually increases from the initial value. When the pH<sub>300°C</sub> value reaches the target value of 7.2, the concentration of boron and lithium are coordinated to maintain the constant pH<sub>300°C</sub>. It may not be possible to reach the target pH<sub>300°C</sub> value at BOC at power operation due to a higher concentration of boric acid, but the time operating under a lower pH<sub>300°C</sub> value will be greatly reduced.

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### **Hydrogen control**

Hydrogen is added into the primary circuit as a gas to maintain the concentration in the operating window during the normal operation. Hydrogen risk is managed via specific devices, such as the Volume Control Tank (VCT) and an on-line recombiner in the Gaseous Waste Treatment System (TEG [GWTS]) loops.

#### 4) Shutdown

In this phase, chemistry operations are as follows:

- Executing boration to prevent the core returning to criticality;
- Monitoring the chemistry parameters in RCP [RCS];
- Monitoring the RCP [RCS] radioactivity to meet personnel protection during the following conditions: prior to PZR bubble collapse, the last reactor coolant pump is stopped and the reactor coolant system is opened;
- When the RCP [RCS] temperature reaches 80°C in NS/RIS-RHR mode, hydrogen peroxide is injected to RCP [RCS] system. Before injection of hydrogen peroxide, the hydrogen is limited at a safe concentration by nitrogen flushing.

### **pH control**

- During shutdown, the RCV [CVCS] hydrogen injection is stopped under NS/SG mode. The primary coolant hydrogen content is mechanically removed through the TEP [CSTS] degasification process, to ensure that acid reducing conditions are maintained to ensure the solubility of fuel deposits.

### **Hydrogen control**

- Mechanical removal of hydrogen is maintained until the hydrogen concentration is lower than 3cm<sup>3</sup>/kg under NS/RIS- Residual Heat Removal (RHR) mode, at which point the risk of a hydrogen explosion is significantly minimised.
- When the temperature of the primary coolant has been cooled down to below 80°C, forced oxygenation can start by dosing the primary coolant with hydrogen peroxide through the RCV [CVCS]. The conditions of the primary coolant chemistry will then be changed from acid reducing to acid oxidising conditions, which will further accelerate the decomposition and dissolution of fuel deposits. The dissolved fuel deposits will then be removed by the RCV [CVCS] purification unit.

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- The hydrogen concentration in the primary coolant is continuously monitored through sampling by the REN [NSS].

#### **21.4.4 Substantiation of System Requirement**

##### 21.4.4.1 Chemical and Volume Control System

###### a) System functional requirements

The chemical function of RCV [CVCS] is non-safety related, and is required to perform the following chemistry related functions in the normal operation:

- 1) RCV [CVCS] is required to perform purification function to remove corrosive and fission products from the reactor coolant;
- 2) RCV [CVCS] is required to inject lithium hydroxide into the reactor coolant as needed, so as to maintain the weak alkalinity of the reactor coolant during normal operation;
- 3) RCV [CVCS] is required to inject hydrazine into the reactor coolant as needed for de-oxygenation during plant startup;
- 4) RCV [CVCS] is required to inject hydrogen peroxide to remove hydrogen and transition the coolant chemistry from reducing to oxidizing to allow the crud burst to be contained and cleaned up before the circuit is opened for refuelling;
- 5) RCV [CVCS] is required to continuously add hydrogen into the reactor coolant so as to keep the dissolved hydrogen concentration at the required value.

###### b) System design requirements

The chemistry design requirements for RCV [CVCS] include:

- 1) The purification unit of RCV [CVCS] consists of two reactor coolant filters, two mix-bed demineralisers, one cation-bed demineraliser and two resin trap filters. During normal operation, one reactor coolant filter, one mixed-bed demineraliser and one resin trap filter are required to put in operation while the other is standby and the cation-bed demineraliser can be put into intermittent operation as needed.
- 2) The chemical injection unit of RCV [CVCS] consists of one chemical injection tank and one chemical injection pump, and is required to inject lithium hydroxide, hydrazine and hydrogen peroxide into the reactor coolant as needed during normal operation.
- 3) The hydrogenation station of RCV [CVCS] consists of one water jet pump, one mixing pipe and one gas separator. It is required to detect the hydrogen

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concentration in the room to prevent the hydrogen explosion via Nuclear Island Hydrogen Detection System (KRH [HDS]).

c) System operational requirements

The chemistry operating requirements for RCV [CVCS] include:

- 1) Perform purification function to remove corrosive and fission products from the reactor coolant during normal operation;
- 2) Inject lithium hydroxide into the reactor coolant to maintain the weak alkalinity of the reactor coolant during normal operation;
- 3) Inject hydrazine into the reactor coolant as needed for deoxygenation during plant startup;
- 4) Inject hydrogen peroxide to remove corrosion products during plant shutdown;
- 5) Add hydrogen into the reactor coolant to keep the dissolved hydrogen concentration at the required value during normal operation.

d) Substantiation of requirements

The system has been designed to meet the relevant requirements mentioned above, and detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Primary Circuit*, Reference [44]. The system configuration is presented in the *System and Component Design*, Reference [45], and the operation control is presented in the *System Operation and Maintenance*, Reference [46].

#### 21.4.4.2 Reactor Boron and Water Makeup System

a) System Functional Requirements

The chemistry design requirements for Reactor Boron and Water Makeup System (REA [RBWMS]) include:

- 1) REA [RBWMS] shall be designed to prepare the boric acid for the plant operation;
- 2) The REA [RBWMS] shall also provide borated water to RCP [RCS] to adjust its boron concentration via RCV [CVCS], for the purpose of controlling the slow reactivity change in the core;
- 3) The demineralised water injection subsystem (REA4&5) can be used to inject demineralised water to the primary circuit through RCV [CVCS].

b) System Design Requirements

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The boric acid mixing and distribution subsystem (REA1) shall be designed to prepare 4% boric acid solution and serve other boron-bearing systems.

The boric acid storage tanks shall be equipped to store the boric acid solution. The capacity of boric acid storage tanks shall be sufficient to bring the core to subcritical state in cold shutdown from power operation following refuelling shutdown.

The boric acid make-up flowrate should be able to control the boron concentration in the RCP [RCS] and the volume control tank level during normal operation.

c) System Operational Requirements

During normal operation, the REA [RBWMS] is required to provide the initial filling of borated water and makeup for RCP [RCS] and other boron-bearing systems when the user systems required.

1) Reactivity control:

During normal operation, the REA [RBWMS] is required to control the boron concentration in the RCP [RCS] (via the RCV [CVCS]) to control slow reactivity change in the core, and tracking the expected load changes by the following means:

- Increasing the boron concentration in RCP [RCS] in case of shutdown.
- Decreasing the boron concentration in RCP [RCS] in case of startup.
- Adjusting the boron concentration in RCP [RCS] during the operation in response to the reactivity change due to xenon or samarium poisoning, load following or burn-up change.
- Enabling the core to be kept sub-critical by providing borated water to the RCP [RCS] in case of refuelling outage with all the control rods unloaded.

2) Makeup:

During normal operation, the REA [RBWMS] is required to provide borated water makeup to all the systems or equipment which store or contain borated water. In addition, the REA [RBWMS] is required to:

- Provide borated makeup water, with the same boron concentration as the primary system, to control the tank volume level during normal operation.
- Provide borated makeup water to the primary system via the RCV [CVCS] at the required concentration to compensate for the volume

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reduction of the reactor coolant during shutdown.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above, and the detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Primary Circuit*, Reference [44]. The system configuration is presented in the *System and Component Design Reference* [47], and the operation control is presented in the *System Operation and Maintenance*, Reference [48].

21.4.4.3 Coolant Storage and Treatment System

a) System functional requirement

The Coolant Storage and Treatment System (TEP [CSTS]) receives and stores reusable primary coolant during normal operation. It prepares demineralised water and 7000mg/kg boric acid solution via an evaporation process and transfers them to storage tanks for reuse. It reduces radioactivity level in the primary coolant through the degasification process.

The TEP [CSTS] stores the primary effluents discharged by the RCV [CVCS] and collected by the Nuclear Island Vent and Drain System (RPE [VDS]), and then purifies them through the demineraliser (whose main function is removing caesium which is not eliminated by the RCV [CVCS], meanwhile the excess lithium can be also removed) and separates the primary effluents into demineralised water for reuse and concentrated boric acid at 7000mg/kg via the evaporation unit. The TEP [CSTS] can degasify the demineralised water makeup from the nuclear island demineralised water distribution system.

b) System design requirement

The chemistry design requirements for TEP [CSTS] include:

- 1) The radioactive liquid is collected by coolant storage tanks and the liquid in each tank is sampled before treatment;
- 2) The chemistry parameter including pH, radioactivity, and sodium-to-boron ratio are analysed when the liquid is sampled;
- 3) The treated liquid is collected and sampled again before transferring to downstream system to ensure it is qualified for discharge;
- 4) Oxygen content of the treated demineralised water does not exceed 0.05ppm;
- 5) Boron content of the concentrated boric acid is controlled at 7000ppm and boron content of the treated demineralised water is not more than 5ppm.

c) System operational requirement



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TEP [CSTS] is put into operation in normal operating conditions of the plant, the operating requirements for TEP [CSTS] include:

- 1) Coolant storage and supply;
  - 2) Coolant purification;
  - 3) Distillation separation without degasification and reuse after treatment;
  - 4) Distillation separation with degasification and reuse after treatment;
  - 5) Distillation separation with degasification and condensate discharge after treatment;
  - 6) Degasification of makeup water;
  - 7) Degasification of coolant which is piped from RCV [CVCS].
- d) Substantiation of system requirements

The TEP [CSTS] is divided into the following subsystems:

- 1) Coolant storage and supply subsystem

The coolant storage and supply subsystem is mainly comprised of the following components:

- Six coolant storage tanks;
- One borated water pipeline;
- One demineralised water pipeline.

Each coolant storage tank is connected to the borated water pipeline and demineralised water pipeline through an isolation valve.

The tanks are constantly swept with nitrogen taken from the TEG [GWTS] to prevent accumulation of flammable gas mixtures in the system free spaces. Additionally, the tanks are operated below atmospheric pressure to prevent hydrogen leakage from the system.

- 2) Coolant purification subsystem

The coolant purification subsystem consists of:

- Two makeup pumps of the boric acid distillation tower;
- One mixed bed demineraliser;
- One cartridge filter (resin trapper).

The mixed bed demineraliser and downstream resin trapper are installed between the coolant storage and supply subsystem, and coolant treatment

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subsystem.

3) Coolant treatment subsystem

The coolant treatment sub-system consists of:

- One evaporation unit;
- One condensate degasification unit.

The coolant treatment sub-system separates reactor coolant into demineralised water and boric acid solution. Redundancy is considered for all important active components to improve system availability.

4) Coolant degasification subsystem

The coolant degasification subsystem mainly consists of:

- One coolant degasification unit.

The degasification vacuum pump will depressurise the coolant when its temperature reaches the boiling point of 50°C. Meanwhile, the vacuum pump is used to extract gases originating out of the degasification tower.

The system has been designed so that it can meet the relevant requirements mentioned above. The design assumption and system operation of TEP [CSTS] is described in Sub-chapter 23.5. The system configuration is presented in the *System and Component Design*, Reference [49], and the operation control is presented in the *System Operation and Maintenance*, Reference [50].

21.4.4.4 Liquid waste treatment system

a) System functional requirement

The Liquid Waste Treatment System (TEU [LWTS]) is non-safety related, which is designed to monitor, collect, store and treat the unrecyclable radioactive liquid waste produced during normal operation. It is used to separate radionuclides from radioactive liquid wastes so that the activity concentration of the treated liquid wastes reaches an appropriate level.

The TEU [LWTS] contribute to the confinement of radioactive material in normal operation. The following chemistry parameters are controlled in the system to reduce the leakage of radioactive liquid, reduce the discharge of radioactive nuclides to environment to the extent as low as reasonable possible, and minimise second waste to the extent as low as reasonable possible. Please refer to T-21.4-5 for summary of TEU [LWTS] chemistry control.

T-21.4-5 Summary of TEU [LWTS] Chemistry Control

<b>Parameter</b>	<b>Reason</b>	<b>Treatment Method</b>
pH	To inhibit corrosion and reduce leakage	Nitric acid addition Sodium hydroxide addition
Radioactivity	To reduce the discharge of radioactive nuclides to environment to the extent as low as reasonable possible	Demineralisation Evaporation Retention pit
Sodium-to-boron ratio	To inhibit boron crystallization to minimise second waste	Sodium hydroxide addition
Total salinity	To protect ion-exchange resins from adsorption saturation and minimise second waste	Evaporation
Detergents	To protect ion-exchange resins from being contaminated and minimise second waste	Evaporation

b) System design requirement

- 1) The radioactive liquid waste is collected by category and the liquid in each tank is mixed and sampled before treatment;
- 2) The chemistry parameter including pH, radioactivity, and sodium-to-boron ratio are analysed when the liquid is sampled;
- 3) Different treatment methods including chemistry addition (nitric acid addition, sodium hydroxide addition), filter, demineralisation and evaporation are provided according to the result of the sampling;
- 4) The treated liquid waste is collected and sampled again before transferring it to the downstream system to ensure it is suitable for discharge;
- 5) The retention pit is provided for the room where the radioactive liquid tank is located.

c) System operational requirement

The TEU [LWTS] is designed to treat four categories of liquid radioactive wastes

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which are process drains, chemical drains, floor drains and laundry drains. They are treated by different methods according to their activity and chemical compositions:

- 1) Process drains are radioactive liquid waste with low chemical content. They are usually treated by filtration and demineralisation because of the low total salinity and the high decontamination factor of demineralisation under this water condition. If the composition is complex and it is difficult for demineralisation to achieve the treatment criteria, they will be treated by evaporation;
  - 2) Chemical drains are radioactive liquid waste with high chemical content. They are usually treated by filtration and evaporation because the total salinity is usually too high to treat by demineralisation. If the radioactivity concentration in chemical drains meets the discharge management objectives, they will be treated by filtration only;
  - 3) Effluent from floor drains and laundry drains contain particles and fibre, which needs to be treated by filtration. Generally, the radioactive concentration of these effluents meets the discharge management objectives. If effluents from these systems have higher radioactive concentration, they will be treated by evaporation.
- d) Substantiation of system requirements

The TEU [LWTS] is divided into the following subsystems:

- 1) Liquid waste storage subsystem, which consists of process drains storage tanks, floor drains storage tanks, chemical drains storage tanks and laundry drains storage tanks for storing different categories of liquid wastes. The steel liners and retention pit are placed in the rooms where the storage tanks containing medium or higher radioactive liquid wastes are located to provide liquid waste retention function in case the leakage of storage tank, thus reducing the escape of inventory and the spread of contamination;
- 2) Liquid waste treatment subsystem, which consists of demineralisation unit, evaporation unit and filtration unit. Different liquid wastes are treated by different treatment units according to their activity and chemical compositions;
- 3) Monitoring and discharge subsystem, which consists of two monitoring tanks and one monitoring tank pump. The liquid wastes after treatment is monitored, and if suitable, they will be discharged. Otherwise, they will be undergo further treatment by the evaporation unit or demineralisation unit;
- 4) Chemical dosing subsystem, which consists of metering pumps and auxiliary

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parts, meeting requirements for pH and sodium-to-boron ratio adjustment of liquid waste in the storage tank and anti-foam reagent to the evaporator;

- 5) Sampling analysis subsystem, which consists of special sampling glove boxes and local sampling funnels, which are used to gather the sampling lines around the system for sampling and analysis.

The system and subsystem has been designed that can meet the relevant requirements mentioned above. The design assumption and system operation of TEU [LWTS] is described in Sub-chapter 23.5. The system configuration is presented in the *System and Component Design*, Reference [51], and the operation control is presented in the *System Operation and Maintenance*, Reference [52].

#### 21.4.4.5 Gaseous waste treatment system

##### a) System functional requirement

TEG [GWTS] is non-safety related, which is a gaseous radioactive waste management system which is designed to collect, treat and discharge the gaseous radioactive waste generated from the containers, tanks and other degassing components which contain reactor coolant under all the normal operation conditions. TEG [GWTS] system also aims to keep the hydrogen/oxygen concentration in the TEG [GWTS] and connected components within flammability limits to avoid explosive mixtures.

T-21.4-6 Summary of TEG [GWTS] Chemistry Control

Parameter	Reason	Treatment Method
Hydrogen/oxygen concentration	Keeping the hydrogen/oxygen concentration in the TEG [GWTS] and connected components within flammability limits to avoid explosive mixtures.	Nitrogen flushing and recombination.
Radioactivity	Reducing the radioactivity of the gaseous waste to reach an acceptable radiation level before discharge to the environment.	Delay of the radioactive noble gases in the gas stream by activated charcoal.

##### b) System design requirement

The chemistry design requirements for TEG [GWTS] include:

- 1) The flushing gas flow rate provided by the TEG [GWTS] is designed to ensure the dilution requirements for the concentration of the hydrogen and

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oxygen generated by the connected components, and to keep the concentrations of hydrogen and oxygen in TEG [GWTS] below the explosion limit of 4% and 2%;

- 2) The capacity of recombiner is designed to ensure that the hydrogen and oxygen in the flushing gas can be efficiently recombined. Controlling the oxygen concentration in the gas phase contributes to the reducing of the dissolved oxygen in the reactor coolant, therefore reducing corrosion;
  - 3) The hydrogen and oxygen concentration can be monitored, adjusted and controlled to avoid explosion;
  - 4) The capacity of the delay unit is designed to treat the excess gas generated in normal operation conditions and provide enough delay time for the radioactive noble gases.
- c) System operational requirement

TEG [GWTS] is put into operation in normal operating conditions of the plant, such as power operation, some transients and shutdown condition (including shutdown for refuelling), to flushing the relevant system equipment and treat the radioactive waste gas before it is discharged via Nuclear Auxiliary Building Ventilation System (DWN [NABVS]) to environment.

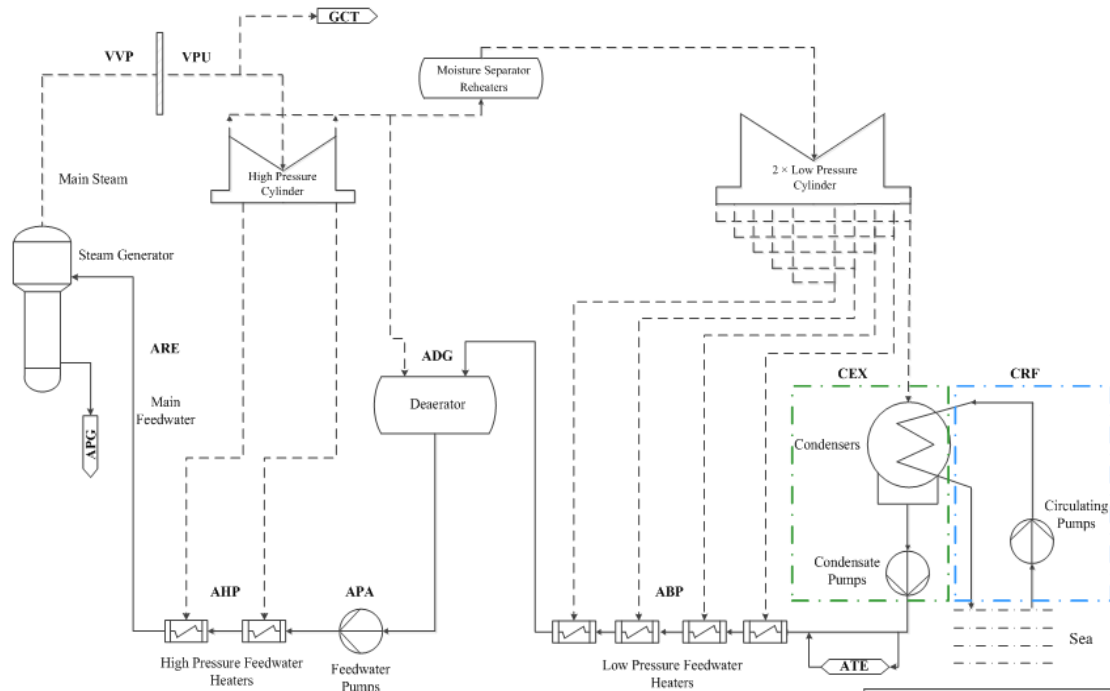
- d) Substantiation of system requirements

The system has been design that can meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [53], and the operation control is presented in the *System Operation and Maintenance*, Reference [54].

## 21.5 Secondary Water Chemistry and Associated Systems

### 21.5.1 Description of Secondary Circuit

The secondary coolant is conditioned in order to control the corrosion of secondary circuit materials to maintain the integrity of the secondary side at the SG tubes, including primary shell (channel head), tube sheet and secondary shell; and reduce the heat transfer degradation of SG. The main equipment of the secondary circuit covers the SG, steam turbine, Moisture Separator Reheater (MSR), condenser, condensate pump, low pressure feedwater reheater, deaerator, feedwater pump and high pressure feedwater reheater. The simplified diagram of secondary circuit is shown in F-21.5-1. The detailed description is presented in Chapter 11.



F-21.5-1 Simplified Diagram of Steam and Water Conversion Systems

The basic design parameters of secondary side are shown in the T-21.5-1.

T-21.5-1 Basic Design Parameters of the Secondary Side

Parameter	Value
Design Temperature of Secondary Side	303°C
Main Feedwater Inlet Temperature	228°C

### 21.5.2 Material Selection

Material selection of the SSC of secondary circuit aims to reduce the risk due to corrosion of SSC, the most notable of which is Flow-Accelerated Corrosion (FAC).

According to the *Material Selection Methodology*, Reference [23], achieving good resistance to ageing and degradation throughout the design life against the risk of performance degradation and failure of SSC is a key principle for material selection.

UK HPR1000 components in the secondary circuit do not contain copper. The main materials used in secondary circuit for the UK HPR1000 are listed in the following tables (T-21.5-2, T-21.5-3 and T-21.5-4).

In the secondary circuit, stainless steel, nickel based alloy, as well as carbon or low alloy steels with the Cr content controlled are selected to reduce FAC. Material Selection Report of Main Feedwater Line will be submitted to demonstrate judicious

material selection against FAC. In this report, SSC of the secondary circuit will be screened according to their susceptibility to FAC. For SSC that is highly susceptible, the demonstration of judicious material selection against FAC will be conducted.

#### T-21.5-2 Materials of Major Assemblies in SG Secondary Side

<b>Equipment and Component</b>	<b>Type of Material</b>	<b>Chapter of Code</b>
Secondary Shell Cans (including feedwater nozzles)	Low alloy steel	ASME SA-508 Gr.3 Cl.2 (Cr: 0.10 wt. %-0.25 wt.%)
Shell Cone	Low alloy steel	ASME SA-508 Gr.3 Cl.2 (Cr: 0.10 wt. %-0.25 wt.%)
Steam Drum Head (including steam outlet nozzle)	Low alloy steel	ASME SA-508 Gr.3 Cl.2 (Cr: 0.10 wt. %-0.25 wt.%)
Tubesheet	Low alloy steel	ASME SA-508 Gr.3 Cl.2 (Cr: 0.10 wt. %-0.25 wt.%)
Feedwater assemblies	Low alloy steel	ASME SA-335 P22, SA-234 WP22 (Cr: 1.9 wt. %-2.6 wt.%)
Tube support plate	Stainless steel	ASME SA-240 Type 410S
Separator	Stainless steel	ASTM A 511 MT304L ASME SA-240 Type 304L
Main Feedwater Header J-tube Assembly	Nickel based alloy	ASME SB-167 UNS N06690
Tubes	Nickel based alloy	ASME SB-163 UNS N06690

#### T-21.5-3 Materials for the Pipeline of Secondary Systems

<b>System Pipeline</b>	<b>Material type</b>
Feedwater pipeline	Carbon steel (Cr: 0.2 wt. %-0.3 wt.%)
Condensate system pipeline	Carbon steel (Cr: 0.2 wt. %-0.3 wt.%)
Drain water pipeline	Stainless steel

#### T-21.5-4 Materials of Equipment in Secondary Systems

<b>Equipment</b>	<b>Assemblies</b>	<b>Material type</b>
------------------	-------------------	----------------------



Feedwater heater	Impingement plate	Stainless steel
	Tubing	Stainless steel
Moisture separator reheater	Tubing	Stainless steel
Condenser	Tubing	Titanium alloy

Material Selection Summary Report will be produced to summarise the outcome of all the material selection reports, ageing and degradation reports, referring to the safety case for reactor chemistry.

### 21.5.3 Chemistry Control

The main objectives of the secondary water chemistry are to maintain the integrity and performance of the SGs and secondary systems through chemistry conditioning, material selection and clean-up design to avoid the following risks:

a) SG tube corrosion and heat transfer degradation

In general, the materials of SG tubes (Alloy 690TT) and tube support plate (stainless steel) have very low corrosion rates, but corruptions e.g. pitting and IGA/SCC would occur in the SG if concentrated impurities (e.g. sodium, chloride and sulphate) existed. The corrosion products released from the secondary circuit surface and transported into the SG could also contribute to the formation of deposit that leads to SG tube fouling and tube support plate clogging. These phenomena can lead to the heat transfer degradation and create confined areas within which localised corrosion of SG tubes can occur, together with the detrimental effects of those impurities.

b) General corrosion and FAC in secondary systems

FAC is a corrosion of carbon steel and low alloyed steels accelerated by increased flow velocity which is caused by the protective oxide layer on carbon steel and low alloyed steels being dissolved and removed by water. FAC could occur under both single and two-phase flow conditions but does not occur in dry or super-heated steam conditions.

Several influence factors are identified for the FAC mechanism:

- 1) Temperature;
- 2) Material composition (chromium content);
- 3) Redox environment (oxygen content and hydrazine injection);
- 4) Hydrodynamic factors (flow velocity, geometry and surfaces roughness);
- 5) pH value.

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FAC mitigation is a major consideration of secondary water chemistry, because it could lead to significant damage of the secondary components and lead to corrosion products entering the SGs.

The determination of chemistry control parameters is based on the maintenance of SG and materials integrity. The *Topic Report on Power Operation Chemistry*, *Topic Report on Startup and Shutdown Chemistry*, and *Topic Report on Commissioning Chemistry*, Reference [37], [38] and [39] provide the chemistry regime and provisions for the UK HPR1000.

#### 21.5.3.1 Chemistry Regime

The optimal chemistry conditioning and impurity control contribute to the minimisation of the corrosion, fouling and clogging risk of SG tube and tube support plate. It also prevents impurity ingress and corrosion products transferring to the secondary side of SG, together with appropriate material selection and clean-up systems.

##### a) pH

The general corrosion and FAC of secondary side materials is dependent on pH. Optimised pH will reduce corrosion in the secondary steam-water circuit and limit corrosion products entering into SG, thus reduce SG fouling, clogging and corrosion. The *Topic Report on the Application Analysis of Alkaline Agent in the Secondary Circuit*, Reference [55], provides further information regarding the justification for All Volatile Treatment (AVT) in the UK HPR1000 secondary circuit.

##### 1) pH impact on generalised corrosion

Carbon steel and low alloyed steel in the secondary systems are sensitive to generalised corrosion. At operating temperature of the secondary side, the pH impact is related with the solubility of the protective oxide layer. Minimal corrosion is found to occur when  $\text{pH}_{25^\circ\text{C}}$  is higher than 9.

##### 2) pH impact on FAC

Optimal pH could contribute to a decrease of FAC rates in the secondary circuit. The selection of pH control reagent and localised pH at sensitive areas to FAC is taken into consideration for the justification of optimal pH range.

##### 3) pH impact on SG fouling and clogging

The SG fouling phenomena is caused by corrosion products entering into the SGs and depositing on the surface of SG tubes. The deposit can grow and solidify to form a thermally resistant layer which impacts the heat removal

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function of SG tubes from the RCP [RCS].

Corrosion products entering the SG are also the major cause of tube support plate clogging phenomena. Iron oxides e.g. magnetite particles could precipitate in the tube support crevices and interstices between the SG tubes and tube support plate.

The pH impact on the SG fouling and clogging is rated at its reduction of the general corrosion and FAC rates, thus reducing the corrosion products transport into the SG.

AVT in the UK HPR1000 is performed by volatile chemicals being added into the feedwater. Hydrazine is added for scavenging the trace amount of oxygen and ammonia is added for pH control. The AVT allows for no other chemicals to react in the steam generator. It is based entirely on the removal of oxygen and the exclusion of other contaminants from the feedwater before entering the SG.

b) Dissolved oxygen

Oxygen reacts with various materials to form corrosion products, including stainless steel at high temperatures, carbon steel at various temperatures and copper alloy in alkaline condition. The main hazards caused as a result of these corrosion products within the secondary circuit include: increasing the amount of sludge in SG, increasing corrosion on the secondary circuit of heat transfer tube of SG, and increasing the SCC risk of stainless steel. Even if there is a low concentration of dissolved oxygen in coolant, it will have a harmful effect on the IGA of the pipeline.

In order to protect SG materials, the dissolved oxygen concentration is controlled during both normal operation and commissioning. The bulk of oxygen is removed by the deaerators of the Feedwater Deaerating Tank and Gas Stripper System (ADG [FDTGSS]).

Hydrazine is injected into the secondary feedwater cycle as an oxygen scavenger and reductant, in order to maintain the reducing condition in the secondary water. Hydrazine does decompose at high temperatures into  $\text{NH}_3$  and  $\text{N}_2$ , which contributes to an increase of pH in feedwater.

1) Oxygen/hydrazine impact on IGA/SCC

The IGA/SCC phenomena are directly related with the electrochemical potential. In oxidising conditions the risk of IGA/SCC increases. Dosing of hydrazine as a reducing reagent is considered necessary to prevent IGA/SCC by decreasing the corrosion potential of metal in the secondary circuit e.g. Alloy 690TT, stainless steel, carbon steel and low-alloyed steels.

2) Oxygen/hydrazine impact on FAC

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In terms of SG design and operation, corrosion of SG tubes is the major issue affecting selection of water chemistry parameters. Low oxygen together with optimal pH contributes to decrease in the FAC rate, but very low oxygen levels could lead to accelerated FAC with low pH. The presence of hydrazine could adversely affect FAC if the hydrazine concentration is reduced and the oxygen concentration falls below the critical value to maintain a stable oxide layer.

c) Impurity control

Impurities can have a detrimental impact to the secondary system. This impact consists of four groups which are generally considered responsible for corrosion of SG tubes in confined areas:

- 1) Highly concentrated caustic impurities e.g. sodium;
- 2) Sulphate species which could come from resin thermal decomposition;
- 3) Reaction products from the sulphate species in a reducing condition (and associated species like sulphides, sulphates and thiosulphates);
- 4) Highly concentrated salty solutions, coming from condenser leakages e.g. sodium, chloride.

To prevent corrosion, for example IGA/SCC in the secondary circuit, as well as SG fouling and clogging, the following impurities are limited in the secondary circuit: sodium, cation conductivity, chloride, sulphate, silica, iron, and lead.

Impurities that can cause corrosion to the boundary materials in the secondary circuit include sodium, chloride, sulphate and dissolved oxygen (discussed in the previous sub-chapter). These impurities can also cause localised corrosion of boundary materials. These impurities are mainly from: makeup water, chemical additives, condenser leakage and resin decomposition.

To prevent corrosion e.g. IGA/SCC in secondary circuit, as well as SG fouling and clogging, the following impurities are limited in the secondary circuit:

1) Sodium

In the secondary circuit of a PWR, sodium is the main cause of IGA of SG. Sodium can become concentrated within crevices inside SGs, leading to caustic conditions which may result in IGA/SCC of nickel-based alloys and stainless steels. Sodium can also be present in the secondary circuit for the slippage from the ion exchange resin due to selectivity issues with ammonia and as an impurities following regeneration of the cation bed. Sodium can also be present in the secondary coolant due to sea water ingress from leaking condenser tubing.

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2) Cation conductivity

Cation conductivity measurement is performed to assess for the presence of anionic or organic impurities. A small amount of chlorides or sulphates could result in cation conductivity variations.

3) Chloride

SCC of stainless steel can be induced by chloride in the primary and secondary circuits of a PWR under high temperature and in aerobic conditions. Alloy 690TT has high resistance to chloride-induced stress corrosion.

Although Alloy 690TT has good resistance to chloride stress corrosion, SG chloride levels are restricted by the need for high water quality for AVT control. The presence of chloride in the blowdown is normally indicative of a condenser leak, generally detected by an increase in cation conductivity.

The magnitude of such a leak can be determined from blowdown rate and chloride concentration in the makeup water, blowdown water and condenser cooling water.

4) Sulphate

In oxidising and acid condition, sulphates can attack Alloy 690TT. But Alloy 690TT has a very good resistance to SCC due to sulphates in neutral or mildly alkaline condition. In AVT condition and very low concentration of impurity concentrations, sulphates do not lead to SCC of Alloy 690TT. In the reducing condition of the secondary circuit (as a result of hydrazine addition), sulphate can cause IGA of the heat transfer tube of the secondary side of SG as the fully oxidised specie ( $\text{SO}_4^{2-}$ ) can be reduced by hydrazine to a reduced sulphur species.

5) Silica

Silica is a volatile element whose concentration in the steam depends on the pH of the water in the SGs, the silica content and steam pressure.

If the silica content is reduced in the SGs, its concentration in the steam can be minimised and silica deposit are avoided on the turbine blades and valves.

6) Iron

The oxidising state of corrosion products is a key factor in determining their aggressiveness towards materials. The presence of hydrazine in the secondary circuit is to keep iron in an insoluble magnetite form, which is not aggressive to tube alloys.

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7) lead

Lead assisted stress corrosion cracking can affect all steam-generator tubing materials of nickel alloy and the physical chemistry of lead compounds. The possible sources of lead in the secondary system of PWRs are from the materials, makeup water and additions. According to the state-of-knowledge regarding lead transport, the quantitative recommendation of specific concentration limits cannot be technically justified. However, it is available to monitor in the laboratory for the trending once founded in the circuit.

Elevated ionic impurities have been found to be present in sludge piles or crevices, these have demonstrated the ideal conditions which are conducive to denting, resulting in localised stress conditions within the pipework.

Further information on the consideration of impurities and the determination of concentration limits is provided in the *Topic Report on Impurity Control for the Operation*, Reference [43].

#### 21.5.3.2 Chemistry Provisions for Operation

The chemistry regime for operation for the UK HPR1000 is defined based on the reference plant of HPR1000 (FCG3), which has been developed using OPEX from the similar PWRs of CGN. The normal operating conditions of the secondary circuit contain startup, power operation and shutdown.

a) Commissioning

The chemistry provisions for commissioning and operation for the UK HPR1000 are based on the reference plant of HPR1000 (FCG3).

Industry OPEX will be taken into account when developing the commissioning chemistry regime and the principles applicable to chemistry commissioning for the UK HPR1000 as described in the *Topic Report on Commissioning Chemistry*, Reference [39].

The activities for the secondary circuit in the commissioning phases for the UK HPR1000:

- 1) The secondary side of SG is in layup condition before HFT;
- 2) Water quality control during HFT is same as normal operation.

b) Startup

During plant startup, the dissolved oxygen is controlled to minimise the corrosion of secondary circuit and keep a reducing medium in the SG. The oxygen concentration is limited within 100µg/kg when the temperature is higher than 120°C, which is generally considered as a temperature threshold beyond which

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corrosion issues can appear in some conditions, especially oxygenated media. Removal of oxygen depends on the deaerators of the ADG [FDTGSS] and addition of hydrazine.

The impurity level of secondary circuit during plant startup needs to be controlled to minimise the inventory of corrosion products in the feedwater, which could be transported to the SG. The parameters of sodium, cation conductivity and suspended solids are monitored in the feedwater as indicators of impurity ingress to the SG. The APG [SGBS] is operated with the maximum blowdown rate to reach the impurity level of power operation in the SGs.

The Condensate Polishing System (ATE [CPS]) is put on-line during plant startup to remove the impurities of corrosion products, dissolved solids and other impurities from the condensate by condensate polishers and ensure the feedwater quality during startup.

c) Power operation

The parameters with their operating window and hard limits during plant power operation are those currently considered appropriate to protect the SGs and balance of plant.

d) Shutdown

1) Hot shutdown

During hot shutdown, the feedwater dissolved oxygen concentration is also limited within 100µg/kg by hydrazine addition. The hydrazine concentration is the same as that used during power operation.

Due to the thermal exchange between the primary and secondary coolant being reduced, the water chemistry conditions in the SGs is less aggressive during hot shutdown than it is during power operation; however, the reduction of thermal exchange could also lead to the hide-out return phenomena, leading to pollutants concentrated in SG crevices being released, resulting in an increase of impurities e.g. sodium, cation conductivity, etc. The impurities have to be limited in order to maintain an optimal operating condition.

2) SG Layup

The SG layup during shutdown is to keep the SGs in a clean state and allow startup in good condition. Two types of SG layup including wet layup and dry layup could be performed depending on the shutdown operation.

– Wet layup

The SG wet layup with chemical treated water is desirable to minimise

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corrosion and oxidation during plant shutdown and subsequent startup and power operation. Protection is provided by ammonia for pH control and hydrazine to maintain a protective oxidising film and a reducing condition.

The specification of SG wet layup depends on the duration. For a short layup of less than a week, the SG does not need to be drained and filled with the secondary medium; the water quality required is the same as hot shutdown. For layup of more than one week, additional ammonia and hydrazine are injected into the SGs to limit the risks of corrosion.

– Dry layup

Dry layup can also be implemented when maintenance activities require it and before the first fill of the SGs. The relative humidity is controlled and limited to limit the condensation of impurities, especially chlorides, which could be present in the air.

#### **21.5.4 Substantiation of System Requirement**

##### 21.5.4.1 Steam Generator Blowdown System

###### a) System Functional Requirements

The blowdown and treatment functions of APG [SGBS] are non-safety related. In order to maintain the SG secondary side water chemistry within the chemistry specifications, the continuously blowdown water from the SG secondary side is required to be performed by the APG [SGBS].

Furthermore, in order to ensure the reuse of the secondary side water resource, the purification function is required to be performed by the APG [SGBS].

###### b) System Design Requirements

The chemistry design requirements for APG [SGBS] include:

- 1) The blowdown flowrate should be able to maintain the SG secondary water chemistry during normal operation, when the feedwater meets the water chemistry specification;
- 2) Demineralisers shall be designed to remove impurity ions from the blowdown water;
- 3) Filters shall be equipped to protect the demineralisers from being plugged by solid impurities;
- 4) Resin trap filters shall be equipped to prevent resin fragment from entering the condenser;



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5) The discharge of the blowdown flow shall be considered when the chemistry parameter cannot meet the requirement of Condensate Extraction System CEX [CES];

6) Monitoring measures shall be designed to monitor the secondary side water chemistry.

c) System Operational Requirements

During normal operation, the blowdown operation is required to be performed continuously. If the chemical character beyond the limitation defined in the chemistry specification, the fall back action is required to be taken.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above and detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Secondary circuit*, Reference [56]. The system configuration is presented in the *System and Component Design*, Reference [57], and the operation control is presented in the *System Operation and Maintenance*, Reference [58].

21.5.4.2 Condensate Polishing System

a) System functional requirement

The function of ATE [CPS] is non-safety related, which is designed to remove traces of silicon, copper, iron and dissolved salts from the condensate by filters and ion exchanger, to ensure the feedwater and steam qualities meet the requirements during the following conditions:

- 1) When there is a condenser tube leakage;
- 2) During the startup of plant.

b) System design requirement

The chemistry design requirements for ATE [CPS] include:

- 1) Design capacity of the full load steam flow during normal operation;
- 2) Clear-up ion resin can be regenerated, impurity in resin and the fine resin can be controlled;
- 3) Water quality after clean-up unit meets the requirement of defined limits of feedwater;
- 4) Selection of anti-corrosion materials for high concentration of impurity ingresses from cooling water.

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c) System operational requirement

The ATE [CPS] is put into operation in case of condenser leakage, to prevent the impurity ingress e.g. chloride from the circulating water to SG, and provide extra time for unit maintenance or shutdown when serious condenser leakage is detected.

The chemistry operating requirements for ATE [CPS] include:

- 1) Put into operation in case of condenser leakage according to the monitoring information;
- 2) Resins and the periods of regeneration meet the requirement of continuous operation;
- 3) System is put into stand-by after plant startup.

d) Substantiation of system requirements

The ATE [CPS] consists of a full flow bypass design for operation flexibility. The polishing units of ATE [CPS] mainly consist of five multiple cation polishing units, five multiple mixed bed polishing units and 3×50% booster pumps.

ATE [CPS] is put into operation during startup of the plant. Condensate enters into the ATE [CPS] via the condensate header and loops through the cation polishing units and the mixed bed polishing units so as to allow removal of the suspended solids and ionic impurities. The purified condensate is pumped back to the condensate header by the booster pumps.

During the plant power operation, the ATE [CPS] is in a standby state. In case of condenser leakage, the ATE [CPS] is put into operation to remove the impurities from the condensate and give the operator more time and flexibility of operation before shutdown.

The system has been designed to meet the relevant requirements mentioned and detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Secondary circuit*, Reference [56]. The system configuration is presented in the *System and Component Design*, Reference [59], and the operation control is presented in the *System Operation and Maintenance*, Reference [60].

#### 21.5.4.3 Chemical Reagents Injection System

a) System functional requirement

The function of the Chemical Reagents Injection System (SIR [CRIS]) is to provide a chemical means of controlling the water chemistry of the feed cycle in order to minimise corrosion and deposition of solids in the steam generators. In

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addition, a separate chemical injection facility provides corrosion inhibition for the closed loop cooling facilities.

b) System design requirement

The system is designed to inject three types of chemicals into the water systems.

- 1) Alkaline reagent, e.g. ammonia and hydrazine are injected into the main feed cycle at the condenser discharge, deaerator downcomers, deaerator recirculation line and the NI feedwater dosing points.
- 2) Tri-Sodium Phosphate (TSP) is introduced into the closed loop cooling system. The system consists of two sets of dosing devices located within the turbine hall with stainless steel pipework running from the dosing devices to the relevant dosing points.

c) System operational requirement

During normal operations, chemicals are normally dosed continuously to make up losses due to steam generator blow down and condenser vacuum. The rate of dosing is varied as indicated by the SIT [FCSS].

d) Substantiation of system requirements

During system design process, the selection of equipment is configured through the functional requirements, as well as the material selection. The system has been designed to meet the relevant requirements and detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Secondary circuit*, Reference [56].

## 21.6 Auxiliary Water Chemistry and Associated Systems

### 21.6.1 Description of Auxiliary Circuits

Auxiliary circuits in Chapter 21 are focused on the control of water quality for the SFP water, component cooling water and makeup water, in relation to the chloride pitting corrosion.

### 21.6.2 Material Selection

Material selection of SSC of auxiliary systems related to chemistry aims to minimise the corrosion of material and thence to minimise radioactive source terms.

The materials selected for the SFP racks which contain fixed sources of boron as a neutron absorber are aluminium-boron carbide composite. It is fixed outside the wall of the storage cell with stainless steel cover plate. BORAL<sup>TM</sup> is not used in the SFP of the UK HPR1000. Detailed information of neutron absorber is provided in the *Material Selection Report of Neutron Absorber of UK HPR1000*, Reference [61].

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The SFP liner is made of stainless steel. The pipes of auxiliary cooling water systems for RRI [CCWS], Safety Chilled Water System (DEL [SCWS]) and Operational Chilled Water System (DER [OCWS]) are all made of carbon steel.

#### T-21.6-1 Materials of Equipment and Pipeline in Auxiliary Systems

<b>Equipment and Pipeline</b>	<b>Material type</b>
Demineralised water storage tanks	Stainless steel
Demineralised water pipeline	Stainless steel
Closed cooling water pipeline	Carbon steel
Boric acid storage tanks	Stainless steel
SFP liner	Stainless steel
SFP racks	aluminium-boron carbide

### 21.6.3 Chemistry Control

The demonstration and justification of chemistry control parameters are based on the materials ageing of related systems. The *Topic Report on Power Operation Chemistry*, *Topic Report on Startup and Shutdown*, and *Topic Report on Commissioning Chemistry*, Reference [37], [38] and [39] provide the chemistry regime and provisions for the UK HPR1000.

#### 21.6.3.1 Chemistry Regime

##### a) Water quality for SFP

The SFP water chemistry is controlled to reduce corrosion of the spent fuel assemblies and the structural components through filtration and the surface skimming to maintain visibility in the SFP. Water chemistry is controlled to ensure that radionuclides are contained within the SFP.

SFP comes in contacts with the primary coolant during the refuelling. The quality of SFP water is therefore controlled to the same level as the primary coolant, including the soluble boron concentration and the impurities.

##### b) Water quality for cooling water

Neutral demineralised water is corrosive to the carbon steel, so the water used in the cooling water systems needs to be conditioned with alkaline agent. Compared with the other corrosion inhibitors, Tri-Sodium Phosphate (TSP) is a non-volatile base that maintains a sufficient high pH to minimise the corrosion of the carbon steels. In addition, the phosphate also enables the formation of oxides with protective properties.

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For the closed cooling circuits even those in contact with air, TSP constitutes a more efficient corrosion inhibitor than volatile bases whose efficiency decreases, due to their volatility leading to a lower pH with more carbonation risk.

In addition, TSP has been used in many PWRs including CPR1000. Considering the different material makeup of the components, a pH value of more than 10 (treated with TSP) is used to prevent corrosion for the UK HPR1000.

c) Water quality for make-up water

The make-up water, which is the one source of impurity into the coolants, is supplied by the demineralised water production and distribution system. Therefore, the water quality control of the demineralised water is controlled at source, including the conductivity, silica, chloride/Fluoride and sodium.

21.6.3.2 Chemistry Provisions for Operation

a) Clean-up for SFP water

The provision of clean-up of SFP water is demonstrated in the Sub-chapter 21.4.3.

b) Water quality control for cooling water

The provision of water quality control includes the following measures:

- 1) pH condition: TSP solution is added to the cooling water according to the NI Chemical Reagents Distribution System (SIH [CDS]).
- 2) Refilling; when the impurity in the cooling water exceeds the limit, this can be refilled by the make-up water.

c) Water quality control for demineralised water

The provision of water quality control of demineralised water is sampled and monitored to meet the make-up requirement.

**21.6.4 Substantiation of System Requirement**

21.6.4.1 Fuel Pool Cooling and Treatment System

a) System Functional Requirements

The purification function of the PTR [FPCTS] is non-safety related, which is designed to remove the impurities and dissolved radionuclides from the water to maintain the chemical concentration and to maintain the visibility of the water.

The PTR [FPCTS] is also required to maintain the suitable temperature in the SFP to ensure the safety of nuclear and environment.

b) System Design Requirements

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The chemistry design requirements for PTR [FPCTS] include:

- 1) The purification flowrate shall meet the requirement of controlling the concentration of radionuclides below the limit value in the SFP.
- 2) The design of the PTR [FPCTS] mixed-bed demineraliser shall meet the requirement of removing the ionic impurities during the service life, and the design of the filters meets the requirement of removing suspended particles.
- 3) The design of the PTR [FPCTS] cooling trains shall meet the requirement of maintaining the suitable temperature in the SFP.

c) System Operational Requirements

The chemistry operating requirements for the PTR [FPCTS] include:

- 1) During normal operation, the purification loop of the SFP is required to operate continuously. The SFP skimming loop is required to continuously operate.
- 2) The cooling trains of the PTR [FPCTS] are required to operate to maintain the water temperature in the SFP during the normal operation.
- 3) During fuel handling, the skimming loop in the reactor pools is required to operate usually to provide good visibility.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above and detailed substantiation is demonstrated in the *Design Substantiation Report on Associated Chemistry Control Systems: the Spent Fuel pool*, Reference [62]. The system configuration is presented in the *System and Component Design*, Reference [63], and the operation control is presented in the *System Operation and Maintenance*, Reference [64].

#### 21.6.4.2 Component Cooling Water System

a) System Functional Requirements

The Component Cooling Water System (RRI [CCWS]) falls into the category of Auxiliary System. RRI [CCWS] provides cooling water for the users of Nuclear Island (NI) systems (including nuclear auxiliary systems and safety-classified systems) under normal operating conditions.

b) System Design Requirements

RRI [CCWS] system through the following method to satisfy the chemistry specifications:

- 1) The NI Chemical Reagents Distribution System (SIH [CDS]) provides

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$\text{Na}_3\text{PO}_4$  for RRI [CCWS].

- 2) Monitoring of chemistry parameters of RRI [CCWS] by local sampling.

The chemistry related functions above are required to be performed during normal operation; RRI [CCWS] is not required to deal with accidents.

- c) System Operational Requirements

In normal operation, the SIH [CDS] provides  $\text{Na}_3\text{PO}_4$  for RRI [CCWS] in case of the water quality does not satisfy the chemistry specifications.

- d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [65], and the operation control is presented in the *System Operation and Maintenance*, Reference [66].

#### 21.6.4.3 Demineralised Water Distribution System

Demineralised water distribution systems contain NI Demineralised Water Distribution System (SED [DWDS (NI)]) and CI Demineralised Water Distribution System (SER [DWDS (CI)]).

SED [DWDS (NI)] has a set of neutral demineralised water storage and distribution tanks. These are used to receive and storage demineralised water from the demineralised water production system,

SER [DWDS (CI)] has a set of alkaline demineralised water storage and distribution tanks. Dosing of the ammonia solution into the demineralised water from the demineralised water production system occurs before entering the storage tanks.

## 21.7 Accident Chemistry and Associated Systems

Accident chemistry is not a separate field and should be considered suitably and sufficiently in the fault study and severe accident scenarios. In the UK HPR1000, accident chemistry contains three main aspects, including fission product control, combustible gases control, and core melt and in-vessel corium retention.

The detailed assessments of fault study and severe accident related to accident chemistry are incorporated in PCSR Chapter 12, Chapter 13 and relevant accident analysis documents.

### 21.7.1 Fission product chemistry

Fission product chemistry includes chemical effects in the fault study and severe accident source term analysis.

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For fault study source term analysis, chemical related assumptions that are critical to fission product control are identified, which includes pH management and iodine chemistry, decontamination of the SFP. They are applied in the specific DBC source term analysis according to the *Design Basis Accident Source Term Methodology Report*, Reference [67].

For severe accident source terms analysis, fission product chemistry includes fission product physical and chemical forms, iodine chemistry, and pH analysis etc. Physical and chemical form plays an important role in the process of fission products release, transport, and retention. The chemical forms of caesium, iodine, tellurium, and molybdenum have been researched because of their volatility and chemical reactions on each other. The pH of In-containment Refuelling Water Storage Tank (IRWST) sump is modelled and analysed by Accident Source Term Evaluation Code (ASTEC), and the results prove the pH control of IRWST in the long term of accidents is effective. Based on the analysed results of pH, iodine chemistry in the severe accident is analysed. Iodine chemistry includes gaseous phase chemistry, liquid phase chemistry, and mass transfer reactions. The results prove that the volatile iodine released from IRWST is limited and accepted. The analyses of physical and chemical forms, iodine chemistry and pH assessment in the severe accidents are demonstrated in the *Severe Accident Source Term Analysis*, Reference [68].

The important considerations about fission product chemistry are listed below:

a) pH management and iodine chemistry

Fission product of volatile iodine is one of the most important parameters needed to evaluate the potential radiological consequences under accident condition, while pH value is the key factor in determining the extent of airborne iodine. Establish and maintain an alkaline pH within the IRWST can minimise the release of volatile iodine following pipe breaks within containment, since alkaline conditions favour the formation of soluble iodide ions and elemental iodine is only stable in acidic and oxidizing conditions. The pH value of the IRWST/sump in a PWR is required to be controlled at 7 or greater to stabilise iodine in the solution as iodide or iodate ions.

The passive pH adjustment baskets of Safety Injection System (RIS [SIS]) are designed to control the IRWST pH value at 7 or greater to stabilise iodine in the solution as iodide or iodate ions. The adjustment basket containing granulated TSP is made of stainless steel with a meshed front which permits TSP contact with water. The basket is placed in the reactor building and in the water flow path to the IRWST after the occurrence of a Loss of Coolant Accident (LOCA). In the case of a LOCA, the borated water flowing from the break dissolves the TSP granules in the basket and enters into the IRWST and the TSP is used to maintain the sump pH above 7.



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b) Decontamination of the SFP

The decontamination factors of SFP water for elemental iodine and organic iodine are assumed to be 500 and 1 respectively. Since the lowest water depth above the spent fuel meets the minimum water level requirement of SFP described in the *Design Basis Accident Source Term Methodology Report*, Reference [67].

### 21.7.2 Combustible gases chemistry

Combustible gases chemistry in the containment includes production chemistry, combustible gases distribution, combustion phenomena, and the chemistry of the Passive Autocatalytic Recombiner (PAR).

During severe accidents, the zirconium in the fuel cladding reacts with steam to produce hydrogen and release heat. The heat released from this reaction elevates the temperature of the fuel cladding and in turn accelerates the reaction rate. This reaction tends to be quick and not to be stopped until the isolation of fuel clad to the oxidant occurs when it has melted through to corium. For a typical severe accident scenario, hundreds of kilograms of hydrogen could be generated during the in-vessel process. In a similar manner to zirconium, stainless steels may be oxidised by high temperature steam, but the heat released from steel oxidation is several orders of magnitude lower and the reaction rate is much slower.

The hydrogen released from the primary loop then diffuses or jets into the containment, mixes with steam and air and forms combustible gases. If the hydrogen concentration is high enough, the combustible gases may burn to produce high temperature and pressure which will threaten the integrity of the containment. For the UK HPR1000, there are mainly two types of combustion mode which can lead to different consequences on the containment. When the premixed hydrogen cloud reaches the flammability limit, the hydrogen may burn in deflagration mode. A slow deflagration is allowable since it generates bearable pressure increase and eliminates the hydrogen simultaneously. However, if the hydrogen concentration is much higher and there is an obstruct along the flame progression, the deflagration flame tends to be accelerated by the turbulence effect. In this case, the resulted pressure may become significant. If the accelerated flame is speeded up to higher than sonic speed, the shock wave tends to form ahead of the flame and detonation with the scheme of Deflagration-Detonation-Translation (DDT) may occur. In this case, the pressure pulse may threaten the integrity of containment.

To mitigate the hydrogen risk, PARs are adopted in the UK HPR1000 to eliminate the hydrogen and thus reduce the hydrogen concentration. The PARs use catalytic material (e.g., Palladium or Platinum based) to help the oxidation of hydrogen in normal atmospheric condition. When the hydrogen concentration reaches the threshold value (e.g., 2 vol%), the PARs start automatically. The gas mixture flows into the inlet of PARs and the oxidation of hydrogen with oxygen occurs at

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atmospheric condition on the catalytic surface to produce steam and heat. The heat released by chemical reactions can increase the atmosphere temperature and promotes the reaction products to flow upward. The PARs are passive and therefore requires no external inputs to function.

Detailed description of the combustible gases chemistry can be found in the *Assessment of containment combustible gas control system by lumped parameter method*, Reference [69].

In the UK HPR1000, 29 sets of PARs are adopted to eliminate the hydrogen in severe accidents. Among the 29 sets of PARs in the UK HPR1000, there are 2 PARs designed with the same equipment qualification requirement as that for the 27 PARs combined with a higher level function class of F-SC2 because these 2 sets of PARs are designed for DBC conditions while also available in severe accident conditions. Therefore, all the 29 sets of PARs are capable of managing hydrogen risk during severe accident conditions.

The hydrogen control aim is decided as follows:

- a) Hydrogen concentration must be limited in containment during and following severe accident conditions, uniformly distributed, to less than 10 vol%;
- b) Following severe accident conditions, if local hydrogen flame occurs, the integrity of containment should be maintained.

In the UK HPR1000, the analysis and assessment of EUH [CCGCS] are performed through a systematic methodology, which is also described in the *Overall Methodology of Severe Accident Analysis*, Reference [70]. ASTEC code is used to perform the analysis of hydrogen sources and evaluate global hydrogen risk with EUH [CCGCS], *Assessment of Containment Combustible Gas Control System by Lumped Parameter Method*, Reference [69].

The limiting case for EUH [CCGCS] is studied thoroughly by a 3D Computational Fluid Dynamics (CFD) code GASFLOW, Reference [71]. The results show that the performance of the PARs management to control the containment concentration below 10 vol%. The DDT can be safely excluded for the containment during the whole process of accident. Pressure loads induced by slow deflagration or flame acceleration will be assessed in the Assessment of EUH [CCGCS] by CFD method, to evaluate the threat to the integrity of containment. The assessment of EUH [CCGCS] for the reference plant shows that the hydrogen explosion risk can be prevented and the integrity of the containment is not threatened.

In DBCs, the hydrogen generated in the containment is eliminated by two sets of F-SC2 PARs, which meet the Single Failure Criteria (SFC) and redundancy requirement. According to Reference [72], hydrogen volume concentration in the containment will never exceed the flammable limit of 4% during DBCs.

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### 21.7.3 Core melt and in-vessel corium retention

Accident chemistry in core melt mainly considers the physico-chemical phenomena which affect the melting process, sources of fuel heating, fuel morphology and so on. This progression involves the following issues, including:

- a) Metal-steam interaction, metal oxidation and release of volatile radionuclides which affect the sources of heat inside the RPV;
- b) The gradual change of the fuel morphology which is related to the fuel-cladding interaction, physical and chemical properties of the mixture;
- c) Radial and axial movement of molten material, sideward or downward relocation and thermal load to the RPV wall which will influence the focusing effect and challenge the RPV integrity.

As for the chemical aspects out of RPV, the chemical properties of coolant which have impact on the outside cooling will be considered. The detailed description of the core melt and in-vessel corium retention chemistry is provided in the *Assessment of In-Vessel Retention Strategy*, Reference [73]. Further analysis on the impact of the physical and chemical properties of materials will be provided.

### 21.7.4 Substantiation of System Requirement

#### 21.7.4.1 Containment Combustible Gas Control System

##### a) System Functional Requirements

The Containment Combustible Gas Control System (EUH [CCGCS]) performs the following chemistry related post-accident functions to satisfy the safety requirement:

- 1) Hydrogen removal under design basis accident conditions, which is FC2 safety function.
- 2) Hydrogen removal under severe accident conditions, which is FC3 safety function.

##### b) System Design Requirements

The following main equipment is designed to fulfil the functions:

- 1) The PARs are used to remove the hydrogen by combining the hydrogen and oxygen into water under ambient temperature conditions. There are 29 PARs in the recombiner sub-system.
- 2) During DBCs (particularly LOCA), two PARs are provided due to the single failure criterion and redundancy requirement are considered in design. The two PARs could also be used in severe accident conditions.

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3) In severe accident conditions, 27 PARs are dedicated to provide the hydrogen elimination function. The single failure criterion and redundancy requirement are not applied.

c) System Operational Requirements

The PARs, which are passive autocatalytic components, are put into operation passively when the hydrogen concentration in the containment rises up to the threshold value.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [74], and the operation control is presented in the *System Operation and Maintenance*, Reference [75]. Moreover, the capacity of the system is also evaluated in the accident analysis.

#### 21.7.4.2 Safety Injection System

a) System Functional Requirements

The safety injection function and the IRWST pH adjust function of RIS [SIS] are safety-related. In order to control the reactivity and maintain the water inventory compensation, the RIS [SIS] is required to inject borated water into the RCP [RCS] under the conditions of DBC-2/3/4 and DEC-A.

In order to keep the radionuclides in the sump water and reduce the possibility of stress corrosion, the pH value of the IRWST water source is required to be adjusted after accidents such as LOCAs.

The IRWST is required to be purified and mixed, which is non-safety related.

b) System Design Requirements

The chemistry design requirements for RIS [SIS] include:

1) The RIS [SIS] is required to inject borated water into the RCP [RCS] when receiving the safety injection signal in order to control the reactivity of the reactor and maintain water inventory;

The IRWST and the ACC is required to store borated water which serves as the water source during the safety injection. The water boron concentration is required to meet the boron concentration requirement under the shutdown phase, which is 1300mg/kg~1400mg/kg;

2) The pH value of the IRWST water source is required to be maintained above 7.0 after accidents such as LOCAs. This function is achieved by the passive pH adjustment basket containing granulated Tri-Sodium Phosphate (TSP);

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- 3) The IRWST water source is required to be purified by the PTR [FPCTS]. The IRWST water source is required to be mixed in order to homogenise the boron concentration.

c) System Operational Requirements

The chemistry operating requirements for RIS [SIS] include:

- 1) The safety injection lines are required to be filled with borated water and the safety injection pumps are required to be in the standby state when the reactor is in power operation, hot shutdown and hot standby;

The RIS [SIS] is required to inject borated water into the RCP [RCS] under the conditions of DBC-2/3/4 and DEC-A to control the reactivity of the reactor and maintain water inventory.

Moreover during IB-LOCA and LB-LOCA, the safety injection line of the Low Head Safety Injection (LHSI) can be switched to the simultaneous injection mode to the cold leg and hot leg (operated by the operator manually), which can avoid the crystallisation of boron on the fuel.

- 2) The passive pH adjustment basket is required to be set on the flow path of the borated water flowing from the break. The TSP granules in the basket are dissolved in the recirculation water to adjust the pH value of IRWST water source to alkaline after accidents such as LOCAs, or some other accidents where containment spray is required, etc.
- 3) The IRWST water source is required to be purified by the PTR [FPCTS].

Moreover, the IRWST is required to be mixed by the LHSI mini-flow lines to homogenise the boron concentration during plant normal operation.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [76], and the operation control is presented in the *System Operation and Maintenance*, Reference [77].

#### 21.7.4.3 Containment Filtration and Exhaust System

a) System Functional Requirements

During severe accident, the filtration assembly of Containment Filtration and Exhaust System (EUF [CFES]) can effectively detain radioactive aerosol and iodine in the exhaust gas.

b) System Design Requirements

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The chemistry related function is required to be performed after accidents. The radioactive aerosol and iodine in the exhaust gas during the discharge of the system can be effectively detained through the filtration assembly, which are specifically designed by supplier of the EUF [CFES]. The aerosol and iodine retention rates of the filtration are required to be more 99.9%.

c) **System Operational Requirements**

The isolation valves of the containment can be opened manually to start the system when the containment pressure is higher than the design pressure after 24 hours following severe accidents.

d) **Substantiation of system requirements**

The system has been designed to meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [78], and the operation control is presented in the *System Operation and Maintenance*, Reference [79]. Moreover, the capacity of the system is also evaluated in the accident analysis.

21.7.4.4 Containment Heat Removal System

a) **System Functional Requirements**

The EHR [CHRS] is required to remove radioactive iodine and reduce radioactivity in the containment effectively through containment spraying. The reactor pit flooding tank is required to be purified.

b) **System Design Requirements**

The chemistry design requirements for EHR [CHRS] include:

- 1) The EHR [CHRS] pump takes water from IRWST whose pH value is adjusted by passive pH adjustment basket containing granulated TSP to perform containment spraying function.
- 2) The spray ring design shall take the accident chemistry into account to meet certain coverage and spray particle size and finally to achieve the purpose of removing radioactive iodine and reducing radioactivity in the containment.
- 3) The reactor pit flooding tank is required to be purified periodically. This is achieved via the design and operation of the PTR [FPCTS].

c) **System Operational Requirements**

The chemistry operating requirements for EHR [CHRS] include:

- 1) The containment spraying function is performed during DEC-B, some DEC-A accidents and 24 hours after DBCs occurring; the chemical additive is added by RIS [SIS].

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2) The purification and sampling of the reactor pit flooding tank is required to be performed during normal operation of the plant.

d) Substantiation of system requirements

The system has been designed to meet the relevant requirements mentioned above. The system configuration is presented in the *System and Component Design*, Reference [80] and the operation control is presented in the *System Operation and Maintenance*, Reference [81].

## **21.8 Sampling and Monitoring**

### **21.8.1 General Principles**

#### 21.8.1.1 Scope of Sampling and Monitoring

Based on the IAEA SG13, Reference [15], the necessary information and assistance for chemistry and radiochemistry for ensuring safe operation, long term integrity of SSC and minimisation of radiation levels are implemented by sampling and monitoring. Normal operation sampling systems and post-accident sampling systems are designed for determining, in a timely manner, the concentration of specified radionuclides in fluid process systems, and in gas and liquid samples taken from systems or from the environment, in all modes of operations.

a) Normal operation

In order to maintain the primary water chemistry regime, the chemistry parameters need to be monitored during the normal operation. The specific scope includes the water chemistry and radiochemistry parameters, which are defined in the specifications.

b) Post-accident

Under accident conditions, the post-accident sampling approach, as taken from the fault studies and accident analysis, is to take gaseous samples from containment atmosphere and liquid samples from IRWST for the purpose of confirming the sample activity.

#### 21.8.1.2 Sampling and Monitoring Methods

According to sampling characteristic from the different locations, the samples can be sampled and monitored through the on-line meters and laboratory. Adopt an appropriate balance between on-line measurements and laboratory analysis depends upon factors such as the importance of the particular parameter, response time requirements, reliability and accuracy of measurement needed and the likely doses accrued from intrusive sampling.

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The use of on-line monitoring of control parameters is defined as the preferable monitoring method for evaluating chemistry conditions in plant systems. Laboratory analysis should be considered a necessary complement in the diagnosis of chemistry problems, to verify the accuracy of on-line monitors and whenever it is either not possible or not reasonable to apply on-line monitoring.

a) On-line analysis instruments

On-line chemistry monitoring and data acquisition systems are used to accurately measure and record data and provide alarms for key chemistry parameters. Other methods that could be used for this task include:

- 1) Boron, hydrogen and oxygen concentration in the primary coolant due to the importance and requirement for monitoring continuously;
- 2) Conductivity, oxygen and sodium in the secondary due to the importance and requirement for monitoring continuously.

b) Manual sampling and monitoring in the laboratory

Laboratory monitoring involves the sampling and analysis of plant systems for specific chemical parameters, concentrations of dissolved and suspended impurities, and radionuclide concentrations. Redundancy or equivalency of laboratory facilities should be provided to ensure analytical services at all times. The manual sampling can be done for each parameter if the on line measurement fails.

Timely calibration, performed comparison of results from on-line monitors and laboratory equipment from different sampling points.

## **21.8.2 Substantiation of Chemistry Sampling and Monitoring Requirement**

### 21.8.2.1 Nuclear Sampling System

The Nuclear Sampling System (REN [NSS]) enables centralised analysis and determination of the chemical and radiochemical parameters of samples taken from RCP [RCS], the SGs, nuclear auxiliary systems and liquid waste and gaseous waste treatment system. The REN [NSS] comprises three sub-systems: the primary sampling system, secondary sampling system and post-accident sampling system.

a) Primary sampling system

The primary sampling system collects liquid and gaseous samples from the primary coolant system, primary auxiliary systems, liquid and gaseous waste treatment systems to determine the physical and chemistry parameters of these samples by measurement and analysis. During normal operation, the REN [NSS] collects liquid and gaseous samples from the following locations:

- 1) RCP [RCS];



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- 2) RCV [CVCS];
- 3) Safety Injection System (RIS [SIS]);
- 4) Other primary auxiliary systems;
- 5) Liquid and gaseous waste treatment systems.

These samples are categorised as active liquid, slightly radioactive liquid and gaseous ones. The sampling features of the REN [NSS] primary sampling system are presented in T-21.8-1.

T-21.8-1 Sampling Categories, Location and Specific Features for Primary  
Sampling System

<b>Sampling Categories</b>	<b>Sampling Location</b>	<b>Specific Feature</b>
Primary coolant	<ul style="list-style-type: none"> <li>• RCP [RCS] hot leg loop 2/3;</li> <li>• Liquid phase of the pressuriser;</li> <li>• Downstream of the three trains of RIS [SIS] RHR exchangers;</li> <li>• RCV [CVCS] downstream the high pressure charging pumps and upstream purification.</li> </ul>	<p>On-line analysers: boron, hydrogen, oxygen and phase separator</p> <p>Grab sampling for on-line checking in the glove box</p>
Radioactive liquid	<ul style="list-style-type: none"> <li>• Upstream of the RCV [CVCS] mixed bed demineralisers;</li> <li>• TEP [CSTS] coolant storage tanks;</li> <li>• Downstream of the TEP [CSTS] resin trap, TEP [CSTS] boric acid evaporation unit, REA [RBWMS] boric acid pumps and RCV [CVCS] the resin traps.</li> </ul>	<p>Grab sampling in the glove box</p>
Slightly radioactive liquid	<ul style="list-style-type: none"> <li>• Liquid phase of accumulators;</li> <li>• The RPE [VDS] drainage sump;</li> <li>• Downstream of the PTR [FPCTS] heat exchangers, the reactor pool purification loop, the spent fuel pool purification loop, TEP [CSTS] degasser column and cooler.</li> </ul>	<p>Grab sampling in the glove box</p>
Corrosion products	<ul style="list-style-type: none"> <li>• Upstream and downstream of the RCV [CVCS] mechanical filters and PTR [FPCTS] mechanical filters.</li> </ul>	<p>Grab sampling in the glove box</p>

<b>Sampling Categories</b>	<b>Sampling Location</b>	<b>Specific Feature</b>
Gaseous	<ul style="list-style-type: none"> <li>• Upstream of the TEG [GWTS] gas drier;</li> <li>• Upstream and downstream of the TEG [GWTS] recombiner and delay beds;</li> <li>• The RPE [VDS] tanks.</li> </ul>	Grab sampling

b) Secondary sampling system

The secondary sampling system collects liquid samples from SGs, APG [SGBS] and the APG [SGBS] purification to analyse the water quality and radioactivity. The sampling features of the REN [NSS] secondary sampling system are presented in T-21.8-2.

T-21.8-3 Sampling Categories, Location and Specific Features  
for Secondary Sampling System

<b>Sampling Categories</b>	<b>Sampling Location</b>	<b>Specific Feature</b>
SG	<ul style="list-style-type: none"> <li>• On the SG close to the inlet nozzle of RCP [RCS];</li> <li>• On the SG blowdown lines of APG [SGBS].</li> </ul>	The secondary sampling lines used for automatic analysis run continuously. Samples can also be routed to the sample room for grab sampling without the glove box.
APG [SGBS] purification	<ul style="list-style-type: none"> <li>• Downstream the cation demineralisation bed;</li> <li>• Downstream the resin trap filters of anion demineralisation bed.</li> </ul>	<p>Each sampling line of SG and APG [SGBS] blowdown water is equipped with a pH meter, a conductivity meter and an activity measurement which are out of scope of this system. A sodium meter is connected to the three SG and APG [SGBS] blowdown sampling lines.</p> <p>Each sampling line of APG [SGBS] purification is equipped with a conductivity meter. A sodium meter is connected to the two APG anion demineralisation beds sampling lines.</p>

c) Post-accident sampling system

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The post-accident sampling system is mainly to be used as part of accident recovery to obtain gaseous samples from containment atmosphere and liquid samples from IRWST in post-accident situation for the purpose of confirming the sample activity.

More information about the representative sampling of NSS [REN] is provided in *Design Substantiation Report on Sampling and Monitoring Systems: Nuclear Sampling System*, Reference [82] and system design manual chapters, Reference [83] and [84]. The design substantiation of sampling requirement support the normal operating, startup and shutdown chemistry control, Reference [37] and [38].

#### 21.8.2.2 Feedwater Chemical Sampling System

The SIT [FCSS] monitors and takes samples of water or steam from the secondary circuit systems with the exception of the SGs and Steam Generator Blowdown System (APG [SGBS]).

The sampling system delivers representative samples of fluids from secondary systems to sample analysers. Secondary sampling monitors send control signals to the SIR [CRIS] that automatically injects chemicals into the condensate and feedwater systems to control pH and dissolved oxygen concentration. The on-line sampling locations and parameters are presented in T-21.8-4. All the on-line sampling points grab samples can be collected in the sampling room. In addition, some sampling points in the turbine hall are grab sampling by the SIT [FCSS] primary cooling rack.

T-21.8-4 On-line Sampling Location and Parameters for SIT [FCSS]

<b>Sampling Location</b>	<b>On-line Parameter</b>
Condensate extraction pump outlets	<ul style="list-style-type: none"> <li>▪ Dissolved oxygen (At condenser outlet)</li> <li>▪ Sodium (At condensate polisher outlet)</li> <li>▪ Cation conductivity (At condensate polisher outlet)</li> <li>▪ pH (At condensate polisher outlet)</li> <li>▪ Specific conductivity (At condensate polisher outlet)</li> </ul>
Drains of HP heaters, LP heaters and MSRs drain	<ul style="list-style-type: none"> <li>▪ Cation conductivity</li> </ul>
Deaerator downcomers and recirculation pump outlets	<ul style="list-style-type: none"> <li>▪ Dissolved oxygen</li> <li>▪ pH</li> </ul>
Main feedwater manifold	<ul style="list-style-type: none"> <li>▪ pH</li> <li>▪ Cation conductivity</li> <li>▪ Hydrazine</li> <li>▪ Dissolved oxygen</li> </ul>

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Sampling Location	On-line Parameter
	<ul style="list-style-type: none"> <li>• Turbidity</li> </ul>
Main steam lines	<ul style="list-style-type: none"> <li>• Cation conductivity</li> <li>• Sodium</li> </ul>

## 21.9 ALARP Assessment

Following the ALARP methodology presented in Chapter 33, it is required to identify RGP and OPEX within the reactor chemistry topic area and to identify potential improvements based on the review against RGP and OPEX.

A specific ALARP demonstration report has been prepared, Reference [85], following Reference [35], [86][87] and internal ALARP guidance, Reference [87]. This report provides information on the ALARP assessment undertaken for the topic of reactor chemistry, introduces the basic ALARP methodology followed, and identifies the key reactor chemistry aspects to be assessed. The ALARP assessment supports the principal safety claim for reactor chemistry, i.e. Claim 3.3.10 - The chemistry aspects of the plant design have been developed to reduce the nuclear safety risk ALARP.

This document presents the basic approach to demonstrate that RGP has been identified and incorporated into the design of the UK HPR1000 and that the optimised reactor chemistry regime reduces risks ALARP. Additionally, the current design and chemistry regime has been reviewed to identify gaps, and a work plan has been proposed to close these gaps and consider further reasonably practicable enhancements. This version of the report represents the current position with respect to the ALARP assessments of the design. As additional ALARP assessment will be completed through GDA.

The UK HPR1000 chemistry optimisation approach balances the benefits, and minimises the drawbacks of the key chemical constituents (chemical parameters) in the primary and secondary water circuits. The overall aim is to optimise the chemistry regime in order to:

- a) Provide a reliable means of reactivity control;
- b) Minimise the threat to pressure boundary integrity from corrosion;
- c) Minimise the threat to fuel cladding and core component integrity from corrosion, and the formation of CRUD;
- d) Reduce out of core radiation fields;
- e) Minimise the generation of waste;
- f) Reduce the risks associated with plant operation management of the source term and spread of contamination.

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### 21.9.1 Sources of RGP and OPEX

RGP and OPEX for the UK HPR1000 are mainly derived from the following sources:

- a) International codes & standards used in the nuclear industry, as described in the Sub-chapter 21.3;
- b) Previous GDA assessment documents relating to chemistry published by ONR described in the Sub-chapter 21.3;
- c) Relevant experience of previous GDA projects;
- d) OPEX from existing PWRs, including:
  - 1) CPR1000 PWRs constructed and operated by CGN in China;
  - 2) EPR and AP1000 PWRs constructed and operated in China
  - 3) Sizewell B PWR in the UK.
- e) Lessons learned during earlier steps of the UK HPR1000 GDA.

The RGPs and OPEX adopted in the design are listed in T-21.9-1 and T-21.9-2.

#### T-21.9-1 Identification of RGP & OPEX for the Primary Water Chemistry

NO.	RGP and OPEX	Source	Applicability
1	Use of lithium hydroxide for pH control of reactor coolant	According to IAEA SSG-13 (Reference [15]): "4.27. Addition or removal of alkaline compounds should be used in order to maintain the optimum pH <sub>T</sub> (pH at operating temperature) at all times during operation. In PWRs, generally, lithium hydroxide is added."  Lithium hydroxide is used for pH control for the UK AP1000, UK EPR and Sizewell B PWRs.	Applicable
2	Use of hydrogen for oxygen control of reactor coolant	According to IAEA SSG-13 (Reference [15]): "4.28. The concentration of hydrogen should be maintained at an optimal level in order to suppress the production of oxygen via radiolysis and to keep the electrochemical potential at a sufficiently low level to prevent the stress corrosion cracking of stainless steel."	Applicable

<b>NO.</b>	<b>RGP and OPEX</b>	<b>Source</b>	<b>Applicability</b>
		Hydrogen is used to suppress oxygen for the UK AP1000, UK EPR and Sizewell B PWRs.	
3	Use of enriched boric acid for reactivity control	<p>According to IAEA NS-G-1.12 (Reference [20]): “IV.7. Because of the higher excess reactivity of the core in a high burnup core, a higher concentration of soluble boron in the coolant may be needed. Such a higher concentration may cause problems relating to the coolant chemistry such as increased corrosion in the primary circuit. Enriched <sup>10</sup>B may be used to reduce the concentration of soluble boron.”</p> <p>Enriched boric acid is used for the UK EPR PWR.</p>	Applicable
4	Use of zinc for radiation field and stress corrosion cracking control	<p>According to Reference [11].</p> <p>Primary Circuit: Depleted zinc injection in reactor coolant for dose rate reduction and mitigating primary PWSCC.</p> <p>Depleted zinc injection is used for corrosion product and dose rate reductions for the UK AP1000, UK EPR PWRs.</p>	Applicable

T-21.9-2 Identification of RGP and OPEX for the Secondary Water Chemistry

<b>NO.</b>	<b>RGP &amp; OPEX</b>	<b>Source</b>	<b>Applicability</b>
1	Use of volatile alkaline reagents for pH control of secondary circuit	<p>According to IAEA SSG-13 (Reference [15]): “4.42. The secondary circuit should be operated according to an ‘all volatile treatment’ or an ‘all volatile treatment with high pH’. All volatile treatment means the use of only volatile alkaline reagents such as ammonia and/or amines (e.g. morpholine, ethanolamine, dimethylamine). A reducing agent should also be added when necessary.”</p> <p>Ammonia is used for pH control in the</p>	Applicable

<b>NO.</b>	<b>RGP &amp; OPEX</b>	<b>Source</b>	<b>Applicability</b>
		secondary circuit for the UK AP1000 and UK EPR PWRs.	
2	Use of reducing reagent for oxygen control of secondary circuit	<p>According to Reference [11] “A5.15. These design choices and potential corrosion and degradation threats limit the feedwater chemistry to an All Volatile Treatment (AVT) with redox control and minimised impurity levels.”</p> <p>Hydrazine is used for oxygen control in the secondary circuit for the UK EPR and was considered for the UK AP1000.</p>	Applicable

### 21.9.2 Consistency Review of RGP and OPEX

By comparing the UK HPR1000 design with the RGP and OPEX requirements outlined above, a consistency review has been undertaken. According to the results of the consistency review, it is considered that the UK HPR1000 chemistry design can comply with RGP and will reflect relevant OPEX. These RGP and OPEX have been analysed as part of this review. T-21.9-3 and T-21.9-4 provide the conclusion of the consistency review against RGP and OPEX.

#### T-21.9-3 Consistency Review for the Primary Water Chemistry

<b>NO.</b>	<b>RGP and OPEX</b>	<b>UK HPR1000 Design</b>	<b>Applicability</b>
1	Use of lithium hydroxide for pH control of reactor coolant	UK HPR1000 has been designed to use lithium hydroxide for pH control of reactor coolant. More information is described in Sub-chapter 21.4.3.	Applicable
2	Use of hydrogen for oxygen control of reactor coolant	Oxygen produced from radiolysis of the coolant is suppressed by adding hydrogen. More information is described in Sub-chapter 21.4.3.	Applicable
3	Use of enriched boric acid for reactivity control	The use of EBA reduces the lithium needed to control the pH and may reduce the risk of boron deposition. It is described in Sub-chapter 21.4.3.	Applicable
4	Use of zinc for radiation	Zinc injection in reactor coolant is	Applicable

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<b>NO.</b>	<b>RGP and OPEX</b>	<b>UK HPR1000 Design</b>	<b>Applicability</b>
	field and stress corrosion cracking control	considered in Sub-chapter 21.4 to determine whether used in UK HPR1000.	

T-21.9-4 Consistency Review for the Secondary Water Chemistry

<b>NO.</b>	<b>RGP and OPEX</b>	<b>UK HPR1000 Design</b>	<b>Applicability</b>
1	Use of volatile alkaline reagents for pH control of secondary circuit	UK HPR1000 has been designed to operating with an 'all volatile treatment' via ammonia dosing and with hydrazine dosing to remove residual dissolved oxygen. More information is described in Sub-chapter 21.5.3.	Applicable
2	Use of reducing reagent for oxygen control of secondary circuit		Applicable

### 21.10 Concluding Remarks

For the UK HPR1000 design, the development of the chemistry control and related material selections are based upon proven RGP and OPEX.

The material selected for SSC is a key parameter for ensuring the safe operation. The optimisation of chemistry control are based on minimising the material corrosion risk, assisting in the integrity of SSC important to safety and minimisation of the source term, are holistically and sufficiently met in the generic UK HPR1000.

The key chemistry parameters have been generically described and justified, and system design can provide the means to maintain the limits and conditions of operation, achieving the balance of chemistry related safety objectives, whilst demonstrating the risks at a level ALARP.

To achieve the goal of maintaining plant integrity and minimising radiation fields, the appropriate chemistry strategy for the UK HPR1000 is prevention, control, and mitigation, thereby resulting in a safe design, which incorporates:

- a) Material selections based on lessons learned, customer inputs, and good practices;
- b) Chemistry regime defined according to the standards, RGP and OPEX;
- c) Chemistry regime controlled through comprehensive related systems to improve the performance of plant operation;
- d) Chemistry effects considered through accident analysis to reduce the risk;
- e) Robust chemistry sampling and monitoring provisions to support plant operation.



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### Appendix 21A: Route Map for Chapter 21

Sub claim	Argument	Sub-argument	Evidence
<b>3.3.10. SC21.1</b> The requirements for chemistry important to nuclear safety have been derived in all operating modes and fault conditions.	<b>3.3.10. SC21.1-A1:</b> The chemistry objectives are adequately specified based on relevant good practice. <b>3.3.10. SC21.1-A2:</b> The parameters of chemistry to deliver the chemistry objectives have been derived. <b>3.3.10. SC21.1-A3:</b> The requirements of chemistry control, sampling and monitoring to satisfy water chemistry parameters have been derived.	<b>3.3.10. SC21.1-A1.1:</b> Deterioration of heat transfer performance for fuel and spent fuel is impacted by limiting impurities related to CRUD formation and deposition on the surface. <b>3.3.10. SC21.1-A1.2:</b> Boric acid concentration satisfies the requirement of controlling relatively slow reactivity changes. <b>3.3.10. SC21.1-A1.3:</b> The risk of radiation dose to the workers is reduced by optimisation of the chemistry regime and material selection. <b>3.3.10. SC21.1-A1.4:</b> Chemistry control assists in mitigating the hydrogen and radiologic release under accident condition to an acceptable limit.	General Safety Requirement- GHX00100017DOZJ03GN
		<b>3.3.10. SC21.2-A1.1:</b> The chemistry regimes for the primary coolant, secondary water and auxiliary water systems are designed based on the safe operation requirements of SSC.	Methodology for chemistry regime: Primary-GHX00100005DCHS03GN Secondary-GHX00100099DCHS03GN
<b>3.3.10. SC21.2</b> The design is substantiated against the requirements for chemistry important to nuclear safety in all operating modes and fault conditions.	<b>3.3.10. SC21.2-A1:</b> Appropriate design methods have been adopted for the definition of chemistry regime.  <b>3.3.10. SC21.2-A2:</b> The appropriate processes have been adopted to substantiate that the chemistry provisions are made to meet the requirement.	<b>3.3.10. SC21.2-A1.2:</b> The limits and conditions of chemistry regimes are defined including the commissioning, startup, shutdown, power operation, and accident chemistry.	Commissioning chemistry-GHX00100102DCHS03GN Power operation chemistry- GHX00100104DCHS03GN Startup and shutdown chemistry- GHX00100105DCHS03GN Accident chemistry- GHX00100002DRAF03GN
		<b>3.3.10. SC21.2-A2.1:</b> Enriched lithium hydroxide coordinated with boron acid is controlled in the whole cycle to maintain pH strategy in the primary coolant.	Selection for EBA -GHX00100003DNHX45GN pH control for the primary coolant- GHX00100007DCHS03GN Design substantiation for primary systems-GHX00100034DNHX03GN
		<b>3.3.10. SC21.2-A2.2:</b> The reducing condition of the primary coolant is controlled by injecting hydrogen during operation.	Hydrogen dosing- GHX08RCV001DNHX03GN hydrogen concentration- GHX00100008DCHS03GN Design substantiation for primary systems - GHX00100034DNHX03GN
		<b>3.3.10. SC21.2-A2.3:</b> The oxygen is removed by hydrazine from the primary circuit during start-up.	Startup and shutdown chemistry- GHX00100105DCHS03GN Design substantiation for primary systems- GHX00100034DNHX03GN
		<b>3.3.10. SC21.2-A2.4:</b> Hydrogen peroxide is added to remains the dominant oxidizing species during shutdown.	Startup and shutdown chemistry- GHX00100105DCHS03GN Design substantiation for primary systems- GHX00100034DNHX03GN
		<b>3.3.10. SC21.2-A2.5:</b> The target concentration levels of impurities and radioactive substances are controlled below the limits by the purification systems.	Impurity control- GHX00100103DCHS03GN Design substantiation for primary systems- GHX00100034DNHX03GN

Sub claim	Argument	Sub-argument	Evidence
			Design substantiation for SFP- GHX08PTR001DNHX03GN
		<b>3.3.10. SC21.2-A2.6:</b> All Volatile Treatment (AVT) is designed for water quality conditioning via ammonia and hydrazine dosing in the secondary circuit with full-ferric system.	alkaline agents in secondary circuit- GHX00100011DCHS03GN Design substantiation for secondary systems- GHX00100100DCHS03GN
		<b>3.3.10. SC21.2-A2.7:</b> The water quality is controlled by purification of APG blowdown water during the operation and by ATE purification during the startup and leakage.	Generic water chemistry specification - GHX00100101DCHS03GN Design substantiation for secondary systems- GHX00100100DCHS03GN
		<b>3.3.10. SC21.2-A2.8:</b> The control parameters for the safety predication are monitored by sampling systems and laboratory in all modes of operations and fault conditions.	Generic water chemistry specification - GHX00100101DCHS03GN Design substantiation for sampling system- GHX08REN001DNHX03GN
		<b>3.3.10. SC21.2-A2.9:</b> The design and operational requirements of chemistry related systems are demonstrated in the system design process.	System design manual-Chapter 4 system and component design, Chapter 6 System operation
		<b>3.3.10. SC21.2-A2.10:</b> The wastes from the primary circuit are treated by adequate chemistry control in gaseous and liquid radioactive waste treatment systems.	System design manual-Chapter 4 system and component design, Chapter 6 System operation
<b>3.3.10. SC21.3</b> The design for chemistry regimes minimises the negative impact of radiation and chemicals on workers, public, plant and environment through ALARP in all operating modes and fault conditions.	<b>3.3.10. SC21.3-A1:</b> The negative impacts have been minimised in the process of deriving the chemistry regime control, sampling and monitoring requirements and substantiating the requirements.	<b>3.3.10. SC21.3-A1.1:</b> EBA in the primary circuit is selected according the optioneering in terms of reactivity control and operating management.	Selection for EBA -GHX00100003DNHX45GN
		<b>3.3.10. SC21.3-A1.2:</b> Application of zinc injection in the primary circuit during the hot function testing is feasible for according the optioneering.	Zinc injection in the primary circuit-GHX00100010DCHS03GN
		<b>3.3.10. SC21.3-A1.3:</b> Low operating range of hydrogen concentration is selected to suppress water radiolysis based on the Alloy 690TT of SG tubes and risk control.	Hydrogen control: DBC hydrogen-GHX00600282DRAF02GN Hydrogen dosing- GHX08RCV001DNHX03GN hydrogen concentration- GHX00100008DCHS03GN
	<b>3.3.10. SC21.3-A2:</b> All chemistry hazards and reasonably practicable mitigations of negative impacts are correctly identified and analysed.	<b>3.3.10. SC21.3-A2.1:</b> The contents of easily activated elements in SSC materials are minimised to release into the primary coolant.	Minimisation for cobalt in SSC: SSC-GHX00100048DPCH03GN Valves-GHX44400004DNHX03GN primary coolant pump- GHX44400003DNHX03GN
		<b>3.3.10. SC21.3-A2.2:</b> The degradation of materials caused by corrosion is minimised by optimisation of the chemistry regime and suitable material surface treatment	Surface treatment for minimisation of corrosion- GHX00100122DPCH03GN Selection of aluminium-boron carbide for spent fuel racks- GHX00100109DPCH03GN



Sub claim	Argument	Sub-argument	Evidence
			<p>Selection of carbon steel with chromium for feedwater piping</p> <p>pH control by alkaline agents:</p> <p>Primary- GHX00100007DCHS03GN</p> <p>Secondary- GHX00100011DCHS03GN</p> <p>Cooling water-</p> <p>Impurity control- GHX00100103DCHS03GN</p>
<p><b>3.3.10. SC21.4</b></p> <p>The ageing effects of the chemistry related systems important to nuclear safety have been addressed in the selection of an optimum chemistry regime.</p>	<p><b>3.3.10. SC21.4-A1:</b> The chemistry parameters effect on the ageing of material is taken corrective actions via monitoring for all operating modes.</p>	<p><b>3.3.10. SC21.4-A1.1:</b> Chemistry limits and conditions are controlled as the requirements to reduce the degradation of system materials during all modes of operation.</p>	<p>Generic water chemistry specification- GHX00100101DCHS03GN</p> <p>Ageing and degradation for SSC:</p> <p>RPV- GHX00100033DPCH03GN</p> <p>SG- GHX00100035DPCH03GN</p> <p>PZR- GHX00100037DPCH03GN</p> <p>MCL- GHX00100039DPCH03GN</p> <p>RVI- GHX00100041DPCH03GN</p>