

**UK ABWR**

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# UK ABWR Generic Design Assessment

## Generic PCSR Chapter 23 : Reactor Chemistry



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## **Executive Summary**

This Generic Design Assessment (GDA) Pre-Construction Safety Report (PCSR) chapter describes the safety case for the reactor chemistry (RC) of the Reactor Coolant System (RCS) and associated systems and auxiliary systems of the United Kingdom (UK) Advanced Boiling Water Reactor (ABWR). The chapter considers the system design, the chemistry regimes and key nuclear safety aspects for all normal operations, including consideration of the commissioning chemistry.

The UK ABWR RCS and associated systems water chemistry regime is based on Hydrogen Water Chemistry (HWC) with On-Line NobleChem™ (OLNC), and Depleted Zinc Oxide (DZO) injection and is optimised with respect to reducing the overall risks to As Low As Reasonably Practicable (ALARP) when operation begins. The UK ABWR structures, systems and components (SSCs) materials have been selected to maximise integrity, and to minimise the corrosion product source term. The design incorporates controls for recombining gases formed from the radiolysis of water in the reactor to prevent build up of flammable atmospheres. The UK ABWR includes systems which ensure the water chemistry is maintained to specification, radioactive wastes are minimised and handled appropriately, and the chemistry is sampled and monitored appropriately to ensure safe and reliable operation.

This chapter also provides:

- Chemical injection system (CIS) design descriptions and justifications
- Description of the chemistry controls for auxiliary systems:
  - Spent Fuel Pool (SFP),
  - Suppression Pool (S/P),
  - Standby Liquid Control System,
  - Make-up water, and
  - Component Cooling Water (CCW) Systems.

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- Design and safety functional requirements for the sampling and monitoring of chemistry parameters,
- Linkage between the radioactive waste streams safety functions and claims and the operational chemistry management controls.

The chapter demonstrates that the risks associated with the reactor chemistry of the UK ABWR are ALARP. It is acknowledged that further work will be required post Generic Design Assessment (GDA) to develop the design and fully incorporate site specific aspects for the optimum chemistry regimes. This work will be the responsibility of the future licensee.

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## **23.1 Introduction**

This PCSR Chapter 23 focuses on the safety case for the UK ABWR Chemistry regimes. It describes the key chemistry related safety aspects of the UK ABWR and how chemistry controls support the wider GDA PCSR Safety Case. Reference is made to the UK ABWR Fundamental Safety Functions (FSFs) and how these cascade into supporting claims on the systems and the associated chemistry control to make the overall safety case for the UK ABWR.

The UK ABWR chemistry regimes and associated controls and methods applied to the RCS and associated systems and the auxiliary systems (which contain water or process fluids) are presented. The regimes and controls have been determined based upon careful consideration of worldwide Relevant Good Practice (RGP) guidance and operating experience (OPEX). Relevant plant systems are briefly described. The reactor chemistry regimes and the Limiting Condition for Operation (LCO) for safe operation have been developed and optimised to contribute to the overall UK ABWR FSFs, and to support the reactor chemistry main safety risk objectives.

The UK ABWR is expected to be operated by the future licensee for a planned operational lifetime of at least 60 years prior to final shutdown and decommissioning. The expectation is that the future licensee will use the chemistry regimes outlined in this PCSR. However, post GDA, the detailed site specific operational chemistry strategy will be the responsibility of the future licensee, who may choose to vary or further optimise the operating chemistry within the safety boundaries defined by the UK ABWR generic safety case.

### **23.1.1 Background**

The chemistry and radiochemistry of the key systems for the UK ABWR are described for each mode of plant operation, including commissioning. The descriptions include details of the chemistry function and the technical basis, the chemistry control and monitoring, and why this is appropriate. The possible faults that can occur during normal operation are described along with the consequences for the design if they should occur.

The PCSR Chapter 4 describes the basis of the application of LCOs for the UK ABWR safety case. In summary, the safety case presented for the UK ABWR demonstrates that the plant can be operated in a manner that satisfies regulatory expectations, complying with relevant regulations, and that the risks to the public and the workforce are ALARP. The plant must also be shown to be

operated by the future licensee in a manner consistent with the safety case. To ensure this, the LCOs have been identified which define the operating envelope within which the safety case of the plant is valid, and within which the future licensee must operate.

The Water Quality Specification [Ref-1] identifies to the future licensee the significant UK ABWR design chemistry and radiochemistry parameters that are to be monitored and controlled for nuclear safety. The most significant chemical additives and impurities that need to be controlled in the RCS and associated systems and auxiliary systems are identified as LCOs. The LCOs are described and referenced to supporting documentation where they have been derived and justified. Operating within the LCO will ensure that the likelihood of a chemistry related initiating event is reduced to ALARP. Additional lower (expected) values are provided within [Ref-1] and supporting documentation to assist in the normal operation and control of the plant to prevent the LCOs being reached.

The parameter LCO values that are required for the reactor chemistry safety case defined in this PCSR are identical for all the operation modes including start-up, power operation, shutdown and outage. Additional specific LCOs for start-up and shutdown in consideration of the aims and objectives for the chemistry control during these modes have also been set and are explained.

### **23.1.2 Document Structure**

This chapter is divided into the following sections:

- Section 23.2 Purpose and Scope
- Section 23.3 Reactor Chemistry Safety Claims
- Section 23.4 Reactor Coolant System and Associated Systems Chemistry
- Section 23.5 Spent Fuel Storage Pool Chemistry Control
- Section 23.6 Suppression Pool Chemistry Control
- Section 23.7 Standby Liquid Control System Water Chemistry
- Section 23.8 Make-up Water, Treatment and Storage
- Section 23.9 Component Cooling Water Systems Chemistry
- Section 23.10 Back-up Building – FLSS Water Chemistry Control
- Section 23.11 Sampling and Monitoring
- Section 23.12 Radioactive Waste Management – Impact from System Chemistry Regimes
- Section 23.13 Summary of ALARP Justification

- Section 23.14 Conclusions
- Section 23.15 References

This chapter has links to several other PCSR chapters that describe the fundamental design aspects of the UK ABWR safety case, or the plant system design and safety functions that are linked to chemistry control and maintenance for structural integrity and operational purposes.

- Chapter 4: Safety Management Throughout Plant Lifecycle – Section 4.12 describes the general principles for the identification of Assumptions and LCOs.
- Chapter 5: General Design Aspects – Section 5.6 lists the High Level Safety Functions and describes the approach used for the categorisation of safety functions and to classify the SSCs.
- Chapter 7: Internal Hazards – Section 7.4 addresses the methods employed in the design to reduce the radiolytic gases and to prevent their accumulation in the plant and process systems.
- Chapter 8: Structural Integrity – describes the justification for the structural integrity of various metal systems, and SSCs for the UK ABWR. The Chapter 8 Appendix D contains summaries of Topic Reports (TRs) that describe the key materials degradation considerations and the materials selection justifications.
- Chapter 11: Reactor Core – fuel assembly and core design.
- Chapter 12: Reactor Coolant Systems, Reactivity Control Systems and Associated Systems – Describes the system designs and safety functions of the RCS, including the Reactor Water Clean-up System (CUW), Residual Heat Removal System (RHR) and Standby Liquid Control System (SLC)
- Chapter 13: Engineered Safety Features – includes engineered safety features descriptions for systems in normal operation and in faults. The Filtered Containment Venting System (FCVS) design is described, and is also linked to Chapter 16 (see below) and 26. The Primary Containment Vessel (PCV) including the Atmospheric Control System (AC) (for management of the inert gas atmosphere in the PCV) is in Chapter 13, and is not described in Chapter 23.
- Chapter 14: Control and Instrumentation (C&I) – includes C&I system designs, safety functions, safety categorisation and classification, in normal operation and during faults.
- Chapter 16: Auxiliary Systems – includes system descriptions, safety functions, safety categorisation and SSC classification of the Suppression Pool (S/P) (see Chapter 26 for link to S/P pH control), Suppression Pool Clean-up System (SPCU), Make-up Water Condensate System (MUWC), Component Cooling Water (CCW) systems, Flooding System of Specific

Safety Facility (FLSS), FCVS design (see also Chapter 13 and 26 for role and functions, the vent filter scrubber solution control is in this Chapter 23, Section 23.4.5.3).

- Chapter 17: Steam and Power Conversion Systems – includes system descriptions, safety claims and functions, safety categorisation and SSC classification of the Condensate and Feedwater Systems (CFDW), Condensate Filter System (CF) and Condensate Demineraliser System (CD).
- Chapter 18: Radioactive Waste Management – radioactive liquid, wet-solid and gaseous waste handling and treatment system descriptions, safety claims and functions, safety categorisation and SSC classification.
- Chapter 19: Fuel Storage and Handling – System descriptions, safety claims and functions, safety categorisation and SSC classification The Spent Fuel Pool (SFP) and Fuel Pool Cooling and Clean-up System (FPC) are specifically addressed in Sections 19.8 and 19.9.
- Chapter 20: Radiation Protection – The UK ABWR source term is described in Section 20.3. Chapter 23 describes the chemistry control aspects for the source term management and minimisation.
- Chapter 24: Design Basis Analysis – describes the systems (including those that control plant chemistry) with a direct or indirect impact on Design Basis Accident (DBA), for example the CUW, Model and Parameter for Analysis in Section 24.5.2(3).
- Chapter 26: Beyond Design Basis and Severe Accident (SA) Analysis – Modular Accident Analysis Program (MAAP) physical model in Section 26.4.4.1(a), S/P pH control in Section 26.4.3.3(11), Post-accident chemistry sampling and monitoring (also see Chapter 23 Section 23.11), FCVS decontamination factor during SA, Source term impacts in SA is addressed Section 26.4.
- Chapter 28: ALARP Evaluation – Describes an overview of how the UK ABWR design has evolved, and how this evolution contributes to the overall ALARP case.
- Chapter 31: Decommissioning – Lifetime chemistry control impacts upon the incorporation and deposition of radioactivity in and on SSCs, and SSC integrity into the decommissioning programme, see also the TR on Decommissioning: Design for Decommissioning [Ref-2].

The environmental and security aspects of the UK ABWR design are described in PCSR Chapter 1, which also contains the links to the Generic Environmental Permit (GEP), and the Conceptual Security Arrangements (CSA) documentation.

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The relationship between the reactor systems, auxiliary systems and the Balance of Plant (BOP) systems and the chemistry controls are described. The tables in each section summarise the chemistry safety case top claims and claims, the location within the chapter section that the argument and evidence is provided, and if another PCSR chapter is linked.

This PCSR Chapter narrative is supported throughout by referencing relevant TRs including on ALARP justifications, design justifications, source term, water quality, specific chemistry regime aspects, and materials degradation and selection aspects. The Level 2 supporting documents to the safety case are shown in the document map in Appendix B. The system functionality is covered within other chapters of the PCSR and in turn by system Basis of Safety Cases, and these are shown as key links in the document map. The chemistry aspects covered in the supporting TRs ensure the ongoing maintenance of the design intent for the UK ABWR systems. Additionally, they specify the requirements that are to be delivered by those systems for effective chemistry monitoring and control.

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## **23.2 Purpose and Scope**

### **23.2.1 Purpose**

The purpose of this PCSR Chapter is to demonstrate that:

- The specification, monitoring and control of the RCS and associated systems and auxiliary systems chemistry regimes are suitable to ensure the safe and reliable operation of SSCs including maintaining the integrity of the Reactor Coolant Pressure Boundary (RCPB) and the fuel and fuel assembly.
- The specification, monitoring and control of the RCS and associated systems and auxiliary systems chemistry regimes are compatible with material selection to ensure SSC integrity and to minimise the source term and generation of environmental discharges and wastes (solid, liquid and gaseous) to ALARP.
- The specification, monitoring and control of the RCS and associated systems and auxiliary systems chemistry regimes ensure that the radiation source term fields are reduced to ALARP, ensuring that dose to operators and the public is reduced to ALARP.
- The hazardous and flammable gases generated from water radiolysis are controlled and managed safely.

### **23.2.2 Scope**

The scope of this chemistry chapter covers the following systems of nuclear safety significance (i.e. SSCs that are classified) that either contribute to the monitoring and control of chemistry, or whose functions including maintaining integrity are supported by chemistry control in normal operational modes and fault conditions:

- Reactor Coolant System (RCS) and Associated systems (including fuel), that are in contact with the RCS and associated systems chemistry,
- Spent Fuel Storage Pool (SFP),
- Standby Liquid Control system (SLC),
- Suppression Pool (S/P),

- Make-up Water Condensate System (MUWC),
- Component Cooling Water Systems (CCW),
- Flooder System of Specific Safety Facility (FLSS),
- Sampling System (SAM),
- Radioactive Waste Management Systems.

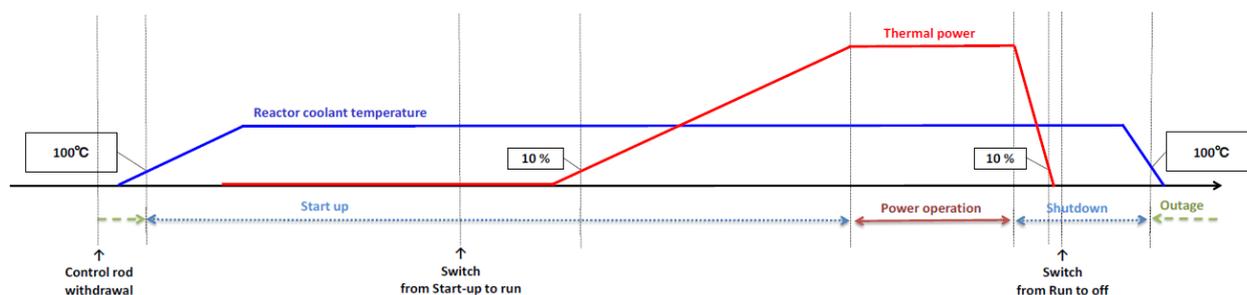
The following sections narrative summarises the evidence and arguments from the safety case documentation that supports the chemistry related claims that contribute to the overall UK ABWR FSFs. This presents the basis of the definition of the LCOs for the UK ABWR systems (see the list above) chemistry controls for normal operation.

The scope of the chemistry control regimes and methodology presented takes into consideration all the UK ABWR operating modes (i.e. start-up, power operation, hot shutdown, cold shutdown and refuelling outage) of the reactor as defined in PCSR Chapter 5: General Design Aspects. The reactor chemistry safety case is generally discussed in terms of the power operation mode, as that is the operation mode that covers most of the operating lifetime. However, there are some important differences for the chemistry control requirements between the operation modes, and these are highlighted and described in the chapter sections where relevant. Additionally, as described in [Ref-1], the RCS and associated systems water chemistry control requires the system water flow rates as well as the coolant temperature and the reactor thermal power to be considered. For this reason, the RCS and associated systems chemistry described in this PCSR Chapter 23 (only), is specified based on the following operational modes:

- **Power Operation for Water Chemistry:** reactor coolant water  $>100^{\circ}\text{C}$ , and after the post start-up expected full nominal thermal power has been first achieved.
- **Start-up/Shutdown for Water Chemistry:** (a) Start-up is the period from the control rod (CR) withdrawal and start of nuclear heating, until the expected full rated nominal thermal power is reached, and reactor water is  $>100^{\circ}\text{C}$ . (b) Shutdown is the period from commencing the reduction in reactor thermal power with the intention to shutdown, and until the reactor coolant water is  $<100^{\circ}\text{C}$ .

- Outage for Water Chemistry:** The period after shutdown and before start-up, and the reactor coolant water will be  $\leq 100^{\circ}\text{C}$ . Prior to start-up the purification of the feedwater and condensate water systems, and the de-aeration of the reactor water prior to start-up are included in this outage period.

These operation modes for the chemistry control are schematically shown in Figure 23.2-1.



**Figure 23.2-1: UK ABWR Operation Modes for the RCS and Associated Systems Water Quality Specification as defined by the Reactor Temperature, Thermal Power Conditions, and System Water Flow Rate [Ref-1]**

Commissioning chemistry is discussed in the following sections, as well as the operational chemistry impact on the decommissioning strategy. However, these aspects will be further developed during the site specific stage.

## **23.3 Reactor Chemistry Safety Claims**

There are four main safety risk objective issues that the UK ABWR reactor chemistry management will positively contribute to for mitigation and these are summarised as:

- material degradation, leading to structural degradation of SSCs
- material degradation, leading to fuel degradation
- radionuclide inventory and release, and radiological dose to the public and workers
- hazardous and flammable gas products generated through radiolysis

The reactor chemistry (RC) safety claims (SC) have been derived from the FSFs of the UK ABWR, which are set out in PCSR Chapter 5 Section 5.6. Of the five FSFs set out in Chapter 5.6, FSF 1 is linked to the chemistry safety claim for the SLC and FSF 2, 4 and 5 are applicable to the other chemistry safety claims. These FSFs are:

- FSF 2. Fuel Cooling
- FSF 4. Confinement / containment of radioactive materials
- FSF 5. Others (largely for support functions whose support is required for one or more of the above safety functions)

These FSFs are further defined into several High Level Safety Functions (HLSFs) that are listed in PCSR Chapter 5, Section 5.6. The HLSFs define the system plant level safety functions and define the more specific means to ensure that individual safety measures are designed such that they contribute to the achievement of the overarching FSFs. The reactor chemistry safety case is not 'a system' that can be defined in this way. However, the chemical management of the system fluids in the RCS and associated systems and the auxiliary systems is a factor that contributes towards those systems being able to meet their safety functions. For this reason, the HLSFs have been considered and linked to the reactor chemistry safety case top claims and claims.

The reactor chemistry top claims and claims are supported by underlying arguments that are discussed in the chapter sections. To allow suitable navigation to the key parts of the case as required each section presents these claims in tables. For example, the Section 23.4: Reactor Coolant System and Associated Systems Chemistry claims table is shown in Section 23.4.2. The tables list the relevant subsection that contains the argument and evidence to support the claims. Links are also shown to other PCSR chapters where relevant.

A complete summary of the linkages summary between the HLSF and reactor chemistry safety case top claims is diagrammatically shown in Appendix A. Full version of Claim, Argument and Evidence table is summarised in the TR on Design Justification in Chemistry Aspect for Primary Water Systems [Ref-3].

The reactor chemistry safety claims are strategically designed to maintain suitable chemical conditions in the systems described within defined LCOs during normal operation modes. The following sections describe a brief justification for the system control parameters including the basis of the LCOs that are associated with them. Most of the LCOs and information is related to the chemistry control for power operation in the RCS and associated systems. Where necessary, further details of the chemistry control in the other modes of operation are provided. This includes justification for the commissioning chemistry and mitigations for the key risks that are considered for the UK ABWR.

**23.3.1 Areas of the Safety Case Relevant to Reactor Chemistry**

The SSCs that are considered within the scope of this PCSR chapter are shown in Table 23.3-1, alongside the key area of the safety case for which they are considered.

**Table 23.3-1: PCSR Chapter 23 - Reactor Chemistry Safety Case Related SSCs**

<b>Reactor Chemistry Scope</b>	<b>Systems, Structures and Components (SSCs)</b>	<b>Safety Category <sup>*1</sup></b>	<b>Safety Class <sup>*1</sup></b>	<b>PCSR Chapter with System Justification</b>
Definition of chemistry regimes  Control and management of the structural integrity of the SSCs and management of the radiological source term	Reactor Coolant System (RCS) including its interaction with the Residual Heat Removal System (RHR)	A	1	12
	Reactor Water Clean-up System (CUW).	C	3	12
	Spent Fuel Storage Pool (SFP)	A	1	19
	Standby Liquid Control	A	2	12

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**Table 23.3-1: PCSR Chapter 23 - Reactor Chemistry Safety Case Related SSCs**

Reactor Chemistry Scope	Systems, Structures and Components (SSCs)	Safety Category <sup>*1</sup>	Safety Class <sup>*1</sup>	PCSR Chapter with System Justification
	System (SLC)			
	Suppression Pool (S/P) including its function as a source of water for Emergency Core Cooling Systems (ECCS)	A	1	16
	Make-up Water Condensate System (MUWC)	C	3	16
	Condensate Storage Tank (CST)	A	2	16
	Emergency Component Cooling System (ECCS) (Reactor Building Cooling Water System (RCW))	A	1	13, 16
	Turbine Building Cooling Water System (TCW)	B	3	16
	Service and Circulating Water Cooling Systems including the Circulating Water System (CW)	B	3	17
	Reactor Building Service Water System (RSW)	A	1	16
	Turbine Building Service Water System (TSW)	B	3	16
	Backup Building (Flooder System of Specific Safety Facility (FLSS))	A	2	16

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**Table 23.3-1: PCSR Chapter 23 - Reactor Chemistry Safety Case Related SSCs**

<b>Reactor Chemistry Scope</b>	<b>Systems, Structures and Components (SSCs)</b>	<b>Safety Category<sup>*1</sup></b>	<b>Safety Class<sup>*1</sup></b>	<b>PCSR Chapter with System Justification</b>
	Fuel	A	1	11
	Fuel Cladding	C	3	11
	Chloride Ingress Protection System (CIPS)	B	3	
	Condensate and Feedwater System (CFDW)	B	3	17
Control of nuclear safety chemistry regimes	Condensate Purification System (CPS, Condensate Filter System (CF) and Demineraliser System (CD) Systems.	C	3	16
	Spent Fuel Pool Clean-up System (FPC).	C	3	19
	Suppression Pool Clean-up Systems (SPCU).	C	3	16
	Sampling Systems (SAM)	C	3	16
	Chemical injection systems and equipment: Hydrogen and Oxygen Injection System (HOIS)	C	3	23
	Chemical injection systems and equipment – Noble Metal Injection System (NMIS)	C	3	23
	Chemical injection systems and equipment – Zinc	C	3	23

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**Table 23.3-1: PCSR Chapter 23 - Reactor Chemistry Safety Case Related SSCs**

<b>Reactor Chemistry Scope</b>	<b>Systems, Structures and Components (SSCs)</b>	<b>Safety Category<sup>*1</sup></b>	<b>Safety Class<sup>*1</sup></b>	<b>PCSR Chapter with System Justification</b>
	Injection System (ZNIS)			
	Oxygen Injection System (OI) and equipment	Non-categorised	Non-classified	23
Mitigation of flammability risk and radioactive release	Off-Gas System (OG).	B	2	18
	Liquid and Solid Radioactive Waste Management Systems (LWMS and SWMS).	(See PCSR Chapter 18)	(See PCSR Chapter 18)	18
	Standby Gas Treatment System (SGTS) and other Radioactivity Filtering Systems, including Filtered Containment Venting System (FCVS).	B	2	13, 16
	Tank Vent Treatment System (TVTS)	(See PCSR Chapter 18)	(See PCSR Chapter 18)	18
	Primary Containment Vessel (PCV) Gas Control Systems (including ACS)	A	1	13

<sup>\*1</sup>: Safety Category and Safety Class are defined in PCSR Chapter 5 - Section 5.6,

The process of categorisation and classification is described in Section 5.6 of Chapter 5. The SSCs that are discussed in this PCSR Chapter are presented with their SSC classification and the related safety functions categorisation stated in Table 23.4-1. This is to demonstrate that the chemistry controls that are required are commensurate with each of the SSC's importance to safety. The detailed justification for the safety function categorisation and SSC classification is referenced to the appropriate engineering PCSR chapters.

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For the SSCs that control the required chemistry regimes, e.g. the CUW, or those which abate/mitigate adverse effects generated by the chemistry regime, e.g. the Off-Gas System (OG), the description and justification for plant designs and the derived safety cases are presented in other PCSR chapters which are referenced in Chapter 23. This allows the PCSR Chapter 23 to be focused on the chemistry aspects for these SSC designs.

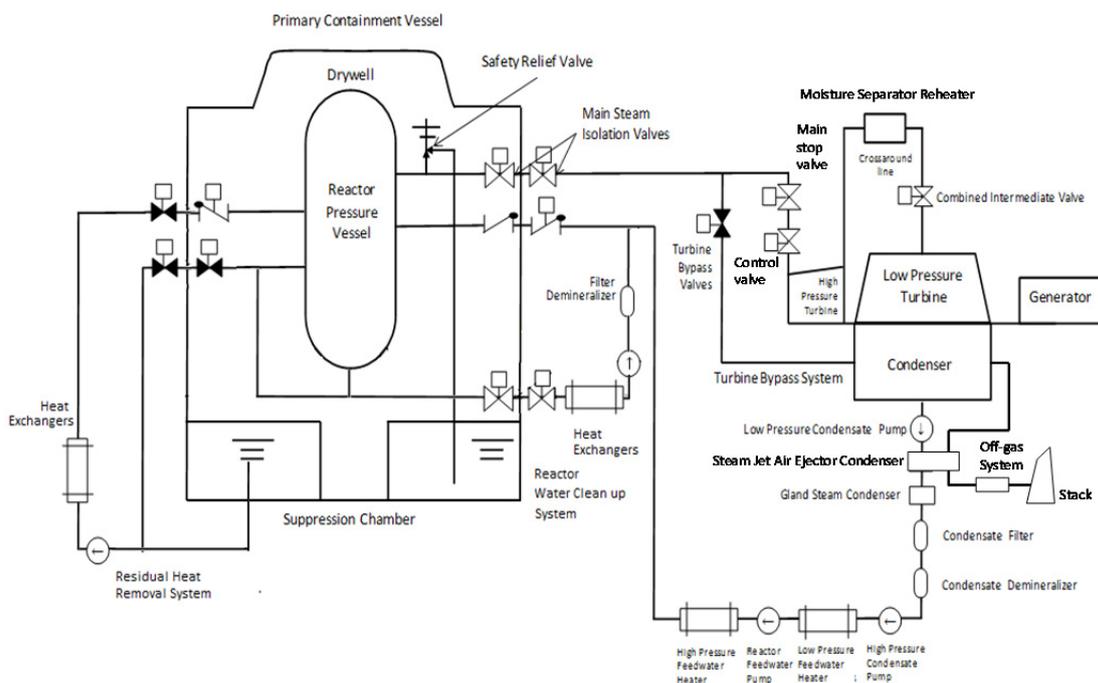
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## 23.4 Reactor Coolant System and Associated Systems Chemistry

This section describes the RCS and associated systems chemistry and the systems that it is in contact with it, in order to maintain, control and monitor the chemistry requirements. This includes the systems that inject the chemical additives and can clean-up and control the impurities for the RCS and associated systems.

### 23.4.1 Brief Description of the Reactor Coolant System and Associated Systems

An outline of UK ABWR RCS and associated systems is depicted in Figure 23.4-1.



**Figure 23.4-1: Reactor Coolant System and Associated Systems Schematic Drawing**

The Reactor Coolant System (RCS) refers to the primary boundary, and is described in PCSR Chapter 12. The RCS and its associated systems are listed in Chapter 12, Section 12.2.2. The RCS and the associated systems that come into contact with the reactor water need to be compatible with the chemistry regime. Additionally, the reactor water comes into contact with the associated systems that have a role in maintaining the chemistry environment, including the clean-up systems and

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chemical injection equipment. The key SSCs in contact with the reactor water and which are described in the following sections are listed below:

- Reactor Coolant System (RCS)
- Reactor Pressure Vessel (RPV) and Reactor Internals (RINs)
- Condensate and Feedwater System (CFDW)
- Reactor Water Clean-up System (CUW)
- Control Rod Drive System (CRD)
- Residual Heat Removal System (RHR)
- Emergency Core Cooling System (ECCS)
- Chemical Injection Systems (CIS):
  - Hydrogen and Oxygen Injection System (HOIS) (see Section 23.4.3.2 for system design details)
  - Noble Metal Injection System (NMIS) (see Section 23.4.3.2 for system design details)
  - Zinc Injection System (ZNIS) (see Section 23.4.5.2 for system design details)
- Oxygen Injection System (OI), (see Section 23.4.3.3 for system details)

The RCS and associated systems of the UK ABWR comprise a once-through cooling water system in which the ‘condensate water, feedwater and the reactor water’ are consecutively connected to make a coolant circuit. Some of the reactor water is converted to steam by nuclear heating, and the steam passes through the turbine and is condensed to water at the condenser to return to the condensate water. The water is then cleaned up, and chemically dosed and the feedwater is then returned to the RPV.

In the context of this PCSR chapter 23, the term ‘reactor water (RW) chemistry’ includes the coolant within the Reactor Pressure Vessel (RPV) and its migration into steam and to the turbines. The ‘feedwater (FDW) chemistry’ includes the condensate and the feedwater which is fed into the RPV. The condensate is mostly controlled through the Condensate Purification System (CPS) which contains the Condensate Filter System (CF) and Condensate Demineraliser System (CD) to ensure suitable purity, and then the feedwater is treated with the chemistry regime additives to achieve the correct reactor chemistry conditions. The condensate water chemistry is monitored but it is not actively controlled and therefore it is not discussed separately.

The history of the boiling water reactor began with the use of purified water. Due to the nature of boiling in the core region and the resulting oxidising environment of the reactor, highly purified coolant was required because any impurities in the coolant could impact upon the structural materials and the fuel cladding. With the advancement of water chemistry-related technologies, not only the reduction of harmful impurities was required but developments on the active control of the water chemistry from the viewpoint of material integrity and dose reduction has also been pursued in Boiling Water Reactors (BWRs). Based on this background, the injection of chemical additives into the CFDW of the UK ABWR is required to achieve an optimised RCS and associated systems chemistry. The RCS and associated systems chemistry regime for power operation of the UK ABWR can be summarised as follows:

- HWC (through continuous injection of hydrogen gas (H<sub>2</sub>) into the CFDW) with OLN (through batch injection of platinum, as sodium hexahydroxy-platinate, into the CFDW) to reduce the risk of Stress Corrosion Cracking (SCC) of the SSCs;
- DZO injection used as a means of reducing activity levels and dose rates under HWC conditions;
- Control of feedwater iron concentration to achieve low circuit dose rates;
- OI to reduce Flow Accelerated Corrosion (FAC) of carbon steel sections of the CFDW system.

Note that the RCS and associated systems chemistry regime for the UK ABWR has no impact on the system reactivity in normal operation, (see TR on Noble Metal Chemical Addition (NMCA) [Ref-4], and TR on Zinc Injection [Ref-5]).

In the context of this chapter, the term ‘reactor water chemistry’ includes the coolant within the Reactor Pressure Vessel (RPV) and its migration into steam and to the turbines. The ‘feedwater chemistry’ includes the condensate and the feedwater which is fed into the RPV. The condensate is mostly controlled through the Condensate Purification System (CPS) which contains the Condensate Filter System (CF) and Condensate Demineraliser System (CD) to ensure suitable purity, and then the feedwater is treated with the chemistry regime additives to achieve the correct reactor chemistry conditions. The condensate water chemistry is monitored but it is not actively controlled and therefore it is not discussed separately.

### **23.4.2 Chemistry Safety Functions of the Reactor Coolant System and Associated Systems**

The safety case for the RCS and associated systems chemistry is developed from the safety objectives identified in Section 23.3, and a number of safety claims have been derived from them as presented in Table 23.4-1.

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**Table 23.4-1 Safety claims for Reactor Coolant System and Associated Systems Chemistry Safety Case of UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC1: The UK ABWR reactor chemistry regime will contribute to the maintenance of the integrity of the Reactor Pressure Vessel (RPV) and SSCs in contact with the reactor coolant by controlling within the limits and conditions.	RC SC 1.1: Stress Corrosion Cracking (SCC) propagation will be mitigated by appropriate Electrochemical Corrosion Potential Control by HWC and OLNC.	23.4.3.2	8, 12
		RC SC1.2: Corrosion (such as SCC, FAC) and corrosion rates will be mitigated by control of impurities by operation of the clean-up systems.	23.4.3.1	8, 12
		RC SC1.3: Stress Corrosion Cracking (SCC) propagation will be mitigated during start-up by minimising the reactor water oxygen.	23.4.3.1	8, 12
	RC SC2: The UK ABWR reactor chemistry regime will contribute to the maintenance of the integrity of the associated SSCs which contact	RC SC1.1 (as above)	23.4.3.2	8, 11, 12, 13, 16, 17
		RC SC 1.2 (as above)	23.4.3.1	8, 11, 12, 13, 16, 17
		RC SC 2.1: Corrosion such as FAC and pitting corrosion will be	23.4.3.2	8, 11, 12,

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**Table 23.4-1 Safety claims for Reactor Coolant System and Associated Systems Chemistry Safety Case of UK ABWR**

Main Nuclear Safety Objective Issues for Chemistry Control	Top Claim	Claim	PCSR Chapter 23 Section	Other Related PCSR Chapter
	with reactor water outside of the RPV by controlling within the limits and conditions.	reduced by oxygen (O <sub>2</sub> ) control.	23.4.7	13, 16, 17
		RC SC 2.2: Impurities such as silica will be minimised to ALARP to reduce the scale adhesion in turbine system by operation of the CUW.	23.4.3.3	17
Material degradation, leading to fuel degradation	RC SC3: The UK ABWR reactor chemistry regime will contribute to the maintenance of the fuel integrity by control within limits and conditions.	RC SC 3.1: The specified levels and timing of noble metal injection will have no detrimental effect on fuel integrity.	23.4.4	11
		RC SC3.2: Suitable zinc injection within the upper LCO will have no adverse effect on fuel integrity.	23.4.4	11, 31
		RC SC3.3: Iron (Fe) concentration in feedwater within the LCO will have no detrimental effect on the fuel.	23.4.4	11, 17
		RC SC3.4: The application of HWC and management of the hydrogen injection concentration in the feedwater to LCO will ensure there is no detrimental effect on the fuel as a result of hydriding	23.4.4	11, 31

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**Table 23.4-1 Safety claims for Reactor Coolant System and Associated Systems Chemistry Safety Case of UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
		RC SC3.5: Adequate control of metal impurities especially Copper in feedwater will have no detrimental effect on the fuel	23.4.4	11, 31
		RC SC3.6: Foreign materials which might cause fretting will be minimised to ALARP before the first fuel loading	23.4.4	11
Hazardous and flammable gas products generated through radiolysis	RC SC4: The UK ABWR pipework and system design will mitigate build-up of hydrogen concentration and mitigate flammability risk and radioactive release from reactor coolant system.	RC SC4.1: Pipework and system design will minimise the build-up of hazardous concentrations of hydrogen.	23.4.5	7, 18, 24
Radionuclide inventory and release, and radiological dose	RC SC5: The UK ABWR reactor chemistry regime will ensure that the source term	RC SC5.1: The source term will be minimised to ALARP in association with material selection.	23.4.5	18, 31
		RC SC5.2: The source term will be minimised to ALARP in	23.4.5	18, 31

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**Table 23.4-1 Safety claims for Reactor Coolant System and Associated Systems Chemistry Safety Case of UK ABWR**

Main Nuclear Safety Objective Issues for Chemistry Control	Top Claim	Claim	PCSR Chapter 23 Section	Other Related PCSR Chapter
	radiological dose to the worker is ALARP by optimising materials selection, operating chemistry and operating practices.	association with operating practices.		
		RC SC5.3: The source term will be minimised to ALARP in association with operating chemistry.	23.4.5	18, 31
		RC SC5.4: Commissioning activities will be optimised to ensure that the longer-term radiation exposure will be minimised to ALARP	23.4.5	18, 31
		RC SC5.5: Source of activation products loaded from condensate and feedwater system to the reactor will be minimised to ALARP by the operation procedure of the condensate purification system.	23.4.3 23.4.5	18, 31
		RC SC6.1 (as below)	23.4.5	18
	RC SC6: The UK ABWR reactor chemistry regime will ensure that the radionuclide releases and exposure to public	RC SC 6.1: The amount of the activation product (N-16) transferred to the steam will be maintained low by the control of HWC+OLNC	23.4.5	18

**Table 23.4-1 Safety claims for Reactor Coolant System and Associated Systems Chemistry Safety Case of UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
	is ALARP.			
	RC SC7: The UK ABWR reactor chemistry regime will ensure that the radionuclide releases and exposure to worker is ALARP.	RC SC 6.1 (as above)	23.4.5	18
		RC SC7.1: Radionuclides in the reactor water will be kept below levels that results in increased radionuclide release and exposure, and minimised to ALARP in normal operations by CUW and OG operations.	23.4.5	18

### **23.4.3 Chemistry Control for Reactor Coolant System and Associated Systems Integrity**

The RCS and associated systems comprise the RPV and the CFDW as discussed in Section 23.4.1. The key aspects for RCS and associated systems integrity are;

- impurity control for mitigation of SCC by minimisation and clean-up and detection by systems such as the CUW, CFCD and the Chloride Ingress Protection System (CIPS),
- the control of the corrosion environment for SCC by using platinum and hydrogen as chemical additives to lower the ECP,
- enhanced mitigation of FAC in the CFDW by Dissolved Oxygen (DO) concentration control by the OI.

The maintenance of the RCS and associated systems integrity and minimisation of the risk of corrosion of the SSCs are achieved by controlling the reactor water chemistry in all operating modes. This includes sampling and monitoring to ensure that the chemical additions and clean-up is sufficiently applied and adjusted to maintain the reactor water within expected levels, and for all modes of normal operation. This ensures that the expected design electricity generation lifetime for the UK ABWR and plant is achieved, as well as the opportunity for ensuring a longer generation lifetime.

Furthermore, the water chemistry regime control and management of the process fluids in the UK ABWR plays a role in controlling the levels of radioactive contamination and radioactive waste that are built up during the operational lifetime of the plant, and that have impact on decommissioning. This includes benefits associated with the reduction of radioactive contamination and activation of the plant SSCs and dose uptake to workers. Additionally, the water chemistry plays a key role in ensuring the fuel integrity, as minimising fuel leaks also has an impact on minimising the radioactivity inventory from the operating lifetime. Therefore, the water chemistry plays an important role in ensuring that the decommissioning source term is optimised. Further information on the decommissioning planning for the UK ABWR is provided in PCSR Chapter 31. The next sub-sections describe the RCS and associated systems chemistry control requirements in normal operation in more details.

### **23.4.3.1 Impurities Control**

The main issue on the integrity of the RPV and RINs is the suppression of SCC and the general corrosion process within the system.

The RPV and RINs constitute the heart of the reactor, and contain the fuel assemblies where the nuclear reaction takes place. Its integrity is the first priority of the UK ABWR operation. The most important defect mechanism for the RPV and RINs is SCC including Intergranular Stress Corrosion Cracking (IGSCC) and Irradiation Assisted Stress Corrosion Cracking (IASCC) for the RINs, as are addressed in the Topic Report on Material Degradation Mechanisms - Stress Corrosion Cracking [Ref-6], Topic Report on Material Degradation Mechanisms – Irradiation-Assisted Stress Corrosion Cracking [Ref-7] and [Ref-2].

The water quality is dependent on the levels of soluble impurities contained in the water, and the sources and control of these chemical impurities are defined in the TR on Impurity Ingress [Ref-8]. The water quality is required to ensure the following in terms of contributing towards maintaining the structural integrity of the primary coolant system [Ref-1]:

- To maintain the soundness of the components and pipes in the plant,
- To prevent the damage of SSCs and fuel cladding tubes caused by adhering impurities to their surfaces,
- To reduce the generation of radioactive waste, and
- To maintain the performance of the purification system.

#### **(1) Reactor Water Chemistry**

This section presents the reactor water chemistry controls during the different modes of operation for the UK ABWR that are associated with the protection of the structural integrity of the RCS and associated systems.

Chemical impurities, such as chloride and sulphate are of the most common that can contaminate the reactor water. Over time, if tolerated, such impurities can significantly impact on the integrity of the RCS and associated systems. This is because these impurities can create a corrosive environment and detrimentally influence the degradation mechanisms such as SCC, pitting and crevice corrosion in austenitic stainless steels and nickel based alloys that comprise the RCS and associated systems SSCs. The corrosive environment is one of the three factors that are required for SCC to occur, and therefore is an issue that needs to be managed in the plant design.

## **Method of Control and Monitoring**

The chloride, sulphate and other ionic impurities are maintained to ALARP by the clean-up systems in the RCS, namely the CUW and the CPS, the use of high purity make-up water from the demineralised water system, and by control of the impurities that can enter the system.

The CUW function provides continuous clean-up of soluble species and particulate matter from the reactor water. A proportion of these soluble and insoluble impurities must be removed from the reactor water by the CUW to maintain the reactor water quality for the integrity protection purposes of the system and to maintain low radioactivity levels [Ref-3][Ref-9]. This is achieved by circulating the reactor water through the powder resin pre-coat Filter Demineraliser (F/D) at a flow rate equal to two percent (2%) of the Feedwater System (FDW) flow rate during all normal operations. The Bottom Drain Line (BDL) located at the bottom of the RPV and connected to the CUW, provides a location to drain off any accumulated corrosion products during construction, commissioning and operation (and later for decommissioning).

A Decontamination Factor (DF) of 10 or more for insoluble substances has been confirmed in the CUW F/D utilised in existing plants in Japan as described in [Ref-3]. For insoluble substances, removal performance generally increases with increased loading on the filter demineraliser. However, accumulation of insoluble substances on the filter demineraliser surface also gives rise to an increase in differential pressure across the unit, which is an indicator for filter demineraliser backwashing and pre-coating. Such actions are performed to prevent the differential pressure from exceeding the CUW filter demineraliser design pressure.

The other main functions of the CUW are described in PCSR Chapter 12.3, as well as the justification for the safety category and class (see also Table 23.3-1). The CUW design justification for the reactor water chemistry management and details of the pre-coat power resin ion exchange and plant performance are provided in [Ref-3].

Control of RCS and associated systems chemistry requires conditions within the coolant to be measured. The direct conductivity, chloride and sulphate parameters as outlined in the [Ref-1] will be sampled and monitored to ensure the SSCs integrity for the mitigation of IGSCC.

The conductivity of water is an indication of the ability of the water to carry an electrical current, and in water that current is carried by the dissolved ionic species in the system. Direct conductivity

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identifies the presence of cations and anions, but it does not differentiate between the impurity species. However, because the reactor water is relatively pure water, the direct conductivity levels are very low in normal operation, and so changes in the impurity levels, such as chloride and sulphate increases, are detected quickly. This provides early warning and protection in ensuring that corrosive and depositing ionic species in the water are minimised, as well as ensuring that chemical additives purposely added to the water are also maintained (see Section 2.4.3.2). Conductivity measurement is usually applied in place of detailed impurity analysis during operation due to the speed of response (as it can be the first indication there is impurity ingress or other problem) and is carried out as online monitoring. It is normal to follow up with additional specific impurities analysis if significant changes in the conductivity level or trend are observed in normal operation.

The impact of operation with chloride at elevated levels is a chronic impact to SSCs related to the concentration and duration of exposure. It is important to mitigate impurity ingress from the feedwater in order to maintain the water quality in the reactor water, since the feedwater impurities are concentrated in the reactor. Impurity removal in the CPS is fundamental in achieving the feedwater quality, and the protection by the CIPS. This is discussed below in part (b) for the CFDW.

Similarly to chloride, sulphate is considered an aggressive ionic impurity in the water systems, and is also associated with IGSCC acceleration, as well as other degradation mechanisms influenced by corrosive environments. Sources of sulphur are described in [Ref-8], but include cooling water in-leakage, resin ingress (from the clean-up systems) or resin decomposition. If organohalides or organosulphates, which are Total Organic Carbon (TOC) species, are present they can break down in the reactor operating conditions to release aggressive chlorides and sulphates into the water.

For the reasons above, the reactor water direct conductivity, chloride and sulphate are considered as key control parameters for ensuring that impurities are managed during power operation, and in practice these impurity operating levels are very low. The safety case margin of the LCO for the reactor water direct conductivity during power operation is a maximum of 600  $\mu\text{S/m}$  (at 25°C), the reactor water chloride during power operation is a maximum of 600 parts per billion (ppb), and the reactor water sulphate during power operation is also set at a maximum of 600 ppb. These UK ABWR LCOs have been determined by the consideration of data acquired from studies on SCC as detailed in [Ref-1]. The LCOs for direct conductivity, chloride, and sulphate, during start-up and shutdown, and for the outage are the same values as at power operation. The reactor water limits for

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direct conductivity, chloride and sulphate during an outage are also based on the Spent Fuel Storage Pool (SFP) and the Suppression Pool (S/P) and the chemistry discussed in Sections 23.5 and 23.6 respectively.

The management of TOC in the reactor water during outage is carried out by ensuring that the Condensate Storage Tank (CST) water TOC concentration is minimised. The sources, impact and control for the TOC impurity is further discussed in Section 23.8.

Impurities generated during the commissioning stage of the UK ABWR have the potential to affect the structural integrity of the SSCs if they remain residual in the RCS and associated systems even after the plant starts to operate. To reduce the risk of SCC the use of high purity (demineralised) water is an important approach during this phase of commissioning, as well as avoiding general corrosion risks. Therefore, the UK ABWR clean-up methods, including the availability and capacity of the designed clean-up systems is one of the considerations included as part of the commissioning programme development by the future licensee. The commissioning strategy proposed for the generic design is detailed in the TR on Commissioning Chemistry [Ref-10]. Systems will be flushed with high purity demineralised water to minimise impurity levels and achieve and maintain the conditions to the water chemistry specification, during the testing and storage of the plant, and to ensure that the water quality is to the same levels as for normal operations prior to the first fuel loading, after which the start-up testing stage of the commissioning commences [Ref-1][Ref-10].

The chemical impurities in the reactor water are grab sampled and analysed in the laboratory or by online techniques in accordance with the sampling and monitoring requirements. The site specific sampling and monitoring layout and equipment requirements will be designed and installed to meet the expectations of the Topic Report on Sampling and Monitoring Philosophy for Chemical and Radiochemical Parameters [Ref-11]. The sampling and monitoring design arrangements for the UK ABWR are described in more detail in Section 23.11.

### **Possible Faults**

The risks associated with the loss of the clean-up capability are addressed in Attachment L (Non-Reactor Faults) systems in the TR on Design Basis Analysis [Ref-12] (see also [Ref-3]).

The sodium concentration in the reactor water increases due to OLNC, which injects sodium hexahydroxy-platinate, and will be evident by increases in the reactor water conductivity. Short

duration increases from this known impurity source can be predicted and is not a concern for IGSCC or fuel cladding corrosion. Therefore, the sodium increase during OLNC is not a fault, and OLNC has been determined to be ALARP overall [Ref-8].

## **(2) Condensate and Feedwater Chemistry**

The condensate water chemistry is monitored but it is not actively controlled and therefore it is not discussed separately from the feedwater.

The ionic (soluble) impurities, such as chloride and sulphate and particulate impurities such as crud in the condensate and feedwater should be removed to maintain the material and fuel integrities, as these are introduced from the feedwater to the reactor internals and become concentrated in the reactor water. The impurity control and monitoring in the feedwater is therefore important to maintain the water quality in the reactor water. Many of the impurities that enter the feedwater are based on the make-up water quality and the quality of the condensate, and as result of cooling water in-leakage. The CFDW impurity removal is carried out by the CPS. Impurities can also ingress into the RCS and associated systems from sources such as the chemical additives that are purposely added to the system, (e.g. depleted zinc oxide and sodium hexahydroxy-platinite). All of the possible sources are considered in detail in [Ref-8].

The CPS has a CF and CD arrangement and continuously purifies the condensate. The CF is used to remove particulate from the CFDW water using filter technology. The main function of the CD is to remove the impurity ions from the condensate water by ion exchange, but it also has a small additional filtering function to remove particulate. The detailed design description of the CPS, CF and CD is presented in the PCSR chapter 16.

The CF flow rate is at its maximum when the Low Pressure Condensate Pump (LPCP) operates at its maximum capacity. The maximum flow rate of one CF unit (of which there are three) is equal to one third of the maximum condensate flow (5400 m<sup>3</sup>/h). As such, the maximum flow rate for one CF unit is equal to 1800 m<sup>3</sup>/h/unit. When the CF is being backwashed, the flow corresponding to one CF unit is able to be bypassed. The facilitation of this bypass function means that it is possible to achieve the maximum CF flow rate even when the CF is undergoing backwash.

The flow arriving at the CD system inlet has two origins:

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- the condensate which is pumped by two LPCPs, and
- the low pressure FWH drain which is pressurised by two Low Pressure Drain Pumps (LPDPs).

The maximum flow rate of the entire CD system is set at 6720 m<sup>3</sup>/h which corresponds to the maximum capacities of both LPCPs and LPDPs (i.e. four pumps). As this flow is processed by six CD vessels, the maximum flow rate per CD vessel is 1120 m<sup>3</sup>/h/unit. The volume of resin in the CD is determined so that the water quality at the outlet remains acceptable, even at the maximum flowrate. When the CD system is required to be backwashed, only one CD vessel at a time is backwashed. As only five vessels are in service which provide the required clean-up function during this period, the flow from both of the LPDPs bypasses the CD system so that the maximum flow rate for each CD vessel is not exceeded.

The CPS, CF and CD system justification is further detailed in [Ref-3] and the details regarding the design control are in [Ref-8]. These systems design specification, safety category and classification and SFCs are detailed in PCSR Chapter 17.

Direct conductivity, chloride and sulphate LCO values are not set in the safety case for the feedwater as these are already set for the reactor water. However, the future licensee should set action levels to control the site specific chemistry control regime for these parameters.

The CFDW LCOs that are related to impurities management have been set based upon the fuel integrity requirements, and these are discussed in Section 23.4.4.

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**Possible Faults**

The CD provides protection from seawater that could ingress into the condensate water via condenser tube leakage. Due to the titanium condenser tubes that are used in the UK ABWR, cooling water in-leakage is not expected to be an issue. However, if a condenser tube leakage should occur, the impurities from seawater could potentially flow into the reactor water, and so the CD is installed at the condenser outlet. It is designed to protect the plant against chloride ingress in the case of a single condenser tube leakage, maintaining the water quality for a required period. The postulated unmitigated consequence in the case of a large amount of seawater ingress is not severe because there is enough time to shutdown the reactor after the initiating event. This is because the CD design provides sufficient ion exchange capacity based on normal flow rates to allow a response time before impurities break through if a single (guillotine fracture) condenser tube leakage occurs. The occurrence of the leakage will be promptly detected by conductivity measuring equipment. If the conductivity at the condenser hotwell and CF inlet shows an increasing trend, and the CF inlet conductivity, the CD outlet conductivity and reactor conductivity are still below the operational target value, then a minor tube leakage is assumed and repair of the leak can be performed during partial operation of the condenser. However, if a large leak occurs, and the impurities cannot be controlled to maintain the water quality for the required period, this can adversely affect the structural integrity of the reactor components. In this case, the plant will be shut down and the damaged condenser tube or tubes repaired [Ref-8]. In the case of a large seawater cooling water leak, such as a complete guillotine failure of two or more condenser tubes then the operating margin from the CD capability may be compromised. For this reason, a CIPS will be installed for the UK ABWR, which is based upon conductivity sensors and meters linked to an automatic interlock system which can close the High Pressure Condensate Pump (HPCP) downstream of the CF and CD to prevent contaminated condensate being fed forward. The CIPS interlock will be activated when conductivity measurements reach the instrumentation logic set points for both the CD inlet and CD outlet positions.

**23.4.3.2 Corrosion Environment Control**

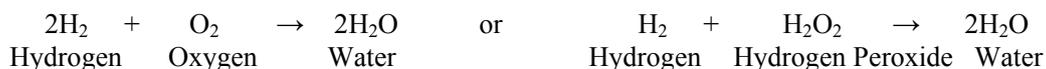
It is required for the safety case that the three factors that are required for SCC must be considered for achieving the goal of SCC propagation mitigation. This is especially needed for the UK ABWR to ensure a long plant life of 60 years. It has been recognised that the presence of the oxidising species such as DO and hydrogen peroxide in the water strongly affects the SCC mechanism [Ref-12][Ref-13]. Therefore, the UK ABWR reactor water coolant regime uses hydrogen and platinum to

reduce the oxidising species in the reactor water and result in a reducing environment, and the Electrochemical Corrosion Potential (ECP) is suppressed into a region where SCC is prevented.

**Method of control and monitoring**

With respect to the oxidising species, it had been the DO that was considered to affect the SCC in the early stage of BWRs development, but recently the importance of hydrogen peroxide generated by the water radiolysis has been recognised; a small amount of hydrogen peroxide strongly affects the behaviour of SCC. Hydrogen peroxide is unstable in a hot water environment and easily decomposes to oxygen and water. The ECP indicates a relative potential with respect to the standard hydrogen electrode (SHE), and the higher oxidant concentration brings about the higher ECP.

Regarding the relationship with SCC behaviour, it is known that the crack growth rate is sufficiently mitigated if the ECP level is reduced to under -0.23 V (vs SHE) by the re-combining reaction which is represented as follows, [Ref-4]:



By adoption of HWC only, high levels of hydrogen are needed to achieve the full suppression of the oxidants in the reactor water. However, an injection of a sufficient amount of hydrogen for suppressing the oxidants and SCC increases the nitrogen-16 (N-16) radiation level in the turbine system and piping dose rate, and this aspect is further discussed in Section 23.4.5 regarding the radiation source term control. It is sufficient to say here that N-16 dominates the radiation field in the turbine system, and is a significant contributor to worker dose during power operation.

To mitigate the N-16 radiation increase, the UK ABWR will implement a noble metal (platinum) injection technique known as OLNC during power operation [Ref-4]. HWC with OLNC needs less hydrogen for achieving the targeted ECP than HWC only due to the catalytic process by the platinum. Theoretically the HWC plus OLNC regime gives platinum potential around the -0.5 V (vs SHE). By the reduction of the required hydrogen quantity (e.g. in the feedwater line, typically from 1 part per million (ppm) to 0.15 to 0.3 ppm), the volatile N-16 compounds are suppressed.

Suppression of the SCC environment by HWC + OLNC can be achieved when the hydrogen:oxygen ratio in the reactor water exceeds 2. To achieve this, the dissolved hydrogen concentration in the feedwater is monitored. The hydrogen demand to mitigate the environment is plant specific, and so the lower LCO for hydrogen is set based on achieving dissolved hydrogen in the feedwater at 0.15

ppm. This is the preliminary value required to achieve a hydrogen:oxygen ratio  $>2$ , as described in [Ref-1], [Ref-4] and the TR on Radiolysis and Electrochemical ECP model [Ref-14].

The dissolved hydrogen upper limit is set at 0.5 ppm, which is based on

- ensuring that the N-16 source term is not increased as a result of excess hydrogen, and
- the safety management of hydrogen (see Section 23.4.6).

For the site specific stage, the ECP and hydrogen injection model prediction of hydrogen and oxidant behaviour generated by water radiolysis, and the benchmark testing will be conducted by the future licensee to confirm the plant specific value and the control within the LCO, [Ref-14].

The 'HWC availability' parameter is used for monitoring the performance of HWC regime operating plants as a function of the availability of hydrogen and protective ECP as a function of time at power [Ref-1]. The focus on HWC availability has been used at stations to improve performance by minimising downtime of the hydrogen injection system by using this as a key performance indicator. Minimising the risk to plant if the hydrogen injection is lost for a period is desirable, and important in the demonstration of safe operation within the safety case. These aspects are also discussed in details in [Ref-4], and for this reason the LCO for the HWC availability will be  $>90\%$  at power operation for the UK ABWR (see the loss of HOIS discussion in 'possible faults' at the end of this sub-section).

Hydrogen dosing during the start-up and shutdown phases will at the same  $H_2/O_2$  ratio as power operation. During the latter stages of shutdown once the reactor is no longer critical, feedwater flow is too low to maintain the injection. Therefore, before air is admitted and before the reactor head is removed, hydrogen dosing will be secured. The LCO for the feedwater hydrogen concentration during start-up and shutdown is has a minimum concentration of 0.15 ppm and maximum concentration of 0.5 ppm, when the HOIS system is in service. These limit values are based on the same principles as the LCO for the feedwater hydrogen concentration during power operation, and so are the same. For the start-up, the hydrogen injection is reinstated when the feedwater flow is re-established and this is required to be within 5 to 10% of thermal reactor power. This is described in the TR on Start-up and Shutdown Chemistry [Ref-15].

The UK ABWR chemistry regime will apply OLNC during normal power operation conditions. An application takes several days (approx. 10 days are typical, though it is site specific). The application periodicity is also site specific, although the generic safety case considers annual applications will be carried out to ensure continued plant protection. There are some restrictions to when OLNC can be applied, and these are:

- The amount of platinum added to the reactor is controlled due to concerns about fuel integrity, which is mostly driven by the fuel vendor guidance. The fuel vendor guidance imposes a limit of  $60\mu\text{g}/\text{cm}^2$  over the lifetime of the fuel, or  $10\mu\text{g}/\text{cm}^2$  per year (which pessimistically assumes that all the platinum has been loaded onto the fuel and none onto other structural surfaces). Current OPEX indicates that the  $60\mu\text{g}/\text{cm}^2$  level has not caused any fuel failures or concerns. Based on the guidance, the upper LCO for platinum injection for the UK ABWR is set at 920 g/year. It is expected that during operation the full 920 g of platinum will be used during the OLNC injection period on an annual basis. The procedure will include creating a platinum solution and placing it in the injection tank in several batches. This method will ensure that overdosing cannot occur, as the amount of platinum is limited at the injection point. Additionally, laboratory experimental data has been reviewed. From these data, the platinum deposit amount required is about  $0.05\mu\text{g}/\text{cm}^2$  to achieve an ECP of -500 mV (vs SHE) [Ref-1]. Based on the surface area of the reactor internals and consideration of OPEX data from the United States, the lower LCO for the total platinum injection amount is conservatively set at 20 g/year for OLNC application in the UK ABWR during power operation [Ref-1][Ref-4]. The calculation is noted in [Ref-1],
- The application should not be carried out before 60 days at power operation have passed following a refuelling outage. This is to allow a 60-day preconditioning period of the fuel clad of new fuel that has been loaded, because of concern about abnormal corrosion of the fresh fuel surfaces. Therefore, the injection timing for OLNC platinum injection is set at being >60days of operation after an outage [Ref-1][Ref-4], and
- OLNC will not be carried out within a period of less than three months prior to the planned shutdown of the reactor. This is due to OLNC causing restructuring of the corrosion films on surfaces and because this results in a release of Co-60, it could increase the upcoming outage radiation dose exposure (shutdown dose rates). As operational conditions could lead to an earlier outage that expected on occasions, this is not set as an LCO requirement, but it should

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be taken into consideration for the injection timing and the outage planning by the future licensee during operation [Ref-1][Ref-4].

The oxidising environment is a concern for SCC during a plant start-up after an outage. Before start-up, the concentration of DO in the coolant is saturated (around 6 to 8 ppm) because the RCS and associated systems are exposed to air during the plant shutdown. During the plant start-up, there is a period during which the transfer efficiency of oxygen into the Main Steam System (MS) is low because the steam generation during start-up is lower than that during operation. This results in high oxygen concentrations during the start-up stage [Ref-15]. In addition to this, a temperature change during the start-up stage gives rise to an increase of strain of the structural materials [Ref-16]. These factors are considered to accelerate the SCC. To avoid this situation, deaeration is conducted and the DO concentrations controlled. The reactor water DO for start-up is an LCO. It is sampled and monitored during the start-up to ensure that the deaeration of the reactor water achieves a DO level of 200 ppb (maximum) before start-up is commenced [Ref-15].

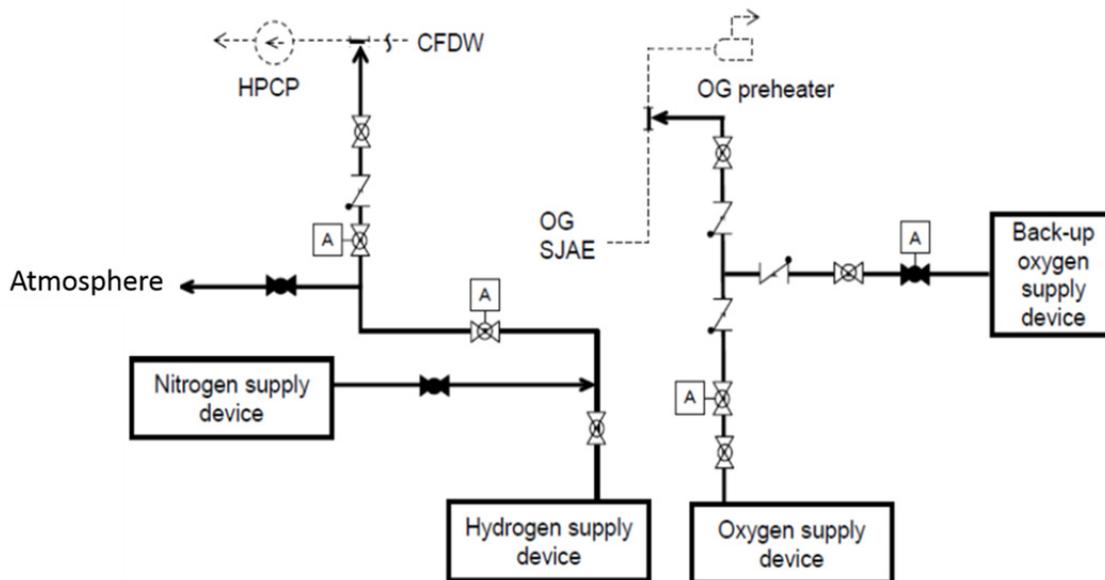
The HOIS is described in the Chemical Injection System System Design Description [Ref-17]. The HOIS purpose is to inject hydrogen gas into the CFDW during normal plant operation to reduce the DO (and oxidants) concentration in the reactor water, and the ECP of the reactor water.

The HOIS consists of two sub-systems:

- Hydrogen injection system, and
- Oxygen injection system.

A schematic diagram of the HOIS is shown in Figure 23.4-2

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**Figure 23.4-2: Schematic of the Hydrogen and Oxygen Injection System (HOIS)**

The hydrogen injection system of the HOIS supplies hydrogen gas to the CFDW from the hydrogen supply source during normal plant operation. A flow rate control valve is mounted on the hydrogen injection pipe to adjust the dissolved hydrogen concentration in the feedwater. The hydrogen injection point will be selected based upon consideration of the hydrogen accumulation in the system and building, and the hydrogen gas injection pressure needs to be higher than the operation pressure at the injection point in the FDW. In normal operation, including start-up and shutdown modes, the HOIS injects hydrogen into the feedwater line when the thermal output is equivalent to 5% rated power or higher. At 50 to 100% of rated power the hydrogen injection flow rate into the feedwater can be automatically controlled to be proportional to the feedwater flow rate. The hydrogen injection is automatically stopped on detecting low CFDW flow rate on plant shutdown. The HOIS has a nitrogen gas purge system to prepare the system for plant maintenance.

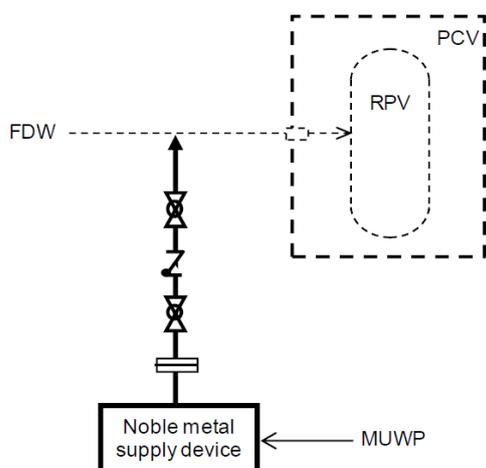
The hydrogen injection is classed as an ancillary system, as it is designed solely for this purpose during plant operation. The system is designed to control hydrogen within the LCO for all modes of operation.

The oxygen injection system of the HOIS supplies oxygen gas into the OG from the oxygen supply device during normal operation to compensate for the excess hydrogen conditions resulting from hydrogen injection into the feedwater by the HOIS. The HOIS also provides oxygen injection back-

up system to secure oxygen injection function even if the oxygen injection failed. This oxygen injection requirement is further discussed in Section 23.4.6. The OG recombiner description is addressed in PCSR Chapter 18.

The HOIS is designed such that it meets safety class and regulatory requirements for safe storage of the gases, and safe operability and maintenance. The details of this are provided in [Ref-17].

The HOIS, NMIS and ZNIS, all have a small contribution to the dose accrual in the plant, and hence have a small effect on the source term, and for this reason are category C and class 3 systems. The platinum chemical for the OLNLC methods will be injected using the NMIS during the normal power operational period, and as per the conditions on timing of the injection as stated above. The NMIS injects a diluted solution containing sodium hexahydroxy-platinate ( $\text{Na}_2\text{Pt}(\text{OH})_6$ ) into the feedwater line, after which the injected platinum deposits on the surfaces of the reactor internals and other RCS and associated systems components with which it comes into contact. A schematic of the arrangement of the NMIS is shown in Figure 23.4-3.



**Figure 23.4-3: Schematic of the Noble Metal Injection System (NMIS)**

The NMIS is designed such that (a) it meets safety class and regulatory requirements for safe storage of the chemical, safe operability and maintenance, and (b) the system can effectively dilute the solution of sodium hexahydroxy-platinate with pure water from the Make-up Water Purified System (MUWP) and inject it into the feedwater lines at an appropriate flow rate. The detailed NMIS system design description, including dilution requirements and flow rates, is provided in [Ref-17]. The justification for OLNLC is described in [Ref-4].

**Possible Faults**

During noble metal injection for OLNC, the direct conductivity will increase due to the increases in sodium from the platinum compound. The conductivity increases are short duration and from this known source the impurity and sodium level can be predicted in advance. The increased sodium is not a concern for increased risk of accelerating IGSCC or fuel cladding corrosion because the small amount of sodium does not have an adverse effect on material and fuel cladding as is described in [Ref-8].

The possible faults and consequences of loss of the injection systems are described in [Ref-3]. These are summarised below.

The HOIS is designed to be isolated from the main plant either manually or automatically in case of an abnormality. Such operations and abnormality alarms can be monitored and controlled from the Main Control Room (MCR). The HOIS has been designed such that gas leakages from the injection system, its structures, systems and components are prevented, detectable and can be controlled.

There are three key scenarios associated with a loss in the function of the HOIS. These are the loss of the hydrogen injection system, excess hydrogen injection and loss of the oxygen injection for the OG recombiner. The latter is considered in Section 23.4.3.3.

If there is a loss in the ability to inject hydrogen by the HOIS, this results in a loss of SCC mitigation. While the ability to mitigate SCC is lost during such periods, there will be no significant impact on reactor safety for the following reasons:

- (1) The main impact is on ECP which returns to a level measured at operational Japanese (A)BWRs with no issues for SCC having been reported.
- (2) Improved materials have been selected for the UK ABWR to construct the SSCs as compared to those used in the Japanese ABWRs.

The time period in which the system may be lost is assumed to be a one cycle period because any failures relating to the injection systems can be repaired and maintained during the outage phase. In addition to this, the loss of hydrogen injection is not immediately classified as an emerging issue because of the 90 % availability of the HOIS has been shown to be acceptable [Ref-14]. This is equivalent to a loss period of 50 days in an 18-month operating cycle.

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It is recognised that when hydrogen injection is stopped, the chemistry regime shifts from a reducing environment to an oxidising environment, and this can result in an increase in the dissolution of chromium from the system materials. From the standpoint of zinc injection, stable zinc chromite is formed. As chromium spikes are not observed in most plants, there is no requirement to secure (stop) zinc injection when there is a loss of hydrogen injection [Ref-3].

In the case of an excess hydrogen injection the Main Steam Line (MSL) dose rates increase significantly due to the presence of N-16 in the reactor system. For the UK ABWR this is classified as a temporary event. The MSL dose rate is monitored during operation, and an alarm is activated if the radiation level exceeds a pre-determined set point.

There are two key scenarios associated with a loss in the function of the NMIS, which is either the loss of impact that the noble metal has on the performance of the UK ABWR, or an excess of noble metal is injected.

In the event of noble metal injection failure, the injection will be restarted after the cause of failure is determined and remedied. It is judged that no emerging issues will occur because of the improvement in materials and tensile stress methods in the UK ABWR design which is also a factor of the SCC mitigation. If the OLNC injection fails, the benefit associated with hydrogen injection is greatly reduced as the hydrogen injection will not be sufficient to reduce the ECP to a desired level on its own. However, the benefit associated with the deposition of noble metals will last unless the noble metal deposits are removed, and hence the presence of existing noble metal deposits serves to reduce the ECP (at the desired hydrogen concentration). The hydrogen injection can continue if noble metal injection ceases. Even if noble metal is removed, hydrogen will continue to be effective. Noble metal injection will be completed as projected when the cause of the injection failure has been resolved.

If an excess of platinum was injected that exceeds the LCO ( $60\mu\text{g}/\text{cm}^2$  per fuel lifetime), the risk of crud spalling will increase. However, a predetermined amount of the platinum solution is loaded on to the injection skid, and it is injected in batches, so it will not be possible to inject an excess of noble metal into the UK ABWR. Therefore, even if the NMIS fails open, the loading amount of platinum will not exceed its defined upper limit.

It has been found that the use of OLNC does not affect corrosion rates of the feedwater pipes and Cobalt based alloys, or the mechanical properties of nickel based alloy, low alloy steel and stainless

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steel. Evidence is provided in [Ref-4] where it is demonstrated that OLNC rather reduces FAC in carbon steel by promoting the generation of a passivating oxide layer. Test results show no significant increase in fracture rate, rupture stress or breaking strain for these materials under HWC with OLNC conditions. Based on the small increase in oxygen concentration in the materials' surface due to the reduced amount of injected hydrogen, the acceleration of corrosion rates on cobalt based alloys is negligible. The influence of OLNC on the CUW F/D is described in [Ref-4]. It states that performing a backwash / precoat of CUW demineralisers is recommended in the week before the start of injection, and that after OLNC injection there is no impact on the operation of the CUW.

#### **23.4.3.3 Feedwater Dissolved Oxygen Control (including the Oxygen Injection System (OI))**

The degradation risk of FAC is mostly associated with the CFDW part of the RCS. This is because the materials in the RPV are FAC resistant due to their composition. The concentration of DO in the condensate water is expected to be typically less than 10 ppb at power operation, as it is removed by the vacuum deaeration in the main condenser. This low DO concentration accompanied with a high flow velocity of coolant is the FAC risk to the plant. Therefore, the water chemistry control for FAC which is by OI is focused on the CFDW.

Flow Accelerated Corrosion (FAC) is an important defect mechanism for the CFDW. Materials selection for structural integrity in support of the chemistry controls including mitigation of the FAC risk is discussed in Section 23.4.7. The materials selection for the CFDW and the purpose of the enhanced protection by oxygen injection into this system for mitigation of FAC of the CFDW is justified in the TR on Degradation Mechanisms – Flow-Accelerated Corrosion and Erosion-Corrosion [Ref-18].

#### **Method of control and monitoring**

The influencing parameters on FAC are material composition, temperature, DO concentration, and flow velocity of the coolant through the system piping and components [Ref-19][Ref-20][Ref-21][Ref-22]. The pH is also a factor for FAC, but the UK ABWR chemistry regime does not include chemical addition for adjustment of the pH.

The concentration of DO in the condensate is stated in the Oxygen Injection System, System Design Description [Ref-23] and in [Ref-18]. It is for a DO concentration range typically of 20 to 50 ppb. From a chemistry point of view the injection of oxygen into the FDW to achieve a DO concentration of <15 ppb is known from literature to be too low to ensure FAC mitigation, and a DO concentration

that is > 500 ppb can lead to pitting corrosion. The UK ABWR also does not employ a chemistry regime that can control the formation of an oxide layer by pH management. Therefore, the LCO for the feedwater DO during power operation is set at a minimum DO concentration of 15 ppb and a maximum of 500 ppb, [Ref-1].

The main consideration for the reactor water chemistry is the SCC risk for the core structural materials that could be affected by the oxygen injection in the feedwater line depending on the amount of oxygen in the reactor water in power operation. However, the DO concentration in the reactor water of the UK ABWR is expected to be around 150 to 250 ppb in practice taking into consideration the proposed hydrogen concentration in the feedwater [Ref-14] (see Section 2.4.3.2) and it is mostly produced by the water radiolysis reactions in the RPV. The amount of DO injected in the feedwater to prevent FAC is deemed negligible in comparison to this and will not adversely affect the SCC risk in the RPV.

By employing oxygen injection there is also a benefit in preventing the general corrosion of the system, which effectively minimises the quantity of corrosion product and crud that is generated from the CFDW. This has a positive impact on attaining a low iron inventory, which is required by the UK ABWR proposed regime for iron control, and in turn minimises the radioactivity transport in the RCS and associated systems as is discussed in Section 23.4.6.

The OI used to inject oxygen into the CFDW is a separate system to the HOIS oxygen injection described in Section 23.4.3.2. The OI has been designed to safely and continuously inject DO in the CFDW and so that it is a steady supply and it is controllable. Since the OI is for mitigation of FAC which is a long term degradation mechanism, and the failure is linked to commercial risk, the system is not assigned a category and class.

The OI is installed at the Low Pressure Condensate Pump (LPCP) discharge or the CF outlet. The system description is also discussed in PCSR Chapter 17.10. The OI is designed such that it is resistant to any corrosion from the oxygen gas itself, and that the materials, pipework and components are selected based on compatibility and safe use with oxygen systems. The OI is equipped with:

- oxygen (O<sub>2</sub>) gas cylinder rack,
- oxygen (O<sub>2</sub>) gas pressure control rack, and

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- OI instrument rack.

For the injection, the oxygen supply originates from oxygen gas. The OI depressurises the oxygen gas from the cylinders and then injects it directly into the condensate water at the LPCP discharge or the CF outlet to maintain a DO concentration within a specified range that will ensure that the system is protected. When the OI is in service the following will be monitored to ensure the plant is operating as expected and to ensure that it is in an operable state:

- Oxygen cylinder outlet pressure,
- Oxygen injection pressure, and
- Oxygen flow rate.

To prompt plant operators to act if necessary the following alarms will also be used when the plant is in-service:

- Oxygen cylinder outlet pressure, and
- Water level in the oxygen injection pipe.

The system is designed with several controls and interlocks to ensure its safe operation. These include:

- The self-actuated pressure control valve to constantly regulate the oxygen injection into the condensate from start-up to 100% load,
- The oxygen injection stop valve which is closed when the condensate flow rate is below the set point to avoid unnecessary oxygen injection during plant start-up and shutdown,
- The flow control valve (FCV) to automatically regulate the oxygen flow rate by monitoring the condensate flow rate. The oxygen concentration in the condensate will be variable due to the additional oxygen mixed into the system that is carried by the heater drain from the Low Pressure Drain Pump (LPDP), and
- The FCV bypass valve can be operated manually to increase the oxygen injection flow rate for enhancing the anti-corrosion protection during commissioning.

The OI full design requirements are described in [Ref-23].

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**Possible Faults**

The concentration of DO in the feedwater of the UK ABWR is controlled using the OI, whose primary purpose is to reduce FAC of carbon steel piping in the condensate and feedwater line. As the concentration of DO in the feedwater is monitored continuously, any departure from the desired performance of the OI can be detected quickly, i.e. either loss of oxygen injection or excess of oxygen injection can be detected. The localised corrosion risk in case of an excess of oxygen is described in Section 23.4.7.1 (d)

In the case of a loss of oxygen injection during power operation the simple OI can be quickly reinstated, and even if the system were out of service for several days, the corrosion rates are considered negligible before the system can be put back in service.

Loss of oxygen injection will result in increased degradation rates of carbon steel piping due to FAC. Significant corrosion of carbon steel piping in the feedwater line will ultimately result in feedwater piping failure. Therefore, the CFDW piping will use carbon steel, carbon steel with >0.1 % chromium and low alloy steel, and employ OI as an ALARP measure, [Ref-3][Ref-18].

**23.4.3.4 Reactor Coolant System and Associated Systems- Other Chemistry Control**

**Considerations for SSCs**

The impurities contained in the reactor water are transferred to the vapour phase through the boiling process and carried over to the turbine system. Some impurities are deposited on the turbine system which will deteriorate its performance. Among them, silica is a common impurity contained in the reactor water in high concentrations (more than 100 ppb) [Ref-8].

Silica can originate from a number of sources as described in [Ref-8]. This reference mentions that there has been some suggestion that silica has a negligible impact on IGSCC, but there are no effects for IGSCC anticipated for silica under HWC, which is the regime that the UK will employ.

**Method of control and monitoring**

Silica is a major impurity in the reactor water and can have concentrations that are many magnitudes higher than any other impurity species [Ref-8]. Silicate chemistry can be very complex, and as the concentrations can be high, so there is a requirement to ensure silica is minimised as an impurity. For the RCS and associated systems, determination of the silica concentration in the reactor water is important to ensure that levels are below those likely to result in any significant issues related with deposition. The amount of silica carried over to the turbine is dependent on the concentration in the

water and the pressure, the higher concentration and pressure resulting in higher silica carryover. If the silica concentration in steam is saturated, it precipitates on the turbine components affecting its performance. In this condition, the saturated silica concentration in steam is 15.5 ppb, and the concentration in the reactor water which gives the value in steam is estimated to be 9,000 ppb [Ref-24]. For this reason, it is considered that LCO for the reactor water silica during power operation is a maximum of 9,000 ppb [Ref-1].

During start-up if the silica measured in the reactor water is very low, then the requirement for regular sampling is reduced, although it must still be maintained below the LCO of 9,000 ppb.

Control of the silica level is enabled by management of the CUW. The CUW backwash frequency for the UK ABWR is designed to be similar to that of the Japanese Advanced Boiling Water Reactor (J-ABWR). This manages the silica breakthrough and keeps levels well within the LCOs in practice. If the silica concentration of the reactor water reaches a specified value (set at a margin lower than that of the LCO), then a relevant vessel is isolated in the CUW to facilitate backwashing and pre-coating of resins, [Ref-3].

Silica monitoring is carried out by grab sampling the reactor water at the inlet to the CUW. During power operation, weekly sampling is required, and it is also required to be done once or more during the start-up and shutdown procedures. It is not required during the outage period.

#### **Possible Faults**

The risks associated with the loss of the clean-up capability are addressed in Attachment L (Non-Reactor Faults) in [Ref-12] (see also [Ref-3]).

### **23.4.4 Chemistry Control for Fuel Integrity**

Fuel damage due to an unsuitable water chemistry environment or excessive crud deposition can lead to heat transfer impairment, fuel cladding embrittlement, pin failures and corrosion. This can further result in Fission Product (FP) release into the reactor coolant and dispersion to increase dose to workers and the public. This section reviews the chemistry control aspects with respect to fuel integrity within the reactor environment. The storage of spent fuel in the SFP is discussed separately in Section 23.5.

#### **23.4.4.1 Fuel Crud and Cladding Corrosion**

The fuel cladding materials selection for the UK ABWR is Zircaloy-2, and the fuel design arrangement is GE-14 (which includes Inconel springs). Further detail on the fuel and fuel assembly design, and system functional claims are provided in PCSR Chapter 11.

The fuel cladding and fuel design have been optimised to improve corrosion resistance and mechanical properties performance for all water quality options for the BWR fleet, including the HWC + OLNLC + DZO regime. The improvements in fuel cladding materials and manufacturing processes and treatments have virtually eliminated any corrosion issues with the modern fuel, as proven from the BWR fleet OPEX, inspection programmes and testing. This is further described in the GE14 Fuel Mechanical Design Report [Ref-25].

The trend in BWR cases of fuel failure that are induced by localised cladding corrosion and are relevant to the BWR are generally driven by:

(1) nodular corrosion of the cladding (encompassing Crud-Induced Localised Corrosion (CILC), and CILC-like failures). Nodular corrosion causes localised oxide clusters to form on the cladding surface. CILC is a corrosion mechanism combined with the nodular corrosion and copper impurity in the deposit. With the material improvement of Zircaloy-2 and the adoption of titanium condenser tubes these degradation mechanisms are suppressed and are no longer observed in modern fuel.

(2) failures due to extremely heavy thermally-insulating crud [Ref-25]. Crud related fuel failures are extremely rare today. Should they occur, they are typically associated with very high impurities during water chemistry excursions.

#### **23.4.4.2 Impurity Control**

As mentioned in Section 23.4.3.1, impurities, which affect fuel integrity, will be controlled in the CFDW.

### **Condensate and Feedwater Chemistry**

#### **Method of Control and Monitoring**

The chemistry regime LCOs for the reactor water are managed by the requirements for the reactor internal components, i.e. to protect stainless steel and nickel based alloys. The very high concentrations of impurities, such as chloride and sulphate, as well as silica and sodium, required to degrade the zircaloy cladding and impact fuel integrity are considered to be several magnitudes

higher than the impurity limits set to protect these materials (Section 23.4.3.1), and are also controlled continuously by the clean-up system [Ref-25].

The fuel integrity requirements for the water chemistry for all modes of operation are based on the control of metal impurities such as iron and copper, and the control of the chemical additives for HWC, OLNC and DZO.

The water quality specification requirements for the UK ABWR plant commissioning, including pre- and post-fuel loading and for initial start-up will be finalised by the future licensee. Guidance for this is described in [Ref-10]. For the purposes of the generic design, the fuel will only be loaded when the water quality matches the water chemistry specification for the operational modes defined in Section 23.3 and [Ref-1], and described in this section. The recent worldwide trend of fuel performance shows that the majority of fuel damage is caused by fretting. This is attributed to foreign materials, such as a swarf and/or debris trapped between the gap in the fuel spacer and cladding, which is brought into the reactor during the construction, commissioning and refuelling outage. Site specific procedures should ensure foreign material is removed systematically by flushing with high purity water prior to the fuel loading to mitigate the risk [Ref-10].

### Iron

Iron exists in the RCS and associated systems as a result of corrosion of the system materials, and control of the corrosion mechanism in the feedwater is important. Although the concentration of corrosion products impurities in the feedwater is very low, they are introduced into the reactor water. From the reactor water, they then deposit and accumulate gradually on the surface of fuel cladding as an iron oxide 'crud'. In the presence of impurities, such as zinc, the crud formed is tenacious and insulating on the cladding surface. This can cause accelerated corrosion of the underlying cladding. The UK ABWR uses DZO and iron control in the feedwater to manage the crud deposition.

Iron levels are controlled to reduce the risk to fuel integrity and also for the minimisation of the radiological source, as the fuel crud becomes activated. The source term impact of iron is described in Section 23.4.5. It is assumed that the iron concentration will be controlled to an average of <1.0 ppb in normal power operation as per the methodology described in the TR on Fe Concentration Control in Feedwater [Ref-26]. Operational experience in plants with feedwater iron concentrations of <3 to 5 ppb have not caused a fuel reliability concern under HWC chemistry [Ref-1], therefore the normal power operating level will not be a concern. During normal operation, there are likely to be

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occasions when the feedwater iron concentration will 'spike' in concentration trend for short periods of time, due to normal plant operations that cause short term excursions. However, relevant plant OPEX has suggested that there are no fuel failures attributed to this behaviour, and spikes at even 50 ppb are observed, and are not expected to be a concern to fuel integrity. Therefore, for the UK ABWR, the LCO for feedwater iron concentration during power operation is a maximum of 50 ppb [Ref-1][Ref-8]. If the LCO were exceeded due to a continuous large iron input into the reactor water, then it may cause fuel cladding corrosion to occur eventually. However, an iron fluctuation of this magnitude would not impact the UK ABWR safety case. Furthermore, the effect of very high iron concentration is a chronic rather than an acute impact in terms of time and the issue [Ref-1].

During reactor start-up and shutdown, especially the start-up phase, fluctuations in the iron concentration will be expected, such as due to the plant changing conditions that can lead to crud burst or the change in boiling height in the reactor. During the outage, general corrosion may increase, especially in the CFDW which will be out of service and open due to maintenance.

High levels of iron during the start-up period should be prevented since iron can deposit on the fuel during this stage (and also for source term reduction, (see Section 23.4.5.2). On preparing to return the plant to service the CFDW lines will be flushed, recirculated and sampled. This will ensure that the insoluble material (Fe) in the recirculation line of the CFDW is reduced to 1 ppb or less prior to the start-up [Ref-1][Ref-15].

Additionally, the CF will remove much of this iron particulate and the iron feedwater concentration for UK ABWR will be expected to be at low ppb levels with some brief fluctuations during start-up (in line with other J-ABWR OPEX) [Ref-1].

## Copper

Since the UK ABWR will have a titanium tubed condenser there is no direct source for copper in the system, and so copper levels are expected to be very low and possibly below detectable limits. However, it is considered that the lower the copper concentration in the reactor water the better is it for the fuel integrity. The high efficiency demineraliser clean-up for the removal of ionic impurities, and will ensure that copper is very low, should any be present. The LCO upper limit for copper ion concentration in the feedwater is 1 ppb in order to ensure avoidance of CILC on the fuel. The same limit is imposed for the start-up and shutdown feedwater chemistry [Ref-1][Ref-3][Ref-8]. There is not a cliff edge effect at 1 ppb for fuel integrity based on the plant experiences in the industry.

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However, there is limited OPEX for the uncertainties if higher levels than 1 ppb are reached and sustained.

Furthermore, the GE14 fuel for the UK ABWR has a high corrosion resistance, and has specifically been developed for resistance to nodular corrosion related fuel failure by CILC. This fuel has not experienced any corrosion related fuel failures in BWR plants, including plants with brass condensers and with a wide range of chemistry regimes. Therefore, the GE14 fuel for the UK ABWR is not expected to experience corrosion attributable to the water chemistry regimes and the limits set in [Ref-1] and based on OPEX in [Ref-25].

For all of the reasons above, it can be shown that the occurrence of CILC is not expected to be of significance for the UK ABWR.

Further discussion on zinc deposits and its impact on fuel reliability are discussed below.

#### Hydrogen

Since the introduction of HWC the BWR industry has been assessing the impacts of the regime on fuel, including detailed surveillance and test programmes of fuel rods and components. From this the effect of HWC on the zircaloy corrosion, fuel crud deposition and hydriding is concluded as benign. The hydriding process causes embrittlement of materials and is present due to the accompanying corrosion, and the zircaloy cladding metal absorbs a fraction of the hydrogen released by the oxidation reaction. This process also leads to the deterioration of fuel rods. There have been no indications of fuel-related problems for these mechanisms attributed to operation with feedwater hydrogen concentrations up to 2 ppm, which are levels typically expected for plants that do not also employ NMCA [Ref-25]. Under the UK ABWR HWC + OLNC regime the normal operating levels of hydrogen concentration will be much lower than 2ppm. The upper LCO for the feedwater hydrogen concentration is set at 0.5 ppm. The fuel limit for hydriding is much higher than this LCO that has been set for HWC for the UK ABWR, and the hydrogen content of the cladding will be within the normal range. No adverse effect on the fuel integrity is expected [Ref-4].

#### Platinum

The purpose of OLNC is for SCC integrity, primarily for IGSCC, as discussed in Section 23.4.3. However, the reactor water upper limit for the platinum injection amount is related to fuel integrity, and is based upon current industry guidance [Ref-1]. As guidance can change with time, the future

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licensee should ensure that the latest guidance is utilised in the site specific case. The possible fuel reliability concerns related to OLNLC are increased cladding corrosion, fuel crud deposition and hydriding, and these risks have been assessed by a number of fuel reliability programmes to carry out fuel surveillance and to evaluate of OLNLC has impacted on fuel performance. No significant issues have been identified from available reported data (up to 2016), and a summary of the reported observations from these fuel inspections is provided in [Ref-25].

In terms of fuel reliability there are some restrictions on when OLNLC can be applied, and these were first stated in section 23.4.3. In summary, these are (1) that the LCO of platinum added to the reactor is 920 g/year over the lifetime of the fuel, [Ref-1][Ref-4]. Based on OPEX to date, this level has not caused any fuel failures or concerns; and (2) that OLNLC should not be carried out before 60 days at power operation have passed following a refuelling outage to allow a preconditioning period of the fuel clad of new fuel that has been loaded, because fuel vendors are concerned about adding platinum to fresh fuel surfaces [Ref-4].

## Zinc

There are two main fuel performance considerations with thicker tenacious crud deposits that are influenced by the presence of the zinc, and these are (1) crud spallation, and (2) crud-induced cladding autocatalytic corrosion, [Ref-25].

The formation of thick tenacious crud deposition and crud spallation should be avoided to reduce the risk of fuel failures. The criterion for crud spallation avoidance was developed by the fuel vendor from review of the fuel surveillance programme and zinc injection rates. In conclusion, the evidence suggested that maintaining a cycle average for feedwater zinc at  $\leq 0.4$  ppb would be sufficient to avoid crud layer spallation, it was also concluded that it is a low risk to operate with a quarterly average feedwater zinc  $\leq 0.5$  ppb, providing the cycle average was  $\leq 0.4$  ppb [Ref-1].

The UK ABWR optimal zinc injection amount, monitoring and its control, and review of impacts on fuel integrity, and balance with other water chemistry parameters (including iron control as outlined above) is addressed in [Ref-5].

Since there may be some detriment risk for the fuel integrity if a high amount of zinc was injected, it is necessary to ensure that zinc is controlled and limited in the feedwater prior to entering the reactor. It is assumed that in the UK ABWR the zinc concentration in the feedwater will be controlled as described in [Ref-5], which is in accordance with the above discussion. However, short spikes in

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zinc concentration are possible during normal operation. A review of relevant plant OPEX indicates that excursions to around feedwater zinc concentration of 3 ppb have been observed. However, no fuel failure has been associated with such an excursion at this level, and from worldwide practice there is not a concern for fuel integrity at this level. There are some unknowns for operation over 3 ppb for periods of time, and due to the limited OPEX, the UK ABWR feedwater zinc upper LCO limit is set at 3 ppb for power operation [Ref-1][Ref-5]. The same limit is also used for feedwater zinc during start-up and shutdown. Since as discussed, the coexistence of iron and zinc in high concentration is linked to the formation of tenacious oxides which can impede the heat transfer and cause spalling of crud and oxide film, a careful control of zinc and iron concentration is imposed for the UK ABWR.

The chemistry control for maintaining fuel integrity has an impact on the source term through the operating lifetime and on the plant condition at the End of Generation. Minimising the potential of fuel failures will ensure that decommissioning of the UK ABWR can be performed efficiently whilst ensuring that the risk to operators is reduced to ALARP. Maintaining fuel integrity will also ensure that the generation of higher classification wastes during decommissioning are minimised. For further information please see PCSR Chapter 31: Decommissioning.

There are nine LCOs that are linked for the reactor core for the generic UK ABWR design, and have been collated in the Generic Technical Specifications [Ref-27], they are all additionally stated in PCSR Chapter 11, Reactor Core in Section 11.7.2. Those that are relevant to the monitoring of fission products and noble gases, such as for fuel integrity issues, and to minimise impact from the source term are as follows:

- Reactor Coolant System (RCS) Specific Activity — Limits are set to ensure that the specific iodine activity and gross specific activity are kept below DBA assumption, based on surveillance requirements verifying reactor coolant I-131 and gross specific activity [Ref-27], and
- Main Condenser Off-gas Gamma Activity — Limit is set to ensure the gross gamma activity rate of the noble gases is kept below DBA assumption, based on surveillance requirements verifying gross gamma activity rate of the noble gases [Ref-27].

### **Possible Faults**

The release of the radionuclides into the coolant through fuel rod damage during plant operation and shutdown modes of operation brings about the contamination of SSCs and increases the occupational dose.

In the case that failed fuel did occur, then management of damaged fuel by the application of power suppression is considered ALARP for the UK ABWR. The purpose of power suppression is to maintain the off-gas/FP release from the fuel failures ALARP, whilst allowing the plant to continue at power operation. This avoids outages to remove the failed fuel which will have larger dose consequences (from non-fission isotopes) than the fuel failure. There are no limits on the number of failed pins for continued operation with or without power suppression. This is because the activity level changes due to the degree of damage and is therefore used as the criterion.

Power suppression is further described in the Management of Damaged Fuel [Ref-28].

The UK ABWR will also be able to carry out OLNC according to the normal programme with no adverse effects on the failed fuel.

### **23.4.5 Chemistry Control for Minimisation of the Reactor Coolant System and Associated Systems Radioactivity**

The reactor chemistry regime choices are important to manage the risks that are associated with radioactivity and worker and public dose levels, as well as the creation and handling of radioactive waste and the discharges to the environment.

Besides the release of FPs from fuel defects and tramp uranium, an additional radiation source arises from the activation of species within the core region and their transportation and possible accumulation through the RCS and associated systems. The UK ABWR radioactivity behaviour is described in the TR on Radioactivity Behaviour in UK ABWR [Ref-29]. In a normal operational cycle without any fuel defects, this activation and transportation is the dominant radiation source and is a main contributor to:

- the radiation dose to the workers and the public during maintenance and operation activities (see also PCSR Chapter 20: Radiation Protection),

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- the radioactivity release both in normal operation and in fault conditions (PCSR Chapter 24: Design Basis Analysis and 26: Beyond Design Basis and Severe Accident (SA) Analysis), and
- the management of radioactive waste (PCSR Chapter 18: Radioactive Waste Management) and decommissioning (PCSR Chapter 31: Decommissioning) requirements.

The mobilisation of these radioactive products is driven by the following routes:

- Release of FPs from the fuel via tramp uranium, clad defects and fuel damage leakage,
- Corrosion of irradiated components and subsequent distribution and deposition,
- Corrosion products generated in the out of core circuit and transported to the core, then becoming activated and subsequently distributed and deposited on the SSCs that are outside of the RPV, and
- Activation of the coolant (e.g. N-16).

These radioactive products are described by the UK ABWR radioactive source term. The outline description for the UK ABWR source term is addressed in PCSR Chapter 20.3.

The UK ABWR source term is defined as the types, quantities, and physical and chemical forms of the radionuclides that have the potential to give rise to exposure to radiation, radioactive waste or discharges. To help explain the UK ABWR source term there are four categories identified, which are as follows:

- **Primary Source Term (PST)**; defined as the level of radioactivity within the Reactor Pressure Vessel (RPV) in the UK ABWR [Ref-9],
- **Process Source Term (PrST)**; defined as the level of radioactivity within each of the systems in the UK ABWR [Ref-30],
- **Deposit Source Term (DST)**; defined as the level of activity deposited within each of the systems in the UK ABWR [Ref-31], and

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- **End User Source Term (EUST)**; defined as the final level of radioactivity considered for a particular assessment within a technical area of the safety and environmental case for the UK ABWR [Ref-32].

The PST, PrST, DST and EUST are further described in how they are used and their derivation is referenced in PCSR Chapter 20, Section 20.3.

Since the RCS and associated systems constitutes the key SSCs in the UK ABWR including the reactor core and generates the radiation source term as a result of the reactor operation, the establishment of methods to ensure the integrity of the related SSCs and the suppression of the radiation dose to workers and public is the top priority for plant operation. To realise this purpose, the appropriate material selection and fabrication management of the facility in parallel with the pertinent control of water chemistry, and the application of key operating practices during the lifetime plays a highly important role. The following sub sections presents how the materials selection, the operating chemistry and the operating practices that are used for the UK ABWR ensure that the source term is reduced to ALARP.

#### **23.4.5.1 Reduction of Source Terms by Materials Selection**

The key reference for this section is the TR on Source Term Reduction by Materials Selection [Ref-33]. A worker's dose increases when performing normal work activities. The dose level also depends on the sources of the radiation and their inventory. The sources of radiation are predominantly activated components from irradiation in the reactor core, from components contaminated with radionuclides, and corrosion products that become activated and are transported in the RCS and associated systems. The materials selection and treatments applied in the design, build and commissioning stages have an impact on the source term, and for this reason the materials have been optioneered, assessed and justified in supporting documentation, in order to ensure that that the UK ABWR source term is reduced to ALARP for the plant lifetime.

##### (1) Cobalt Minimisation

The UK ABWR GDA design minimises the cobalt source term by limiting the cobalt composition in materials, and the use or replacement of cobalt-based alloys (such as Stellite<sup>®</sup> materials) where it is ALARP to do so. These aspects and the process for the identification of where cobalt-based alloy replacement may be achieved in the design are further addressed in [Ref-33].

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The radionuclides of concern for corrosion produce minimisation include Manganese-54, Iron-59, Cobalt-60 (Co-60) and Cobalt-58 (Co-58), in which the first two are activated from iron, Co-60 and Co-58 are activated from Cobalt-59 and Nickel-58 respectively, which are used in the composition of the construction materials in the UK ABWR. Of these radioisotopes, Co-60 and Co-58 are dominant radioactive ions, and Co-60 is the most dominant nuclide as the radiation source for worker dose (PCSR Chapter 20.2). Cobalt-59 (Co-59) is the only stable cobalt isotope and exists naturally on Earth but when Co-59 is deposited on the fuel cladding surface, it is activated by neutron irradiation and then released into the reactor coolant water as Co-60. Co-60 may also be produced in irradiated components before being released directly into the reactor water. High Co-60 concentrations in the UK ABWR water will result in higher Co-60 uptake in the surface corrosion films and hence higher radiation dose levels. For this reason, Co-60 is considered to be the most important radionuclide to be minimised to achieve radiation dose reduction in the UK ABWR, and hence the cobalt source minimisation is required [Ref-33]. Co-60 released from activated components and from crud activated on the fuel cladding is also taken into account for consideration of cobalt reduction.

The RPV contains the RINs. The RINs are made of stainless steel and nickel based alloys, as described in Section 23.4.7. In order to control the contribution to radiation dose from Co-60, the cobalt composition in stainless steel and nickel-based alloys has been reduced to <0.05 wt%. Especially, cobalt is reduced to within <0.02 wt% for the High Pressure (HP) Feedwater Heater (FWH) tubing because the potential for cobalt dissolution from this region is high (see 23.4.7.2(f)). The application of low cobalt materials for components having a large surface area reduces significantly the cobalt dissolution into the reactor water. This means that there is less cobalt in the system in the form of the corrosion products that can become activated. Reduction of the cobalt content does not affect the material properties such as mechanical properties in stainless steels and nickel based alloys [Ref-33].

Stellite<sup>®</sup> materials are used in the UK ABWR design due to their good resistance to impact, wear and galling damage in hard facing areas. The use of replacement materials with no cobalt or low cobalt containing materials for the operational life will be used in the UK ABWR design and has been applied where possible to minimise the potential Co-60 source term where practicable. An example of where cobalt based alloys have been replaced by iron and nickel based alloys are the pins and rollers in the Fine Motion Control Rod Drive (FMCRD) mechanisms. However, changing from Co-based alloys to alternative cobalt free materials such as iron-based and nickel based alloys does

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change the material properties and wear characteristics of the components, and so it is not suitable for all areas. There is a significant possibility the reliability of components such as valves would be reduced, and which could be detrimental to nuclear safety. If a cobalt-free alloy is selected for the plant, e.g. in valve seats materials, then the associated benefits of the source term reduction as a result of the materials selection, must not be strongly outweighed by the detriments, which are the reduction in valve performance and reliability, and their potential consequences. The use of cobalt based alloys in the generic design is restricted to hard-facing components where wear resistance and corrosion resistance is required and a substitute for the hard-facing cobalt based material is not appropriate. For the generic design, these include large sized valves and valve seats in the condensate and feedwater line. The cobalt-based alloy valves that have been identified during GDA are provided in [Ref-33]. These will be considered for Stellite<sup>®</sup> replacement during the site specific stage, where the OPEX that is available to the future licensee and the results of performance testing undertaken by Hitachi-GE (including testing which is ongoing or planned and so the results are not available in GDA) should be taken into account to make a more detailed ALARP assessment.

The cobalt content is very low in carbon steel and low alloy steel materials since they typically do not include nickel as a specified alloying element.

(2) Corrosion Product Minimisation

The SSCs from which corrosion products are released and flow into the reactor coolant are the source of the PST. The SSCs that affect the source term and the SSCs which connect to the RPV or contact to the reactor coolant are the most important. The choice of materials for the RCS and associated systems needs to minimise the radioactive source term, i.e., to minimise the species that are able to be activated in the reactor core. The materials selected from corrosion resistance considerations are also beneficial with respect to minimising the source term, since the corrosion products that are carried into the core and bring about the generation of radioactivity are reduced. Key SSCs and the materials selection and chemistry controls that impact on the UK ABWR source term are discussed in Section 23.4.7.

The corrosion products which are released from the CFDW piping and components upstream of the CF is removed by the CF and the CD such that only the downstream piping is of concern. Downstream of the CD oxygen injection into the feedwater (Section 23.4.3 and 23.4.5) will reduce the feedwater iron to very low levels relative to the industry best practice of  $\leq 1.0$  ppb. Iron also has an important role in crud adhesion on the fuel which reduces the cobalt concentration in the reactor

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water. If the feedwater iron level is controlled to this range, cobalt and nickel will deposit on the fuel as crud and the reactor water cobalt and nickel levels are reduced [Ref-26], reducing the reactor water radioactivity. However, if the feedwater iron level increases, this results in an increased insoluble cobalt level in the reactor water. Therefore, cobalt and iron are the most important elements to consider among the corrosion products.

To minimise the input of iron crud into the RPV where water chemistry control cannot be applied due to the system configuration or lack of effective countermeasures, the UK ABWR uses low alloy steel, for example for the Extraction Steam System (ES) piping, Feedwater Heater Vent System piping (HV) and cross around piping, rather than carbon steel.

The structural materials especially carbon steel will generate corrosion products in wet environments. For this reason, water in the piping of the feedwater and condensate system is drained and the system dried during the outage to reduce the corrosion of structural materials if the outage is of an extended duration. If drainage and/or dry conditions are difficult to achieve, the system is filled with demineralised water.

The UK ABWR pipework has a large surface area in contact with the reactor coolant and the pipe materials can therefore make some contribution to source term. However, where the fluid is dry steam, such as in the MSL piping; the carry-over of Corrosion Product radionuclides is a very small proportion of the water system [Ref-34]. Therefore, the quantity of the source term that comes from the MSL piping is small and so the MS is not considered to have a significant influence on the source term [Ref-33].

The SSCs which are important to source term include the heat exchanger tubes which have a large surface area in contact with the reactor coolant. These include the FWH tube and CUW re-generative heat exchanger tube. Reactor core components such as the CR and fuel assemblies also have impact on source term [Ref-33].

In summary, there are a number of mitigations to minimise the concentration of corrosion products. These include material selection, corrosion mitigation and removal of impurities. A number of documents within the safety case provide further evidence for these mitigations including the system SDDs such as for the CUW CD, CF, and in [Ref-3].

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(3) Surface treatments

Surface roughness and surface chemistry affects radioactivity pickup. The surface treatment of components surfaces in contact with the reactor coolant affects the ability of the passive oxides that form on them to incorporate the activated corrosion products. Surface treatment can therefore reduce contamination rates, and reduce cobalt release rates (Co-60), which is the main contributor to occupational radiation exposure.

The surface treatment selection methodology that has been applied in GDA, has first considered whether the UK ABWR design meets good practice. To demonstrate ALARP for the site specific design an additional optioneering process will be applied, that considers further risk reduction methods, and an ALARP analysis of the options will be undertaken to determine the final surface specification. For the GDA design, to provide confidence that the optioneering process achieves the intended objectives, and the risks are, or are capable of being, reduced to ALARP, the process has been applied in full to several key components. The details of the optioneering process, the factors considered for each component and the results analysis are provided in [Ref-33]. The components for the GDA analysis have been selected based on high source term activities. For example, the HP FWH tubes are considered to be an important SSC for a surface treatment because they have the highest contribution to nickel and chromium release, alongside a notable cobalt input to the reactor water. The optioneering considered factors that included the effectiveness of the treatment, ease of fabrication, OPEX and the impact on operation, maintenance and decommissioning.

To summarise, the components that are considered significant for reducing the risk of radioactive dose to the workers, and therefore have been considered for surface treatments in GDA are shown in Table 23.4-2. From these, the components that have undergone the detailed optioneering process analysis during GDA, reflecting currently available OPEX, are provided in Table 23.4-3. This table shows the construction material and the GDA optioneering process outcome. Further details on the surface treatment specifications for these SSCs in the GDA design, comparison with the J-ABWR reference design, and further options for consideration in the site specific stage are provided in [Ref-33].

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**Table 23.4-2: Key Components Considered for Source Term Reduction With Respect to Surface Treatments in the UK ABWR GDA Design [Ref-33]**

Dominant Mechanism Targeted	Component	Material	
CP and AP dissolution	HP FWH Tube	Stainless Steel (SS)	
	Reactor Internals (RINs)	Dryer	SS
		Separator	SS
		Control Rod guide tube	SS
	Fuel Parts (Spacer Spring)	Inconel	
	Control Rod	SS	
Radioactive deposition	Reactor Well	SS	
	Dryer	SS	
	CUW piping in D/W	SS	
	CUW pump	SS	
	CUW valve	SS	
	RHR piping	CS	
	RHR pump	CS	
	RHR valves	CS	
	MSV	CS	
	SRV	CS	

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**Table 23.4-3: Surface Treatments for Key UK ABWR Components in GDA Design [Ref-33]**

<b>Item</b>	<b>Material</b>	<b>Surface Treatment (GDA Design)</b>
HP FWH Tube	SS	Oxidation (Moisture vapour treatment)
Dryer (Hood, Support)	SS	Mechanical polishing
Reactor Well Liner	SS	Mechanical polishing
CUW Piping	SS	Pickling (acid cleaning)
CUW Heat Exchanger Tube	SS	Pickling (acid cleaning)
CUW Pump	SS	Mechanical polishing
RHR Piping	CS	Oxidation (air passivation)
RHR Pump	CS	Blast Treatment
Fuel Parts (Spacer Spring)	Inconel	Air oxidation (during aging)
MSV/SRV	CS	As-cast

The optioneering study concluded that the majority of the studied components will adopt the J-ABWR reference design surface treatment. The RHR piping, HP FWH tube and the CUW pump will adopt alternative surface treatments from the J-ABWR reference design, subject to further OPEX or relevant data becoming available that could change the outcome.

The final decision on surface treatments specifications for all of these SSCs will be made in the site specific stage, taking into consideration any further information, such as OPEX and performance testing information that is available to the future licensee.

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It is also of note that the surface treatment applied to the UK ABWR materials can also help to achieve the ease of decontamination in decommissioning phase of the facility, and so the use of the treatments is linked to PCSR Chapter 31.

#### **23.4.5.2 Reduction of Source Terms by Operating Chemistry**

A key reference for this section is the TR on Source Term Reduction by Operating Chemistry [Ref-35]. The objective of this section is to demonstrate that the operating chemistry regime for the UK ABWR reduces the Source Term SFAIRP. In this respect, there is a link to the PCSR Chapters 20 in terms of the purposes of the chemistry control for the UK ABWR in ensuring that the generation of radioactivity and its impact on radiation protection.

Operating Chemistry does not reduce the FP and Actinide Product (ActP) release, but Operating Chemistry such as OLNLC, Zinc injection and impurity levels, notably copper are controlled to minimise impact on any fuel failure that may have occurred (see Section 23.4.4). For OLNLC, the platinum deposition amount on fuel has been limited, and for zinc injection, feedwater zinc concentration has been limited and feedwater iron levels controlled to minimise the radioactive inventory, [Ref-1] [Ref-4][Ref-5][Ref-26].

The primary means to reduce Activation Products (AP) levels in the reactor water is through impurity control, as these are formed by activation of impurities. Many of the precursors to the APs are present in water itself, as naturally occurring isotopes e.g. oxygen & hydrogen or as dissolved gases, as in the case of argon and nitrogen. Removal is by control measures such as OLNLC, introduced for N-16 minimisation in the steam due to the HWC regime, and the Off-Gas System (OG) operations required to manage the APs once formed (See OG in PCSR Chapter 18, Section 23.12). For the APs generated through ionic precursors such as chloride, maintaining low impurity levels in the FW and RW will minimise the production of APs, such as Cl-36. The CPS function and design to manage impurity ingress via the feedwater is justified in [Ref-3], and the operating practices to maintain the optimal operability and minimise impurity ingress are described in [Ref-34].

The reduction in the three radionuclides groups present within the reactor water for the UK ABWR will be achieved by either active removal processes of the radionuclide itself as in the case of the CUW and FPC, radionuclide management through fuel integrity, operating chemistry and through elimination of the source/precursors.

The operating chemistry optimised for the source term reduction, such as zinc injection, will be beneficial for the decommissioning phase of the facility, and so this is linked to the PCSR Chapter 31.

**(1) Reactor Water Chemistry**

The management of the source term in the reactor is driven by the chemistry regime of the feedwater as described below.

**(2) Condensate and Feedwater Chemistry**

(a) Hydrogen Water Chemistry (HWC) + On-Line NobleChem™ (OLNC)

Hydrogen and sodium hexahydroxy-platinate are injected into the feedwater to reduce the oxidising environment of the reactor water and mitigate SCC of the RPV and reactor internals by reducing the ECP.

Without OLNC, hydrogen has the potential to impact the source term through the MSL dose rate in terms of N-16 carryover, and is also significant in terms of shine for the public dose. Under HWC the bulk of the reactor water is under reducing conditions, and the chemical forms of the activation product N-16 which is produced in the core shift from soluble species such as nitrate, and which is non-volatile, to more volatile forms such as nitrogen oxides and ammonia. Therefore, under the HWC reducing conditions, more of the N-16 partitions into the steam, the proportion of which increases with hydrogen injection rate. Although the half-life of N-16 is short (7.14 seconds), it strongly affects the radiation field at the turbine system in the turbine building (T/B), giving rise to the increase of radiation dose of workers in the T/B. To minimise this increase in N-16, the addition of platinum using OLNC reduces the quantity of hydrogen required to be injected for decreasing the ECP and also minimises the N-16 migration into the steam. So, the N-16 impact is minimised to a level comparable to that of Normal Water Chemistry (NWC) plants [Ref-35].

The adoption of HWC + OLNC for the UK ABWR effectively minimises the radiation dose resulting from the increased volatile N-16 component in the steam to the turbine to ALARP. To ensure this the hydrogen in the feedwater has an upper limit of 0.5 ppm at power operation. The short half-life of N-16 means that it is not an issue for the shutdown dose rate as it quickly decays after the reactor shutdown. It is therefore only an issue for power operation.

Other aspects of source term reduction by the HWC + OLNC regime are provided in [Ref-35].

(b) Depleted Zinc Oxide (DZO)

Although important for SCC, the adoption of the HWC + OLNC regime for the UK ABWR increases the dose rate of the relevant SSCs, causing the dose increase of workers as a result of the surface oxide structure formed in reducing conditions and the increased affinity for Co-60 to be incorporated [Ref-4]. The UK ABWR uses DZO injection which is effective in compensating for this dose increase. The DZO regime and the cobalt minimisation in the materials selection (Section 23.4.5.1) mean that low shutdown dose rates can be obtained for the UK ABWR. Detailed design requirements for the application of DZO for the chemistry regime are described in [Ref-5].

Adverse effects of zinc injection have also been considered for fuel integrity and the upper level limit for zinc in the feedwater is set at 3 ppb (see Section 23.4.4.2). The DZO used in the system is isotopically depleted in Zn-64 (to <1%), to decrease the quantity of activated Zn-65 that would otherwise be produced, which would contribute detrimentally to the source term. Zinc injection is managed appropriately in consideration of the balance between the merit of the reduction of Co-60 deposition and detriment in the form of risk to fuel integrity.

Operating experience suggests that the longevity effect of reduction of the shutdown dose rates after zinc injection may have a reversal effect, and therefore it is necessary to ensure that zinc is always maintained in the reactor coolant to ensure that the source term is minimised for management of Co-60. To achieve this, the UK ABWR has set an LCO for the reactor water zinc concentration to be a minimum of 2 ppb. The LCO is also the same for shutdown and start-up when the DZO injection is in service. However, it should be noted that the zinc concentration may be lower than the limit at the start of the first cycle during start-up until normal feed flow is established.

The DZO is injected using the ZNIS. The ZNIS consists of a DZO dissolution vessel and piping and valves, and a schematic of the ZNIS configuration is shown in Figure 23.4-4.

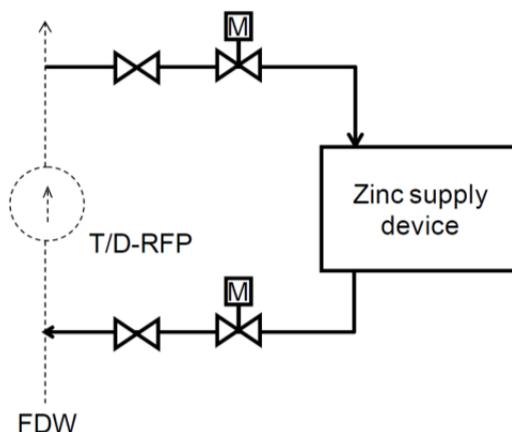


Figure 23.4-4: Schematic of the Zinc Injection System (ZNIS)

The ZNIS is a simple system designed to passively maintain a zinc concentration in the feedwater and to achieve the specified zinc concentration in the feedwater. The ZNIS is designed such that it meets safety class and regulatory requirements for safe storage of the chemicals, safe operability and maintenance. The ZNIS system design description is provided in [Ref-17]. The ZNIS performs a category C safety function and is a class 3 system. The zinc injection method is basically the dissolving of DZO pellets in the dissolution tank and passively allowing the solution to be carried into the feedwater line using the differential pressure at the inlet and outlet of the feedwater pumps. There are no dynamic components to maintain in this simple system. The DZO dissolution vessel can continue to operate in this way for at least one operating cycle without the requirement to reload zinc. The ZNIS is in continuous service during normal operation, start-up and shutdown. The ZNIS injection lines are connected to the outlet and inlet of the Turbine/Driven Reactor Feedwater Pumps (T/D RFP). Since the DZO dissolution vessel is mounted on the injection lines, the zinc solution is circulated passively into the FDW and the RW.

In the UK ABWR, the CUW piping is one of the main areas where dose management is targeted by use of the DZO injection. The influence of DZO on the CUW F/D has been evaluated and the additional ionic loading on the CUW resin as a result of DZO injection will not impact on the UK ABWR goal for F/D run lengths of 40 days, and DZO should not impact the radioactive waste volume generated by the CUW. This detail and the justification for the utilisation of DZO for dose reduction for the UK ABWR are addressed in [Ref-5].

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The ZNIS system is monitored from the MCR and on a local panel to ensure the system is functioning as expected. It has a flow meter, differential pressure meter between the inlet and outlet of the zinc supply device and also a leak detector. The system is designed so that in the case of an abnormality being detected with the system or the dosing, it can be isolated from the FDW by closing the shutoff valves if necessary.

It is concluded that the ZNIS can control the zinc concentration in the UK ABWR.

## **Possible faults**

There are two key fault scenarios associated with the zinc injection system during operation. These are the loss in the ability to inject zinc, or an excess of zinc is injected.

If the zinc is no longer able to be injected into the feedwater, then this will result in a decrease in the concentration of the zinc in the reactor water. During zinc injection, the zinc is preferentially incorporated into the piping and fuel surfaces into spinel oxides rather than cobalt. If the zinc injection stops then the Co-60 precursors (Co-59) are able to be incorporated into the fuel surface oxides more readily. They then become activated and undergo dissolution into the reactor water, resulting in an increase in the Co-60 in the reactor water. Therefore, the loss of zinc may lead to an increase in the Co-60 concentration. However, OPEX dose rates during such a period suggest that the dose rates are below the Basic Safety Objective (BSO) for the UK ABWR. Therefore, it is a Class 3 system [Ref-3]. The reduction in zinc concentration will also be gradual over a significant period, so the fault causing the loss can be repaired.

If excess zinc is injected, then spallation from the fuel cladding could occur. However, this would be a temporary event because the reactor water conductivity, the zinc flow rate being injected and the zinc concentration in the feedwater and reactor water are monitored continuously or periodically. In the event that excess zinc injection results in a concentration that exceeds the cycle average expected value [Ref-1], it is judged that there will be no immediate issue with respect to the operation of the plant [Ref-3].

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(c) Iron Control for Source Term Reduction

Iron control will be implemented for the UK ABWR to control the crud input into the reactor and to reduce the Co-60 in the reactor water. The iron control detailed methodology is detailed in [Ref-26] and the detailed impact on the source term is described in [Ref-35] and the radioactivity transport behaviour is described in [Ref-29].

Metals are dissolved from the components and piping within the RCS and associated systems as corrosion products and enter the reactor. The corrosion products are deposited on the surface of reactor internals such as fuel cladding as a crud. The important corrosion product elements which enter the reactor are iron (Fe), which is the major component, nickel (Ni), chromium (Cr), zinc (Zn) and cobalt (Co), and these form deposits including on fuel. Soluble species are incorporated into the iron oxide fuel deposit, which undergoes neutron activation. The activity can subsequently be released into the reactor water through dissolution and spalling.

Iron concentration control in the FDW plays a crucial role in managing the amount and nature of the formation of fuel crud deposits. A higher iron input results in a higher fraction of CPs in the outer, loosely adhered layer which can subsequently be released into the reactor water, whilst a lower iron input results in a higher CP fraction into the inner, tenacious layer, which is less likely to release into the reactor water.

Conversely, if there is a deficiency of iron (or an excess of other transition metals), soluble monoxides such as nickel oxide (NiO), cobalt oxide (CoO), and zinc oxide (ZnO) may form on the fuel cladding surface. These oxides deposit on the fuel, are activated and then readily dissolve into the reactor water. For plants operating under NWC, it has been observed that low feedwater iron concentrations (<0.1 ppb) can result in increased reactor water Co-60 concentrations due to the increased solubility of fuel deposits. The input of iron will be controlled to ensure sufficient iron is present to prevent the formation of highly soluble mono-oxides within the deposit which can be readily mobilised. The iron control approach for the UK ABWR is to allow the feedwater iron concentration to reach its natural level (expected to be  $\leq 0.1$  ppb for the UK ABWR), whilst retaining the option to increase it (within good practice of  $\leq 1$  ppb) as necessary to stabilise Co-60 deposits on the fuel. Noting that the iron concentration should be controlled so as not to increase Co-60 concentration in the reactor water, there is a possibility to bypass the CF if required to elevate iron to  $>0.1$  ppb. This approach is justified in [Ref-3].

The UK ABWR employs a dual CPS system, i.e., the CF is installed upstream of the CD, and allows the water purification for both ion and particulate impurities removal. By the adoption of CF, as a hollow fibre membrane or pleated filter in the UK ABWR, the iron concentration in feedwater can be suppressed to much lower than  $\leq 1$  ppb. The description of the CPS, CF and CD is in Section 23.4.3.1 (b).

Discussion on sampling and monitoring is provided in Section 23.11.

**Possible Faults**

If the iron exceeded the normal expected value for power operation (1 ppb), this is expected to be due to the concentration of iron in the feedwater of the UK ABWR being controlled by bypassing the CF. The risk of higher insoluble Co-60 in the reactor water increases. However, as the concentration of iron in the feedwater is monitored periodically, the incorrect operation of the CF bypass can be detected quickly, and the CF bypass control valve can be operated to rectify any departure from the desired operational range for feedwater iron concentration [Ref-3].

The iron concentration in the feedwater line that is generated during an outage is removed by recirculation of the condensate and the feedwater lines before start-up, to avoid introducing high levels of corrosion products into the reactor [Ref-15] (see Section 23.4.5.2).

(d) Oxygen Injection

Feedwater oxygen injection to minimise FAC and general corrosion is discussed in Section 23.4.3.3.

(e) Commissioning

To reduce radiation exposure risk for the future operation, the use of high purity (demineralised) water to minimise impurity levels to ALARP is the most important consideration throughout the commissioning stages. The CUW should be used to remove impurities in the reactor water which promote radioactivity generation and/or radioactivity accumulation on SSC surfaces impurities.

From the early stages of the UK ABWR start-up commissioning phase when the feedwater is established, the DZO regime should be established. This is to promote the formation of stable oxides and minimise the build-up of Co-60 on piping. For the first start-up, the DZO regime should be used from when the HWC has first been established to minimise the formation of insoluble zinc chromite and potential deposition on the Reactor Internal Pumps (RIPs). The OI should also be used to

promote the formation of a haematite rich outer oxide layer which will suppress the FAC and result in low iron concentration in the feedwater.

Adoption of a DZO regime during the nuclear heating stage prior to the first start-up could potentially be of some benefit in providing even earlier mitigation against Co-60 build-up on piping, and Early Hydrogen Water Chemistry (EHWC) may also need to be considered. Iron control should also be implemented during the start-up commissioning phase to potentially reduce future Co-60 levels.

It is suggested that further development work and/or information gathering during the site specific stage for the commissioning chemistry should continue, as commissioning chemistry options are not foreclosed to the future licensee.

#### **23.4.5.3 Reduction of Source Terms by Operating Practices**

The TR on Reduction of Source Terms by Operating Practices [Ref-34] demonstrates how the radioactive source term for the UK ABWR has been reduced SFAIRP by consideration of the operating practices that can be employed. The operating practices considered to have a significant impact on the release and clean-up of the corrosion products in the system during the operation modes and relevant to the UK ABWR GDA are discussed in this section.

The use of adequate operating practices for the source term reduction can also be beneficial for the decommissioning phase of the facility, and so this is linked to the PCSR Chapter 31.

#### **(1) Reactor Water Chemistry**

##### **(a) Corrosion product removal by CUW**

The corrosion products carried into the reactor water are activated in the reactor core resulting in a radiation source. For this countermeasure, the CUW is continuously operated even during an outage to remove impurities and radioactive corrosion products to maintain high quality reactor water (see Section 23.4.3.1 (a)).

##### **(b) LCO for Radiological Condition in the Reactor Water - Cobalt-60 Concentration in Reactor Water at Power Operation**

During reactor power operation, corrosion product radionuclides are generated in the core (mainly on fuel assembly crud) and deposited on piping surfaces of systems exposed to the reactor water. These deposited radionuclides contribute to worker radiation dose, especially during outages. For this

reason, it is important to control the source of these radionuclides in the reactor water and their transport into reactor water systems and this is detailed in DST methodology described in [Ref-31]. The most significant contribution to worker radiation dose rate, after a reactor has been operating for about 5-10 years is from Co-60 since it has the longest half-life of the common radioisotopes associated with metal oxides and corrosion products. Therefore, the radiological LCO for the UK ABWR focuses on Co-60 as being representative of the other metal radioisotopes and the Co-60 reactor water concentrations will indicate the general trends across a range of metal radionuclides. The LCO maximum for Co-60 is 43.8 Bq/cm<sup>3</sup> in the reactor water for power operation [Ref-1]. This LCO is intended to ensure that radionuclides in the reactor water are kept below levels that may result in increased release or exposure to the operators. The Co-60 will be maintained well below this level by the normal operation of the CUW.

(c) Reactor Soft Shutdown

During the reactor shutdown and cool down to achieve cold shutdown, there is a possibility for crud deposited in the reactor vessel or on the RHR and CUW piping to detach due to thermal hydraulics or local boiling. Therefore, radioactive crud concentration in the reactor coolant can spike during the decreasing pressure and temperature phase of shutdown. Crud may accumulate in stagnant areas such as the bottom of the RPV and instrument piping, which results in the formation of radiation 'hot spots'. Decreasing the rate of the temperature-drop suppresses the detachment of radioactive corrosion products. Therefore, 'soft shutdown' operation is applied to reduce radiation exposure to operators. The soft shutdown operation will be performed for the UK ABWR with the reactor water temperature drop rate of <30°C/h. However, the beneficial impacts of soft shutdown and the optimum temperature drop are plant specific and dependent on the specific reactor water chemistry. The definition of soft shutdown is described in [Ref-15].

(d) RHR Flushing of Pipework Prior to Placing In-Service

The purpose of the RHR is to remove residual heat during reactor shutdown and reactor isolation and to cool the core during LOCA.

The piping system of RHR in part is made of carbon steel, so some corrosion products may accumulate whilst it is in the standby mode of RHR. For this reason, the RHR system will be subject to a flushing process prior to placing the system into service. This will ensure that the iron levels in the RHR are reduced to less than 500 ppb prior to putting the RHR into service for the shutdown operation to reduce the input of corrosion products into the reactor [Ref-15].

Additionally, reducing the reactor temperature to 120°C prior to bringing the RHR into service for the shutdown cooling has the potential to reduce radioactivity deposition on internal surfaces by a significant amount. The procedure for doing this on the UK ABWR is LT-SHC, and it will be carried out during a shutdown for an outage. The main benefit of this technique is that doses to the workers are reduced during outage activities. However, the radioactivity of pipes and vessels will also be reduced which will lead to a commensurate reduction in maintenance related waste and decontamination fluids. Once the plant has been fully shutdown the condition of the water that remains in the pipes and vessels is managed to minimise radioactivity deposition. Further details on the LT-SHC method are provided in [Ref-34].

(e) RPV Head Lift

Iodine-131 (I-131) is a significant FP/radionuclide during reactor refuelling if there has been fuel damage during the previous fuel cycle and release of FPs into the reactor water. During shutdown, the iodine species concentration may have spiked in the reactor water and there will be an elevated concentration in the reactor water and it will also be carried over into the head space in the reactor pressure vessel (RPV). The iodine that partitions into the head space in the RPV will be removed into the MSL during shutdown until the Main Steam Isolation Valve (MSIV) is closed. However, after the MSIV is closed, the operational mode changes, and the volatile iodine in the reactor water will build up again in the RPV head space to a level that would constitute a dose hazard if released into the reactor containment. To mitigate the risk for the increased worker dose from I-131 during the head removal, an LCO has been set that must be met before the reactor head is removed. This LCO limits the maximum I-131 radioactivity level to 1E-03 Bq/cm<sup>3</sup> prior to the RPV head being lifted [Ref-1][Ref-15].

If the I-131 concentration is not adequately low when checked, the air inside the RPV will be extracted and purged via the charcoal filter and then exhausted to the operating floor, by using temporary ventilation equipment until suitable levels are achieved.

Iodine is one of the most important FPs owing to its radiotoxicity and complex chemistry resulting in volatile forms. The iodine chemistry speciation and the assessment of the impact for the UK ABWR in normal power operation, i.e. power operation, start-up and shutdown is provided in the report - An Assessment of Iodine Behaviour during Normal Operation [Ref-36]. The OG minimises the release of radioactive noble gases and iodine during normal operation of the UK ABWR, and the required functions for this are addressed in Section 23.12.

Iodine chemistry behaviour in the reactor water is significant during accidents (see Section 23.6.3.2). The iodine management in DBA and SA scenarios is addressed in the PCSR Chapter 24 and 26 respectively.

(f) FCVS Vent Filter Scrubbing Solution

The FCVS design specification, modes of operation and safety categorisation and classification is provided in Chapter 16. Chapter 16 states two safety functions for the FCVS in SA, which are:

- The FCVS releases PCV gas through vent pipes to deliver containment overpressure protection and long-term PCV heat removal with water injection system such as the FLSS and the FLSR.
- The FCVS reduces the release of large quantities of radioactive iodine and long half-life fission products contained in venting gas through the FCVS Vent Filter under SA conditions.

The latter FCVS role during SA is also stated in Chapter 26, and it is based on reducing the amount of radioactive particles and elemental iodine that is released in any vented gas prior to discharge to the environment by passing through a scrubbing solution in the vent filter. The FCVS vent filter includes a water scrubbing section and metal filter section to ensure DF performance. The filter requires no manual operation to perform, but the scrubbing solution needs to be maintained, as it can be degraded by evaporation. Therefore, there is an LCO to maintain the scrubbing solution with appropriate sodium hydroxide and sodium thiosulphate concentrations, and to ensure that these reactor chemistry requirements are transferred to the future licensee. This LCO requirement is stated in the Appendix B of [Ref-1], and in PCSR Chapter 26. The LCO scrubbing solution concentrations specification for the FCVS Vent Filter is stated in the Basis of Safety Cases on Severe Accident Mechanical Systems [Ref-37].

**(2) Condensate and Feedwater Chemistry**

(a) Carbon steel management during outage.

The methods to avoid or reduce corrosion as well as to remove corrosion products for the UK ABWR have been developed. Before start-up, the coolant in the feedwater and condensate system is purified by re-circulation through the CF to remove crud which is generated during the outage [Ref-15]. These system designs are described in Chapter 17.6, 17.10 and 17.13.

(b) Sodium Management for the UK ABWR by the CD

The operation of the CD resin will ensure that soluble impurities are minimised by monitoring plant feedback and routine resin sampling to identify the optimal time for resin exchange. The CD resin is to be operated on a non-regenerative regime with the function of the resin verified through resin sampling (monitoring resin exchange capacity and condition during outage). The non-regenerative operation of the resins removes the need for regeneration chemicals, which significantly reduces the volume of effluent discharged to the Radwaste system [Ref-3]. This will reduce the sodium input to the reactor that can be come neutron activated to sodium-24 (Na-24).

The ion removal capacity of the resin will be sufficient for one cycle plus a margin against seawater ingress as justified in [Ref-3] and discussed in Section 23.4.3.1. The CD resin will require back washing periodically, to remove deposited crud and occasionally to remove the resin during replacement activities. The requirement to backwash is determined through experiencing either high differential pressure or low flow measurements across the CD. The design for the UK ABWR is the operation during backwash activities with 5 online CDs and one CD unit offline with normal operation having all 6 CDs online.

**23.4.6 Chemistry Control for Radiolysis and Flammability Control**

Radiolytic gases are generated in the reactor core as a result of the water radiolysis reactions. The water radiolysis reaction products can form hazardous gases, particularly hydrogen and oxygen. If inadvertently released or allowed to accumulate these can form potentially explosive and flammable hydrogen and oxygen concentration mixtures. This is relevant to the RCS and associated systems in normal operation and in fault situations, in the sections located downstream of the reactor core. The UK ABWR is designed to control and safely manage the hazardous gases such that dangerous mixtures will not occur.

The potential risk posed by the generation of radiolytic gases in normal operation for the UK ABWR design is demonstrated in the TR on Safe Management of Radiolytic Gases Generated Under Normal Operations [Ref-38]. The design of the Radwaste systems, including the OG system is addressed in PCSR Chapter 18.

The safe management of the hazard due to radiolytic gases has interactions with the Reactor Chemistry, the Internal Hazards and the Radioactive Waste Management topic areas. The Internal

Hazards safety case details the frequency and severity of the explosions that could occur from radiolytic gases, and the impact of the explosions upon the delivery of the UK ABWR FSFs, and this is addressed in PCSR Chapter 7. The Radioactive Waste Management aspects are related to the management of the radiolytic gases, and the safe storage and handling of the radioactive materials as gas, liquid and solid wastes, and in particular for the dose to the workers and public from the normal operations of the UK ABWR, including the Heating Ventilating and Air Conditioning Systems (HVAC) for the air flows and venting of gas from the waste tanks, this is further addressed in PCSR Chapter 18.

From a reactor chemistry point of view the safety case requirements are directly related to the safe management of hydrogen in all forms in which it occurs across the UK ABWR. This includes limiting the places where hydrogen might accumulate and reducing the likelihood of any internal explosion occurring. The prevention of hydrogen accumulation by design and the minimisation of the ignition frequency and subsequent explosion effects are required to limit the effects of the hazard.

#### **23.4.6.1 Source of Flammable Gases**

##### **(1) Radiolytic Gases Behaviour**

From the UK ABWR reactor water and steam in the reactor, a small proportion of the water molecules can be dissociated by exposure to ionising radiation and will form into hydrogen ( $H_2$ ) and oxygen ( $O_2$ ) gases. This process is known as radiolysis and occurs at normal operation and during accidents. For DBA and SA chemistry regarding radiolysis see PCSR Chapter 24 and 26. Water radiolysis reactions also produce short-lived species such as the hydroxyl radical ( $OH^\cdot$ ), hydrogen atoms ( $H^\cdot$ ), hydroperoxyl ( $HO_2$ ) and more stable species such as hydrogen peroxide ( $H_2O_2$ ). These can react with each other or other species present in the water.

Besides water other species, such as organics, can also degrade under ionising radiation, and a significant source of this will be from the resin used in the demineralisers in the clean-up systems. Unlike the radiolysis of water, no oxygen is produced through the radiolysis of resin compounds. Radiolysis can occur in the reactor core or elsewhere in the RCS and associated systems. Further detail on radiolysis gases products, production rates and other factors on behaviour are provided in [Ref-38].

##### **(2) Hydrogen Water Chemistry Effect**

Prior to any hydrogen production from water radiolysis in the reactor, hydrogen is already going to be present in the feedwater entering the RPV since the UK ABWR will use the HWC + OLNC + DZO water chemistry regime at power operation. The HWC will reduce the oxygen and hydrogen peroxide concentrations in the reactor water. The injection of hydrogen in the feedwater to around  $\leq 0.5$  ppm (see LCO for HWC stated in Section 23.4.3), also reduces the overall concentration of hydrogen in the steam from the reactor compared with NWC. The addition of the feedwater hydrogen tends to force the net radiolysis reaction towards the recombination of hydrogen and oxygen to water at a sufficient rate to maintain the low oxygen levels, (and producing a more reducing environment in terms of the SSCs structural integrity mitigation, Section 23.4.3). This also results in a reduction of in the concentration of hydrogen in the MSL, with a minimum concentration achieved when the concentration of hydrogen in the feedwater is around 0.5 ppm. Any further increase in the concentration of hydrogen in the feedwater results in an increase in the concentration of hydrogen in the MSL, and would be comparable to NWC conditions. Therefore, to ensure the hydrogen dosing is within an acceptable limit, an interlock is provided to avoid further increase in hydrogen concentration in the MS. The injection of hydrogen into the feedwater for the UK ABWR begins when the MSIVs are opened at around 5 % thermal power, and continues throughout power operation. During shutdown, the injection of hydrogen is continued for as long as practically possible i.e. until a low feedwater trip occurs. The justification for HWC is already discussed in Section 23.4.3. However, for the purposes of assessing the potential accumulation of radiolytic gases as stated in [Ref-38] it has been conservatively assumed that NWC is used which would result in a concentration of hydrogen in the MS of 2 ppm.

#### **23.4.6.2 Control of Flammable Gases**

##### **(1) Identification of Susceptible Areas for Flammable Atmospheres**

The areas of plant where flammable gases can accumulate are in the Reactor Building (R/B) systems, turbine building systems and the radioactive waste systems, most of which are in the radioactive waste building. These areas have been assessed to eliminate the accumulation of radiolytic gases or to reduce the concentration of the radiolytic gases. The adopted methodology approach for the assessment is consistent with UK regulatory requirements for nuclear and conventional safety, with the aim of reducing the risk of radiolytic hydrogen in the UK ABWR design to ALARP. The methodology developed is in line with the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), the associated Approved Code of Practice (ACoP), and incorporates the

Japan Nuclear Technology Institute (JANTI) Guideline applied by Hitachi-GE to ABWR designs. The detail of this is provided in [Ref-38].

The assessment has demonstrated that the UK ABWR design in most cases has eliminated the risk of radiolytic gas accumulation completely. However, in some areas it is not possible to completely eliminate the accumulation, and so there is a residual risk that the radiolytic gases could accumulate [Ref-38].

The risk of accumulation of radiolytic gases has been considered at all stages of the UK ABWR design, and is under constant review. The JANTI Guideline and worldwide OPEX have been applied in optimising the UK ABWR design to reduce the risk of hydrogen accumulation and combustion, and, where necessary, by increasing the robustness of pipework and equipment to withstand internal overpressures where there is potential for internal hydrogen explosion to occur [Ref-38].

The UK ABWR pipework and system layout has been designed to mitigate the accumulation of radiolytic gases. In particular, the design prevents the accumulation of the radiolytic hydrogen concentration to levels that would constitute a flammability risk and increase the radioactive release from the reactor coolant system. This has been achieved by the application of piping design standards to the UK ABWR design, including the JANTI Guidelines and relevant standards. The UK ABWR design assessment methodology is in line with current DSEAR and ACoP. An example of this is that the methodology used for the design applied the 25 % Lower Flammability Limit (LFL) from the ACoP as an assessment criterion, and to ensure that the UK ABWR design reduces risks to an acceptable level. The majority of piping that was assessed as having the potential to accumulate radiolytic gases has been redesigned to completely eliminate hydrogen accumulation [Ref-38].

## **(2) Design and Management of Flammable Gases**

The catalytic recombiners in the OG reduce the volumes of hydrogen and oxygen that are in the steam leaving the reactor during normal operation. The design justification for the OG system is provided in the OG Basis of Safety Case [Ref-39] and TR on ALARP Assessment for OG [Ref-40]. The OG reduces the risk of hydrogen combustion arising from the radiolytic gases produced in the reactor. The safety functions associated with this system are addressed in PCSR Chapter 18. From a chemistry perspective, the radiolytic gases that are produced in the reactor will transfer in the steam to other systems in the plant where a potential source of internal explosion hazard could exist. The

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concentration of hydrogen in the steam could accumulate in piping and stagnant areas to could cause the concentration of hydrogen to increase in local areas to potentially flammable levels.

To maintain the main condenser vacuum, the OG system extracts non-condensable off-gas by the SJAEs. Radiolytic hydrogen and oxygen are contained in this off-gas thus the OG treats these and maintains these concentrations below the acceptable level.

The OG recombines the radiolytic gases hydrogen and oxygen that pass from the reactor in the steam to the turbine to prevent the risk of a flammable mixture occurring. The UK ABWR design reduces the concentration of radiolytic gases entering the OG by incorporation of a SJAE, which dilutes the radiolytic gases with steam before it enters the OG. Then additional oxygen is also injected from the HOIS system (see Section 23.4.3.2) upstream of the OG recombiner. This oxygen ensures that the hydrogen, whilst diluted with steam from the SJAE, recombines to produce water as it is passed over the catalyst bed in the recombiner. The water is removed in the OG condenser and the remaining gases are passed through activated charcoal before being released to atmosphere. To ensure the correct amount of oxygen is injected and a sufficient amount of hydrogen is recombined in the OG recombiner, the OG has an online hydrogen monitor downstream of the OG recombiner. The monitoring of process hydrogen concentration is discussed in Section 23.10, sampling and monitoring section.

The OG also transfers the off-gas from the Gland Steam Exhauster to the stack. The system performs the required functions during all operating modes based on established environmental design conditions and requirements. The radiolytic gases are continuously removed by the OG, although some remain in the RCS and associated systems and more are produced continually. Thus, there remains the possibility that some radiolytic gases could accumulate in parts of the RCS and associated systems, particularly inside closed end ('dead end') branches such as instrumentation lines or branches leading to closed valves. These have therefore been assessed in the design according to the assessment methodology above [Ref-38].

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**Possible Faults**

Operation of the OG recombiner: In the event that the normal supply of oxygen upstream of the OG recombiner system is lost, the hydrogen injection will be stopped to the feedwater to avoid the hydrogen concentration increasing in the OG. In spite of this, the residual hydrogen in the RCS and associated systems will still ingress to the OG. Therefore, there is a back-up OG oxygen injection that will inject oxygen to the recombiner. Although it is much less frequent, if the back-up oxygen is also lost at the same time as the loss of the main oxygen injection, then the concentration of hydrogen at the outlet of the recombiner will exceed the LFL for hydrogen in air (4 vol%). In this event, the OG will be isolated.

The internal hazard faults that could occur are addressed in PCSR Chapter 7: Internal Hazards.

**23.4.6.3 Primary Containment Vessel (PCV) Gas Control System**

The Primary Containment vessel (PCV) Gas Control System consists of the Flammability Gas Control System (FCS) and the Atmospheric Control System (AC). These systems have the principal role of maintaining an inert and non-explosive atmosphere within the PCV in normal operations and during a design basis event. The FCS (Passive Auto-catalytic Recombiner (PAR)) and AC design and operation are described in Chapter 13: Engineered Safety Features, Section 13.3.

The PCV and hence FCS and AC system design, safety functional claims, and control of the atmosphere by the Containment Atmospheric Monitoring System (CAMS) is described in PCSR Chapter 13, Section 13.3.

**23.4.7 Materials Selection for Reactor Coolant System and Associated Systems Chemistry**

The structural integrity (SI) of SSCs in the UK ABWR is concerned with the material degradation caused by mechanisms such as corrosion, irradiation damage, or fatigue. These aspects are presented in PCSR Chapter 8 and linked to the appropriate safety case document references. Among these concerns, the RCS and associated systems chemistry has a key function in controlling the corrosion of the system materials that it is in contact with. The materials selected for the UK ABWR take into consideration the chemistry and the operating conditions for corrosion resistance and the reduction of the corrosion products. A brief summary of the key materials, where they are used, and the key aspects of the materials properties for corrosion resistance are provided in this section. Further detail

on the RPV and internals is provided in Chapter 12: Reactor Coolant Systems, Reactivity Control Systems and Associated Systems.

#### **23.4.7.1 Corrosion Mechanisms**

The following types of corrosion are considered relevant to the UK ABWR design and can be influenced by the chemistry control:

- (1) SCC – including:
  - (a) IGSCC,
  - (b) TGSCC, and
  - (c) IASCC.
- (2) FAC
- (3) General corrosion.
- (4) Localised corrosion (such as pitting, crevice corrosion and galvanic corrosion)

Corrosion can prevent the plant safety systems from performing their safety functions by degrading the structural integrity, for example, by breakage failures, causing blockages or by cracking in the structures. These undesirable defects in the SSCs can result in reactor water leakage, fuel damage, and possibly the release of radioactivity to the environment.

#### **(1) SCC**

The most important defect mechanism to which the RPV structural materials of austenitic stainless steel and nickel based alloys are susceptible is SCC including IGSCC and IASCC for the core internals that are in contact with the reactor coolant [Ref-6][Ref-7]. OPEX of SCC in low alloy steel is very limited. In all cases, the fabrication processes led to very high residual stresses and conditions not associated with modern construction practices.

IGSCC is affected by water chemistry factors which include increased conductivity, ingress of harmful impurities such as chloride and sulphate ions and an increase in the ECP.

IASCC occurs in the core region as a result of the high neutron irradiation, and further investigation on the effectiveness of the environmental mitigation is ongoing, in order to prioritise the adoption of improved material.

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Trans-granular Stress Corrosion Cracking (TGSCC) is a type of SCC caused by the presence of hazardous impurities such as chloride [Ref-6].

It is well known that SCC is caused by a combination of the three major risk factors;

- material sensitisation (susceptible material, welding heat affected zone (HAZ))
- tensile stress (residual stresses from fabrication)
- corrosive environment (high chemical impurities and oxidising conditions)

The threat of SCC of the main RPV and internal components for the UK ABWR has been minimised by the selection of SCC-resistant materials and the adoption of stress relief measures for the construction [Ref-6].

The residual risk of SCC over the operating design life of 60 years for the UK ABWR is the corrosive environment that must be controlled. This is done by managing the chemistry impurities and chemical additives to the system for the mitigation of SCC, and has been described in Section 23.4.3.1.

RPV materials of stainless steel and nickel based alloys are susceptible to sensitisation when they are exposed to high temperatures (approx. 500 to 750°C) and chromium carbides are precipitated along the grain boundaries. The alloy matrix at that boundary becomes chromium depleted and sensitised increasing the susceptibility to IGSCC to occur. The UK ABWR materials selection approach is to avoid sensitisation and minimise cold work.

The materials being used for the RPV reactor core internals are of two types; Type 316L (NG) with matching weld metal and Alloy 600M and Alloy 82 weld metal. These are chosen for the UK ABWR because of their corrosion resistance and they are low carbon grades and nuclear grades to further inhibit the possibility of chromium carbide nucleation [Ref-6]. Since welds are carried out at high temperature, the weld HAZ is a concern for sensitisation during fabrication of the system components, and this will be mitigated by the alloy composition (low carbon) and restricting the exposure to temperatures where there is highest risk. Additionally, where possible the design has eliminated or reduced the need for welding.

The use of cold worked alloys will be restricted where possible. This will be achieved by controlling the manufacturing processes to avoid or minimise residual cold work that could increase tensile

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stresses in the material. The materials will be solution annealed treated, and reheating of the treated materials afterwards will be avoided. Solution heat treatment (SHT) (or solution annealing) can remove sensitisation, plastic strain and tensile residual stress due to cold work or welding. Additionally, mechanical polishing, pickling, oxidation (air passivation), and oxidation (moisture vapour treatment) are proposed as surface treatments for some components (See Section 3.4.5).

Providing the chemistry environment is controlled (as described in Section 23.4.3) IGSCC of sensitised material should not occur. Further detail on the justification of the austenitic stainless steels and the nickel based alloys to be used in the UK ABWR including the risk ranking of the UK ABWR components identified with respect to SCC risk is provided in [Ref-6].

#### **Possible Faults and Residual Detriment**

The risk of SCC has been reduced by materials selection to ALARP [Ref-6]. It is important to recognise that residual risks remain. However, the mitigation of SCC is by controlling one of the three factors that are required for its initiation. In this context, the UK ABWR design addresses all three aspects, and therefore the risk of SCC is very low. The inherent protection afforded by the materials mitigations from the plant construction will be enhanced by the careful control of the reactor chemistry regime as described in Section 23.4.3.

#### **(2) FAC**

FAC occurs mainly in carbon steel piping (but also affects low alloy steels to a lesser extent) and removes the surface oxide layer of the SSCs in single-phase and two-phase flow regions. FAC is therefore of importance to components external to the RPV. This is because the RPV materials are FAC resistant due to their materials composition and being high alloy materials.

The chromium (Cr) content in steel is the most effective factor to significantly reduce the FAC rate, although other alloying elements can also reduce the FAC rate [Ref-18]. The addition of very low amounts of chromium ( $>0.1\%$ ) to carbon steel can reduce FAC rates to 1/3-1/10th of plain carbon steel.

The influential parameters that can promote FAC in the UK ABWR environment include the material composition, DO concentration, temperature, flow velocity and moisture content in the two-

phase flow regions. FAC is considered particularly a risk in the UK ABWR sections where the temperature is higher than 60°C and turbulence exists.

The FAC mechanism causes localised corrosion that can reduce wall thickness and lead to defects such as through wall failures, and if the thickness is reduced below critical values it can lead to rupture of the component in extreme cases.

The UK ABWR design mitigations that are taken are:

- selection of FAC resistant materials,
- designing the plant to reduce areas of turbulence and optimise the hydro-dynamics, and
- mitigation of the corrosive environment by injecting oxygen into the feedwater (as described in Section 23.4.3.2).

The materials selection process for FAC mitigation in the UK ABWR design requires that the safety class 1 areas of the FDW is manufactured from low alloy steel, and other parts of the system with risk of FAC will be fabricated of carbon steel with chromium (>0.1 %) in the composition. With this material, the DO concentration will further enhance the FAC mitigation, as the oxygen injection is used to form a more corrosive and wear resistant iron oxide known as haematite ( $\text{Fe}_2\text{O}_3$ ), which is more oxygen rich than the magnetite ( $\text{Fe}_3\text{O}_4$ ) that forms in low oxygen environments (dissolved oxygen <15 ppb) on the carbon steel surfaces in the FDW. The oxygen injection and oxygen level control is discussed in Section 23.4.3.2.

In two-phase flow areas of the plant, low alloy steel and stainless steel is used to prevent FAC, such as the materials in the ES, HV and cross-over piping. Here the Low Alloy Steel (LAS) is used for piping with the highest FAC susceptibility, i.e. where the DO is less than 15 ppb, temperature is more than 60°C and the moisture level is more than 1.5 %. Hence the FAC residual risk for this piping is considered very low.

The limit for the carbon steel additional chromium content is 0.2 wt% based on supplier's ability to manufacture the material, and so the range of 0.1 to 0.2 wt% chromium is available without significant procurement limitations. Although this is at the lower level of the FAC mitigation range, however it is still considered to be a conservative with respect to the FAC risk for the plant areas selected. EPRI and JSME indicate that materials with >1.25 % can be exempted from FAC

inspection requirement, and this chromium concentration in the low alloy steel materials will be used [Ref-18].

**Possible Faults and Residual Detriment**

There are some disadvantages associated with the use of higher chromium content materials. This includes higher hardenability in low alloy steels ( $>1.25\%Cr$ ), and so the welds above a certain thickness and/or diameter must be post weld heat treated. Therefore, the materials for FAC mitigation are identified for risk ranking. This is addressed in [Ref-18] for carbon steel, carbon steel with  $>0.1\%Cr$  specified and low alloy steel materials selection for FAC.

The risk of FAC has been reduced by materials selection and OI to demonstrate ALARP. The residual risks that remain must still be managed by the future licensee throughout life to maintain plant integrity of the UK ABWR. This will include the development and implementation of suitable operating practices and maintenance inspection programmes. Commercially available modelling software is often used by nuclear power plant operators to inform their FAC inspection programme. However, the extent, specification of procedures and inspections required to manage FAC risk will be the responsibility of a future licensee during the site specific stage. The application of internationally recognised guidelines for management of FAC has been considered for the GDA to demonstrate that the risk of FAC can be safely managed for the utility, and guidance for the future licensee is provided in [Ref-18].

The detailed description of the FAC degradation mechanism in relation to the UK ABWR, the materials selection justification, the risk ranking procedure to quantify the level of residual FAC risk to the integrity of the UK ABWR SSCs is provided in [Ref-18].

**(3) General corrosion**

General corrosion affects metallic surfaces uniformly, and is effectively the oxidation of the surfaces of the RCS and associated systems materials. It is enhanced by high temperatures and the presence of impurities and increased conductivity of the RCS and associated systems chemistry. Therefore, the austenitic stainless steel, and nickel based alloys used in the RCS and associated systems, as previously discussed, are also selected due to their low corrosion rates in the UK ABWR environment. Low alloy steel can be affected by general corrosion in the presence of harmful

impurities. In particular, the harmful ions such as chloride and sulphates are the most common in the reactor water, and such impurities can accelerate the general corrosion of SSCs. The water chemistry controls discussed in Section 23.4.3 ensure that the impurities and conductivity of the system is maintained low by controlling the impurity ingress and the clean-up to ensure that general corrosion is prevented or minimised.

For the low alloy steel and carbon steel with >0.1 % chromium addition that is used in the CFDW the OI that is employed for the FAC mitigation, also prevents the general corrosion of these system materials. This effectively minimises the quantity of corrosion product and crud that is generated from the CFDW. It also has a positive impact on attaining a low iron inventory, which is required by the UK ABWR proposed regime for iron control, and which is important in reducing the Co-60 in the reactor water and to minimise the radioactivity transport in the RCS and associated systems, as discussed in Section 23.4.5.

The materials in the system design are also built with allowable tolerances for general corrosion, as this mechanism can be predicted based on the operating conditions for the plant. This will allow for the general corrosion during the plant lifetime.

#### **(4) Localised corrosion**

Localised corrosion (such as pitting, crevice corrosion and galvanic corrosion) occurs as a result of localised conditions, such as surface defects that create susceptibility, differential aeration, and electrochemical potential difference between dissimilar metals. Localised corrosion can be enhanced by the presence of susceptible materials, in contact with water with high impurities and high conductivity, and at elevated temperatures. Localised corrosion such as pitting and crevice corrosion tends to occur on materials which have good corrosion resistance due to a thin passive oxide layer, as present on stainless steels. This is because the corrosion mechanism relies upon the disruption of the passive layer by aggressive impurities such as chloride and sulphate ions, and this leads to localised attack that propagates into the materials, causing pits or crevice corrosion to occur. This type of corrosion is mitigated by controlling the water chemistry as described in Section 23.4.3 to minimise the impurities and to maintain low conductivity levels in the coolant. In the reactor water the reducing conditions imposed by the HWC and OLNC chemistry to lower the ECP to the region where SCC is prevented, will also mitigate the localised corrosion mechanisms.

The OI for the CFDW to mitigate FAC will be beneficial for the minimisation of localised corrosion for the low alloy steel and carbon steel with 0.1 % chromium addition. However, as stated in Section 23.4.3 the injection of oxygen to achieve a DO concentration in the FDW is limited due to risk of SCC. This is because if the DO is greater than the upper LCO of 500 ppb the materials in the RPV, can raise the ECP threshold for those alloys into the region where pitting and SCC is more likely to occur [Ref-1][Ref-8]. Therefore, the water chemistry regime is targeted to mitigate this risk.

The materials selection of the following systems is important to the Reactor Chemistry Safety Case, and the key aspects of the chemistry factors are summarised.

#### **23.4.7.2 UK ABWR Systems Materials Selection Chemistry Factors**

##### **(1) Reactor Pressure Vessel (RPV)**

The RPV is fabricated of low alloy steel, clad internally with austenitic stainless steel and nickel based alloy. The reactor core is surrounded by the Core Shroud, which is an austenitic stainless steel cylinder supported by the shroud support.

The dominant structural materials of the RPV and RINs are austenitic stainless steel and nickel based alloys.

Therefore, the reactor chemistry regime for HWC + OLNLC applies for the UK ABWR to reduce the risk of SCC.

##### **(2) Reactor Clean-up System (CUW)**

Since the high temperature region of plant upstream of the F/D in CUW consists of austenitic stainless steel, it is susceptible to increased dose rate as result of the HWC + OLNLC regime. Therefore, the reactor chemistry regime for DZO applies for the UK ABWR to reduce the risk of worker dose. The detail chemistry control for zinc injection, and maintaining a lower limit is addressed in Section.23.4.5.

Since the DO in the reactor water will be reduced as a result of applying HWC+OLNLC the plant may be susceptible to FAC. Therefore, in this area the CUW will be fabricated of low alloy steel to reduce the FAC risk.

**(3) Condensate and Feedwater System (CFDW)**

The UK ABWR CFDW design requires that for the mitigation of FAC the safety class 1 areas of the system are manufactured from low alloy steel, and other parts of the system risk assessed as susceptible to FAC will be carbon steel with a chromium ( $>0.1\%$ ) in the composition. Other parts of the system comprise carbon steel.

For the areas of the CFDW that consist of carbon steel and carbon steel with  $>0.1\%$  chromium, oxygen injection will be applied to reduce the general corrosion and FAC and hence reduce the corrosion product loading into the reactor. The detailed chemistry control for oxygen injection is addressed in Section 23.4.3.3.

The CFDW areas that consist of carbon steel and carbon steel with  $>0.1\%$  chromium can corrode in damp oxygenated conditions. Therefore, the system is drained and dried out for the outage period when possible to reduce the general corrosion and corrosion products as stated in Section 23.4.5.

Since the CFDW consists of areas of carbon steel and carbon steel with  $>0.1\%$  chromium the concentration of the iron crud in the FDW generated during the outage will be reduced by the re-circulation of CFDW before start-up. The detail for this chemistry control is addressed in Section 23.4.5.

**(4) Residual Heat Removal System (RHR)**

The UK ABWR GDA design requires that the RHR system piping will be surface treated by oxidation (air passivation) (see Section 23.4.5.1 (iii)).

Since the UK ABWR RHR consists of carbon steel, it is expected to be flushed prior to being put into service to reduce the corrosion product loading into the reactor. The detail for this operational control requirement to reduce the source term addressed in Section 23.4.5.

It is also expected that during shutdown that the low temperature shutdown cooling mode (LT-SHC) to reduce the DST impact will be applied. The detail for this operational practice requirement to reduce the source term is addressed in Section 23.4.5.

**(5) Feedwater Heater Drain System / Feedwater Heater Vent System (HD/HV)**

The Feedwater Heater Drain System / Feedwater Heater Vent System (HD/HV) will be partially fabricated from low alloy steel to reduce the risk of FAC. The HV is 2-phase flow and therefore low alloy steel is used. In the HD 2-phase flow regions low alloy steel is used, and the other HD areas are carbon steel.

There is also evidence [Ref-41] that the amount of corrosion in the Heater Drain System can be significantly reduced by adopting low alloy steel. This is proposed for the UK ABWR design.

**(6) Feedwater Heater (FWH)**

The UK ABWR GDA design requires that the High Pressure (HP) Feedwater Heater (FWH) tubing will be surface treated by oxidation (moisture vapour treatment) (see Section 23.4.5.1 (iii)).

Since the HP FWH tubes have a large surface area, the corrosion products that are formed through general corrosion are a significant contributor to the corrosion product quota that becomes activated in the core. For this reason, the cobalt content in materials used in the Feedwater Heater and Drain System (FWHD) system is specified so that it will contain less than 0.05 wt% for the Low Pressure (LP) FWH and 0.02 wt% for HP FWH (see 23.4.5.1 (i)). Additionally, to reduce the loading of nickel into the reactor, 304SS will be used for the UK ABWR FWH tubing because the nickel content is lower.

**(7) Main Condenser Tubing**

The main condenser for the UK ABWR is designed with titanium condenser tubes for its high corrosion resistance to seawater, even under high velocity flow conditions. Due to the presence of a tenacious thin layer of titanium oxide ( $\text{TiO}_2$ ), titanium is especially resistant to this form of corrosion. The use of titanium also eliminates the main potential contributor of copper to the reactor water, which is the main ALARP argument in terms of minimising the exposure of copper alloys to reactor water and the risk of copper being carried forward into the RPV. All BWR plants without this significant condenser copper source in the RCS and associated systems exhibited immunity to CILC failure, and therefore this mitigates the risk of CILC for the fuel integrity in the UK ABWR, as described in Section 23.4.4, [Ref-8].

Although titanium condenser tubes are known to have excellent resistance to leaks within the industry, leaks are still possible. The causes of condenser leaks are not always due to corrosion. Mechanical impact damage (i.e. impingement from objects mostly from the steam-side or from loose objects left in the turbine during outages) as well as design flaws are potential issues related to condenser leaks. Therefore, the future licensee will need to consider suitable procedures to ensure foreign materials exclusion. Further discussion on the application of titanium condenser tubes design is provided in [Ref-8]. The management of condenser leaks is described in Section 23.4.3.1, and also see PCSR Chapter 24 for the detailed CIPS design functions.

**23.4.8 Assumptions, Limits and Conditions for Operation**

The design of the UK ABWR RCS and associated systems materials and water chemistry regime has been optimised for the safety of the plant for SSCs integrity, fuel integrity, and to control and minimise the radioactivity and dose to the public and workers, and management of the hazardous radiolytic gases. The discussion presented in this section is consistent with the reactor chemistry safety claims shown in Table 23.4-1 and the LCOs that are listed below. The chemistry regime of HWC+OLNC+DZO, as well as the other measures discussed such as oxygen injection, iron control, and control of impurities, ensures that the safety risk for the system is ALARP.

The LCOs for the RCS and associated systems have been identified throughout Section 23.4.3 and are summarised in Table 23.4-4. These LCOs are taken from [Ref-1], [Ref-3], [Ref-4], [Ref-5], [Ref-15], and [Ref-27].

**Table 23.4-4 Limits and Conditions Operating Controls for Reactor Coolant System and Associated Systems Chemistry**

Parameter	Limit value (LCO)				Section Reference
	Power Operation	Shutdown	Start-up	Outage	
RW Direct Conductivity, $\mu\text{S/m}^{*1*2}$	600 (max)	600 (max)	600 (max)	600 (max)	23.4.3.1
RW Chloride, ppb	600 (max)	600 (max)	600 (max)	600 (max)	23.4.3.1

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**Table 23.4-4 Limits and Conditions Operating Controls for Reactor Coolant System and Associated Systems Chemistry**

Parameter	Limit value (LCO)				Section Reference
	Power Operation	Shutdown	Start-up	Outage	
RW Sulphate, ppb	600 (max)	600 (max)	600 (max)	600 (max)	23.4.3.1
RW Silica, ppb	9,000 (max)	9,000 (max)	9,000 (max)	-	23.4.3.4
RW Zinc, ppb	2 (min)	2 (min)	2 (min) <sup>*4</sup>	-	23.4.4.2, 23.4.5.2
RW Platinum (input), g/year	20 (min) and 920 (max)	-	-	-	23.4.3.2, 23.4.4.2
Injection timing of Platinum by OLNLC	More than 60 days after operation	-	-	-	23.4.3.2, 23.4.4.2
RW Dissolved Oxygen (DO), ppb	-	-	200 (max) <sup>*5</sup>	-	23.4.3.2
RW Co-60, Bq/cm <sup>3</sup>	43.8 (max) <sup>*9</sup>	-	-	43.8 (max) <sup>*8*9</sup>	23.4.5.3
FDW Copper, ppb	1 (max)	1 (max)	1 (max)	-	23.4.4.2
FDW Zinc, ppb	3 (max)	3 (max)	3 (max)	-	23.4.4.2
FDW Iron, ppb	50 (max)	50 (max)	50 (max)	-	23.4.4.2

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**Table 23.4-4 Limits and Conditions Operating Controls for Reactor Coolant System and Associated Systems Chemistry**

Parameter	Limit value (LCO)				Section Reference
	Power Operation	Shutdown	Start-up	Outage	
FDW Dissolved oxygen (DO), ppb <sup>*6</sup>	15 (min) and 500 (max)	15 (min) and 500 (max)	15 (min) and 500 (max)	-	23.4.3.3
FDW Dissolved hydrogen, ppm (Injection) <sup>*7</sup>	0.15 (min) <sup>*3</sup> and 0.5 (max)	0.15 (min) <sup>*3</sup> and 0.5 (max)	0.15 (min) <sup>*3</sup> and 0.5 (max)	-	23.4.3.2
FW hydrogen availability, % <sup>*7</sup>	> 90 %			-	23.4.3.2
RW H <sub>2</sub> /O <sub>2</sub> molar ratio <sup>*7</sup>	>2			-	23.4.3.2
CF Flow maximum rate, m <sup>3</sup> /h/1 unit	1800				23.4.3.1
CD Flow maximum rate, m <sup>3</sup> /h/1 unit	1120				23.4.3.1
Insoluble material (Fe), ppb, in recirculation line of CFDW prior to start-up				1 (max)	23.4.4.2, 23.4.5.2
Before RPV head lift, I-131, Bq/cm <sup>3</sup>	-	-	-	1E-03 (max)	23.4.5.3

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**Table 23.4-4 Limits and Conditions Operating Controls for Reactor Coolant System and Associated Systems Chemistry**

Parameter	Limit value (LCO)				Section Reference
	Power Operation	Shutdown	Start-up	Outage	
Reactor Shutdown - Temperature drop rate, °C/h	-	30°C/h (max)	-	-	23.4.5.3
Insoluble material in RHR prior to in-service, ppb	-	500 (max)	-	-	23.4.5.3
Reactor Temperature for RHR – LT-SHC shutdown cooling, °C	-	120 (max)	-	-	23.4.5.3.

<sup>\*1</sup>: Conductivity can be converted by 1 μS/m = 0.01 μS/cm <sup>\*2</sup>: at 25°C, <sup>\*3</sup>: FDW Hydrogen is initially determined by benchmark test, with 0.15 ppm the preliminary value to achieve hydrogen/oxygen (H<sub>2</sub>/O<sub>2</sub>) ratio >2, <sup>\*4</sup>: The zinc concentration may be below the lower limit during the first few fuel cycles but appropriate control should be established afterwards, <sup>\*5</sup>: DO to be 200 ppb (maximum) prior to reactor start-up, <sup>\*6</sup>: When OI is in service, <sup>\*7</sup>: When hydrogen injection is in service, <sup>\*8</sup>: Prior to flood up of the reactor, <sup>\*9</sup>: Includes soluble and insoluble Co-60.

This section also described the GDA system design for the CIS (Sections 23.4.3.2 and 23.4.5.2) and the OI (Section 23.4.3.3) to demonstrate that chemical injections and the concentration levels are required. It should be noted that the designs described will be taken forward by the future licensee and these will be developed in the site specific stage. Additionally, other designs are not foreclosed if they are demonstrably suitable.

The FCVS Vent Filter scrubbing solution maintenance LCO (Section 23.4.5.3 (a) (vi)) is stated in the Appendix B of [Ref-1], and in PCSR Chapter 26: Beyond Design Basis and Severe Accident (SA) Analysis.

## **23.5 Spent Fuel Storage Pool Chemistry Control**

The SFP chemistry requirements for storage of fuel and for the reactor water chemistry control to protect SSCs and minimise dose are discussed in this section. The detailed design description, justification for the spent fuel storage facility and its safety functions are described in PCSR Chapter 19: Fuel Storage and Handling, Section 19.8. The FPC detailed system description is addressed in Chapter 19, Section 19.9. Further details of the assessment of the SFP and FPC design related to chemistry control are provided in [Ref-3].

### **23.5.1 Brief Description of the Spent Fuel Storage Facility**

The spent fuel storage facility (SFS) consists of the SFP, the cask pit, the spent fuel storage racks and the SFP gates. The SFP provides underwater storage for new fuel assemblies, as well as irradiated and spent fuel assemblies, and non-fuel assemblies which are removed from the reactor for maintenance or replacement during an outage or for disposal.

The SFP is made of reinforced concrete lined with stainless steel plate. The SFP is filled with demineralised water that is maintained by the Fuel Pool Cooling and Clean-up system (FPC) which manages the water temperature and impurities within specification. The FPC delivers the clean-up of the SFP and upper pools during all normal operation modes, and more detail is provided in Chapter 19, Section 19.9.

The SFP water depth is sufficient to provide spent fuel cooling and radiation shielding. The SFP has a capacity allowing the storage of fuel assemblies that have been accumulated from a period equivalent to over ten years of plant operation, and an additional capacity for one core of fuel during offload RPV maintenance.

The SFP water, dryer separator (D/S) pit water and reactor well water are connected during an outage. The SFP contains water at all times, but the D/S pit and reactor well, and the space between them and the SFP only store water during refuelling [Ref-3]. The SFP is isolated from the reactor well by two SFP gates. The gates are removed during refuelling outages to allow the submerged transport of fuel assemblies between the SFP and the RPV. The S/P water is introduced to SFP through Suppression Pool Clean-up System (SPCU) F/D during an outage (See Section 23.6).

As well as impurities removal, the FPC cools the SFP by removing the decay heat from the spent fuel and maintains the temperature below 52°C during normal plant operation. During abnormal conditions, such as a full core off-load or malfunction of one cooling division, the SFP temperature is allowed to reach a peak temperature of 65°C, which is the nuclear safety-related design limit set to maintain the long-term integrity of the concrete composition used in the SFP structure over the lifetime of the plant [Ref-3]. This function is detailed in PCSR Chapter 19, Section 19.8.

### **23.5.2 Chemistry Functions of the Spent Fuel Storage Facility**

The safety case for the SFP water chemistry is developed from the safety objectives identified in section 23.3, and the top claims and claims that have been derived from them are presented in Table 23.5-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

The Spent Fuel Interim Storage (SFIS) Facility is discussed in Chapter 32: Spent Fuel Interim Storage, and Decommissioning for the UK ABWR in PCSR Chapter 31: Decommissioning. The chemistry control of the SFP will be maintained to normal water chemistry specification (see Table 23.5-2) to maintain fuel integrity, whilst the SFP continues to store spent fuel post generation, which will be at least until the SFIS is available. This water specification is discussed in Section 23.5.3, including linkages to the spent fuel storage in SFP in PCSR Chapter 19. After the spent fuel has been removed, the SFP will be used during the decommissioning for the R/B dismantling work. At this time, the SFC water management systems, HVACs, cranes and other associated plant will be intact and continue to be operational to support the facility. The R/B deplanting work is detailed in PCSR Chapter 31. The choice of SFP materials and adherence of the chemistry controls during the UK ABWR operational lifetime will contribute positively to the maintenance condition of the structural integrity of the SFP facility, SSCs and their operability requirements, and the dose rates post generation during decommissioning.

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**Table 23.5-1 Safety Claims for SFP Water Chemistry of the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC 8: The UK ABWR Spent Fuel Storage Pool chemistry regime will contribute to the maintenance of the integrity of the structure and liner in the pool by operating within the limits and conditions.	RC SC 8.1: Impurities will be kept below levels that may result in increased corrosion rates and minimised to ALARP in normal operations by the FPC.	23.5.3.1	19, 31
Material degradation, leading to fuel degradation	RC SC 9: The UK ABWR Spent Fuel Storage Pool chemistry regime will contribute to the maintenance of the spent fuel integrity by operating within the limits and conditions.			
Radionuclide inventory and release, and radiological dose	RC SC10: The UK ABWR Spent Fuel Storage Pool chemistry regime will ensure that the radionuclide releases and exposure to worker is ALARP.	RC SC10.1: Radionuclides in the Spent Fuel Storage Pool will be minimised to ALARP by the FPC and CUW.	23.5.3.2, 23.4.5.3	19, 31
	RC SC11: The UK ABWR Spent Fuel Storage Pool chemistry regime will ensure that the radionuclide releases and exposure to public is ALARP.			

### **23.5.3 Chemistry Control for the Spent Fuel Storage Facility**

The key reactor chemistry requirements for the SFC and FPC are impurity control for maintaining the structural integrity and functionality of the SSCs and for the fuel integrity, and the management of radiological dose and release.

The clean-up function of the FPC provides removal of soluble and insoluble impurities including radioactive substances from the SFP to maintain the water quality of the SFP. This satisfies water quality requirements and also mitigates the degradation of fuels stored in the SFP, the degradation of storage equipment in the SFP, and minimises worker dose. Maintaining the water quality in the FPC is also important for maintaining the cleanliness, and hence the availability and effectiveness of the heat transfer tube surface of the FPC heat exchanger. This is to ensure that the heat removal capacity of the FPC is not impaired for the SFP cooling.

#### **23.5.3.1 Impurities Control (SSC Integrity and Fuel Integrity)**

The DO concentration level in the SFP coolant reaches a saturation level because the pool is open to air and cannot be reduced. However, the corrosion rates for the SSCs in the systems and fuel is suppressed because of the low water temperature, and can be further suppressed by the control of the impurities in the system.

#### **Method of Control and Monitoring**

Since the SFP water, D/S pit water and reactor well water are connected the water chemistry specification for these is the same during an outage. It is also based on the reactor water and the S/P chemistry because the SFP is connected to these systems during an outage. The water chemistry control parameters are direct conductivity, chloride and sulphate. These LCO values are the same as those for the reactor water during power operation as stated in [Ref-1] and described in Section 23.4.3.1. Since the water temperatures are relatively low in the SFP, the conductivity, and the LCOs for chloride and sulphate are more conservative. The F/D design and capacity will reduce the impurities to ALARP in normal operation.

The FPC contains F/Ds to continuously remove impurities from the SFP coolant. Two parallel FPC F/Ds are provided and are capable of simultaneous operation. The FPC filter demineralisers are designed as described in PCSR Chapter 19, Section 19.9, and also in [Ref-3].

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Additional operation modes of the FPC are for make-up water for the SFP, and filling, draining and cooling (combined with the RHR) for the D/S pit and reactor well during refuelling. In the latter case, the S/P water is pumped through the FPC F/Ds (Section 23.6), and detail is provided in [Ref-3].

The FPC uses the powder resin pre-coat type F/D to clean-up the SFP so that both soluble and insoluble impurities are controlled. The FPC F/Ds are pre-coated with material that is a mixture of cation and anion resin powder. The pre-coating material is replaced when the differential pressure across the F/D unit exceeds a determined value or the conductivity rate at the outlet exceeds the determined rate. The F/D is usually backwashed once per cycle so that the full capacity of the system is restored [Ref-3].

Details of the pre-coat power resin ion exchange capacity, and resin change requirements are provided in [Ref-3], which accounts for the estimated capacity required for chloride ions and sulphate ions over a full cycle. Conservatively, in the event that the FPC was to operate with the maximum chloride or sulphate ion concentration that has been experienced in J-ABWRs for the entirety of a cycle, the resin would be required to be pre-coated twice per cycle for the chloride ion case and three times per cycle for sulphate ion case. In practice for the UK ABWR it is expected that the outlet conductivity and differential pressure of the FPC F/D will rarely exceed the set point for replacing the resin, and the operators will routinely replace the resin once per cycle [Ref-3].

The FPC F/D will use different resin to the CUW F/D due to the FPC operating with an open atmosphere system circulating water saturated with carbon dioxide, and the CUW circulating deaerated water (except during outage). Evidence presented in [Ref-3] shows that there is little difference between the exchange capacities and break through capacities of these resins.

A decontamination factor (DF) of 10 for the insoluble substance removal performance by the FPC F/D has been determined based on evidence from existing plants in Japan and existing CUW F/D performance. The SFP water clarity requirement ensures the operators are able to identify the fuel assemblies, as it may affect fuel handling inside the pool. The insoluble impurities are controlled such that the SFP water is maintained as being 'crystal clear', and this is defined in [Ref-1] as:

- Crystal clear: The clarity at which the engraved characters on the upper tie plate of the fuel assembly (at 7m below the water surface) can be read by using an underwater scope and underwater target tube. The height of each engraved character shall be 9.6 mm.

Therefore, the removal capacity of insoluble impurities of the FPC F/D is assumed to be adequate.

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Further detail on the FPC design justification for the chemistry management, and details of the resin and F/D performance are provided in [Ref-3].

In the recirculation loop of the SFP, several sampling points are set to monitor the water quality of the coolant. Sampling points are located at the inlet and outlet of the F/D to enable monitoring of F/D performance. For the purpose of detecting a leakage from the RCW via the heat-exchanger, one sampling point is set downstream of a heat-exchanger. The sampling systems (SAM) and sampling and monitoring design requirements are addressed in Section 23.11.

### **Possible Faults**

The risks associated with the loss of the clean-up capability are addressed in Attachment L (Non-Reactor Faults) systems in [Ref-12] (see also [Ref-3]).

Additional factors that may impact the FPC performance in the UK ABWR are addressed in [Ref-3]. These include:

- Resin oxidation. It is considered that there is no oxidation reaction acute enough to lead to an increase in the resin exchange frequency,
- Thermal decomposition does not pose a challenge to the FPC F/D pre-coat powder resin in normal operation due to the relatively low temperature of the SFP,
- The water of the systems entering the SFP has a more restrictive water quality specification than that of the water in the SFP. Therefore, it is unlikely that the quality of the water in the SFP would degrade due to the introduction of water from these sources,
- Resin fracturing will not occur in the UK ABWR F/Ds, because the F/D units in the UK ABWR use a powdered resin rather than a granular resin. Therefore, no resin will be erroneously discharged during operation, and
- Breakthrough of soluble species will be detected through continuous monitoring of the conductivity of the water at the F/D outlet. When the water conductivity exceeds the specified action level, the F/D is backwashed and pre-coated to recover its performance.

### **23.5.3.2 Suppression of the Radioactivity (Radiological Dose and Release)**

To keep the concentration of the radionuclides in the coolant suppressed to ALARP, the radioactivity emanating from the spent fuel, including damaged fuel, is removed by the FPC F/D. The allowable concentration of the radionuclides in the pool is determined by the radiation level at the operating floor, where the maintenance work is carried out.

#### **Method of Control and Monitoring**

The water chemistry in the SFP is controlled to minimise the radionuclide release to the environment and hence to reduce the resulting radiation exposure to workers and public. The FPC is designed to remove impurities including radioactive species from the pool to minimise dose and in compliance with the ALARP principle.

The principal source of radioactivity within the SFP is caused by activity transfer from the reactor, such as the reactor water mixing with SFP water during the flood-up in an outage, and the release of radioactivity into the pool water from the crud on used fuel transferred from the reactor. To limit the radioactivity transfer into the SFP during an outage, there is a flood-up criterion for Co-60 as being representative of fuel crud radioactivity input. The procedures used to minimise the release of FPs into the environment including the use of sealed bottles for damaged fuel assemblies to be kept within the SFP are described in [Ref-28]. The FP release is regarded as insignificant with respect to contribution to worker dose. Therefore, only Co-60 in the SFP water is set as an LCO.

The release of Co-60 from fuel crud on the surface of stored fuel will tend to occur quite rapidly during the period immediately following the transfer of used fuel assemblies from the reactor during an outage. The majority of the Co-60 during this transient peak in the SFP during the outage will be cleaned up by FPC F/D. The F/D is shielded for radiation protection. Once the peak transient in Co-60 has been reduced the Co-60 concentration in the SFP water will establish equilibrium based on the lower continuous release rate from fuel crud and the absorption by the SFP clean-up system. The process for this is detailed in [Ref-31], with supporting information in [Ref-42]. The LCO for the SFP Co-60 is set at  $2.86 \text{ Bq/cm}^3$  for normal operation [Ref-1].

If the SFP was operated at the best estimate PST values, the proposed discharge limits in the GEP will not be exceeded. Furthermore, the gaseous discharges generated are also comfortably within the allowable limit even if the liquid discharges are reduced to zero. The worker dose exposures that are calculated for the tritium management scenarios in the SFP facility are well below the BSO level of

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1mSv [Ref-1]. The detailed information regarding this is provided in the Primary Source Term Supporting Report [Ref-43].

To monitor the water quality, the sampling and measurements are carried out in line with the parameters stated in [Ref-1], which include the LCO requirements detailed in Table 23.5-2 for the SFP. Conductivity is continuously measured and the other chemistry parameters are monitored by grab sampling. The SAM and sampling and monitoring design requirements are addressed in Section 23.11.

### **Possible Faults**

The risks associated with the loss of the clean-up capability are addressed by the evaluation for the CUW which is presented in Attachment L (Non-Reactor Faults) in [Ref-12] (see also [Ref-3]).

The relevant faults described under Impurities Control (SSC Integrity and Fuel Integrity) are presented in Section 23.5.3.1.

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**23.5.4 Assumptions, Limits and Conditions for Operation**

The LCOs for the SFP water chemistry have been identified throughout Section 23.5.3 and are summarised in Table 23.5-2. These LCOs are taken from [Ref-1] and [Ref-3].

**Table 23.5-2 Limits and Conditions Operating Controls for Spent Fuel Pool Water Chemistry (also for Dryer-Separator Pit Water and Reactor Well Water<sup>\*3</sup>)**

Parameter	Limit value (LCO)	Section Reference
SFP Direct Conductivity, $\mu\text{S/m}$ <sup>*1*2</sup>	600 (max) <sup>*1</sup>	23.5.3.1
SFP Chloride, ppb	600 (max)	23.5.3.1
SFP Sulphate, ppb	600 (max)	23.5.3.1
SFP Co-60, Bq/cm <sup>3</sup>	2.86 (max) <sup>*4</sup>	23.5.3.2

<sup>\*1</sup>: Conductivity can be converted by  $1 \mu\text{S/m} = 0.01 \mu\text{S/cm}$ , <sup>\*2</sup>: at  $25^\circ\text{C}$ , <sup>\*3</sup>: These pools are linked to each other during fuel exchange, and make-up water is used for them, <sup>\*4</sup>: Includes soluble and insoluble Co-60.

## **23.6 Suppression Pool Chemistry Control**

The S/P chemistry requirements for normal operation are discussed in this section. The justification is about the chemistry controls associated with the maintenance of the structural integrity of the S/P and the related SSCs in order that the system can deliver the safety claims and associated arguments that are made for the facility and the UK ABWR safe operation. Therefore, the chemistry control safety claim is based on the SPCU.

Consideration of S/P chemistry control for the clean-up failure and iodine behaviour for the nuclear safety case during DBA and SA is described, and is also separately considered in Chapter 24: Design Basis Analysis and Chapter 26: Beyond Design Basis and Severe Accident (SA) Analysis accordingly.

### **23.6.1 Brief Description of the Suppression Pool and Clean-up**

The S/P is a large pool located at the bottom of the reinforced concrete Pressure Containment Vessel (PCV). The pool is lined with stainless steel for the part immersed in water and coated carbon steel for the dry part above the water level.

The S/P water is used as a water source for the reactor well during refuelling, for filling up the temporary equipment storage pool, and as the water source for tests of the ECCS during normal plant operation.

To maintain the required water quality, the S/P water is circulated in the SPCU as needed, and is shown schematically in Figure 23.6-1. The SPCU transfers the pool water through the FPC F/D where soluble and insoluble impurities are removed, before returning the water back to the S/P. The main functions of the S/P are classified into two categories: safety functions relating to water supply as a normal procedure, and safety functions in the case of the DBA such as LOCA. The accident-related functional requirements and the chemistry safety issues are separately described in PCSR Chapter 24.

The safety functions for normal procedures are:

- (1) As a water source during ECCS surveillance operation,
- (2) As a water source for Dryer and Separator Pit and Reactor well filling during outage.

The SPCU detailed system description and modes of operation for clean-up and filling is addressed in PCSR Chapter 16: Auxiliary Systems, Section 16.6. This includes the system functions justification and system details such as the pool capacity, and design flow rates of the SPCU pumps to ensure sufficient water clean-up. Further detailed assessment of the S/P and SPCU design is provided in [Ref-3].

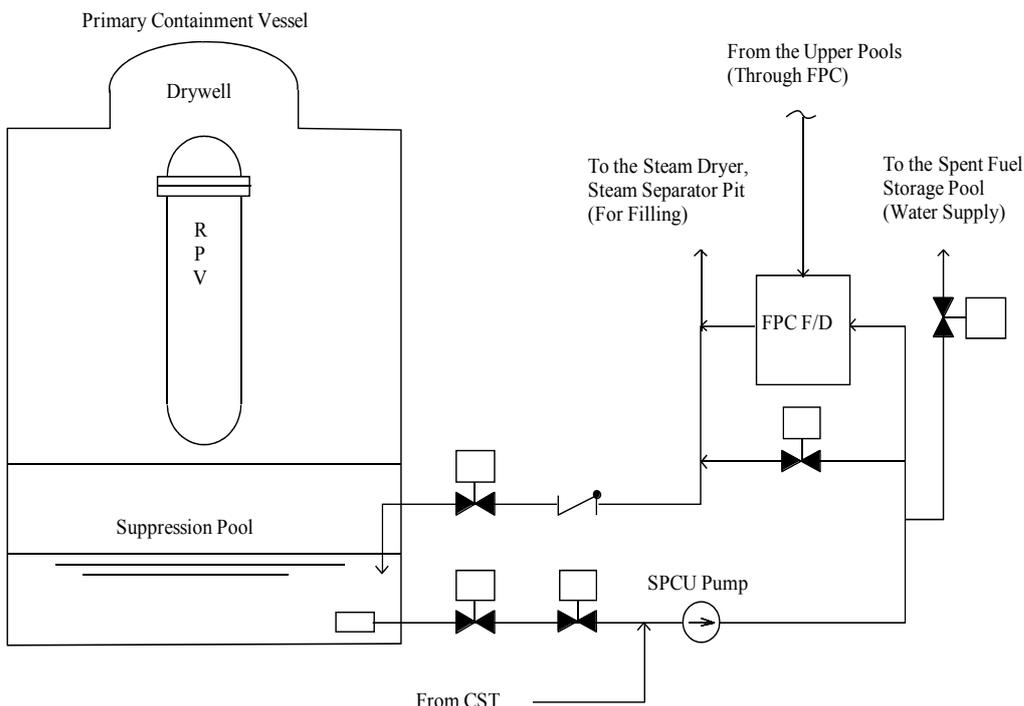


Figure 23.6-1: Suppression Pool schematic drawing

23.6.2 Chemistry Functions of the Suppression Pool and Clean-up

The safety case for the S/P water chemistry is developed from the safety objectives identified in section 23.3, and the top claim and claim that has been derived from them is presented in Table 23.6-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

**Table 23.6-1 Safety claims for Suppression Pool Water Chemistry for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC12: The UK ABWR Suppression Pool chemistry regime will contribute to the maintenance of the integrity of structure and liner in the pool by operating within the limits and conditions.	RC SC12.1: Impurities will be kept below levels that may result in increased corrosion rates and minimised to ALARP in normal operations by the SPCU.	23.6.3	16

### **23.6.3 Chemistry Control for the Suppression Pool and Clean-up**

#### **23.6.3.1 Normal Operation**

The S/P has a role that is to supply demineralised water into the reactor pressure vessel during a refuelling outage and emergency cooling injection or into the RHR during surveillance operations. Therefore, the water chemistry quality for the S/P is high purity (demineralised water) with minimal impurities, and this is not only for the preservation of the integrity of the S/P itself but also for the related reactor SSCs with which the water can come into contact. The integrity of the S/P itself is particularly important to ensure reliable operation and capability to perform the system safety functions, such as in the case of a DBA.

### **Method of Control and Monitoring**

The primary function of the SPCU is to provide continuous purification of the water treatment for the S/P. The SPCU removes miscellaneous impurities by filtration, adsorption, and ion exchange processes, and maintains the S/P water quality within the specification requirements in [Ref-1].

The SPCU also has two other functions which are that the SPCU performs as a means to fill the upper pools prior to refuelling with suitable quality water, and the SPCU provides the make-up water to the SFP from the CST or the S/P. Furthermore, the SPCU is also capable of providing the make-up water to the SFP as a backup in the event that Residual Heat Removal System (RHR) and regular make-up water systems failed. It can be seen that the water quality is very important as it is used in several connected systems.

The S/P chemistry regime will contribute to the maintenance of the integrity of its structure and liner in the pool. The coolant temperature is below 100°C in the system and therefore SCC is not of great concern as a degradation mechanism. Impurities will be kept below levels that may result in increased corrosion rates and minimised to ALARP in normal operations.

Since the S/P water is mixed with the reactor water and the SFP water during an outage the LCO values for the S/P water chemistry are the same as those specified for the reactor water and the SFP (Section 23.4.3.1 and 23.5.3.1). Since the S/P water temperature is low, the LCO values are conservative.

The SPCU uses the FPC F/D, (Section 23.5.3.1), to reduce the impurities to ALARP in normal operation, and so the quality control of the water in the S/P is also the same as that in the SFP. The CST is also connected to the SPCU for an additional supply of demineralised water that is suitable for use in the systems for top-up. Further details of the design, operation and justification for the SPCU are described in PCSR Chapter 16.6.

To monitor the water quality, the sampling and measurements are carried out in line with the parameters stated in [Ref-1], which include the LCO requirements detailed in Table 23.6-2 for the S/P. The SAM and sampling and monitoring design requirements are addressed in Section 23.11.

**Possible Faults**

The risks associated with the loss of the clean-up capability are addressed in Attachment L (Non-Reactor Faults) in the TR on Design Basis Analysis [Ref-12] (see also [Ref-3]).

**23.6.3.2 Iodine Behaviour during Accidents**

Radiologically, the most important fission products are the noble gases, iodine and caesium. The chemistry of the noble gases is relatively simple, in that they are unreactive, and on release from the fuel will remain in the gas phase. In design basis accidents, the chemistry of caesium is also simple, in that the aqueous phase species is the involatile cation  $\text{Cs}^+$ . Caesium ions will therefore be associated with aqueous phase flow in DBAs. In severe accidents, and in particular molten core situations, caesium will mainly be in the form of CsI or caesium uranates, i.e. it will remain in the cation form albeit in the solid state.

In contrast, the chemistry of iodine is complex owing to its wide range of oxidation states and volatility of some of the species. The well-known stable ions and molecules are iodide ( $\text{I}^-$ ), molecular iodine ( $\text{I}_2$ ), hypoiodous acid (HOI), iodate ( $\text{IO}_3^-$ ), and periodate ( $\text{IO}_4^-$ ). Of these species, those of main concern with regard to iodine volatility are  $\text{I}_2$  and HOI owing to the potential release to the environment via the gas phase. The formation of these volatile species in reactor accidents is the reason why pH control of the suppression pool is employed.

Without pH control, the pH of the S/P will decrease owing to the formation of HCl from degradation of halogenated cables, and the radiolytic formation of nitric acid from the containment atmosphere. The molecular iodine will hydrolyse in water to form HOI, which will form an equilibrium with the  $\text{I}_2$ . Both  $\text{I}_2$  and HOI are potentially volatile species which partition into the gas phase. At high pH,  $\text{I}_2$  is completely hydrolysed, and the involatile species  $\text{I}^-$  and  $\text{OI}^-$  are formed. The consequences of low pH, and the effect of pH control are presented in the Suppression Pool pH Model during Design Basis Accident and Severe Accident [Ref-44]. PCSR Chapter 26 provides the context of the S/P pH control and details of severe accident analysis. The engineered solution for the application of the S/P pH control during accidents is a concept design for GDA, as is described in PCSR Chapter 26. The design of the pH control system will be determined post-GDA at the site specific stage. Additionally, the role of the FCVS vent filter for reducing radioactive iodine and long lived FPs release to the environment during SA is described in Section 23.4.5.3 (a) (vi), and in PCSR Chapter 26, Section 16.7.3.5.

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## 23.6.4 Assumptions, Limits and Conditions for Operation

The LCOs for the Suppression Pool water chemistry have been identified throughout Section 23.6.3 and are summarised in Table 23.6-2. These limiting values are taken from [Ref-1] and [Ref-3].

**Table 23.6-2 Limits and Conditions Operating Controls for Suppression Pool Water Chemistry**

<b>Parameter</b>	<b>Limit value (LCO)</b>	<b>Section Reference</b>
S/P Direct Conductivity, $\mu\text{S/m}^{*1*2}$	600 (max)	23.6.3
S/P Chloride, ppb	600 (max)	23.6.3
S/P Sulphate, ppb	600 (max)	23.6.3

\*1: Conductivity can be converted by  $1 \mu\text{S/m} = 0.01 \mu\text{S/cm}$ , \*2: at  $25^\circ\text{C}$

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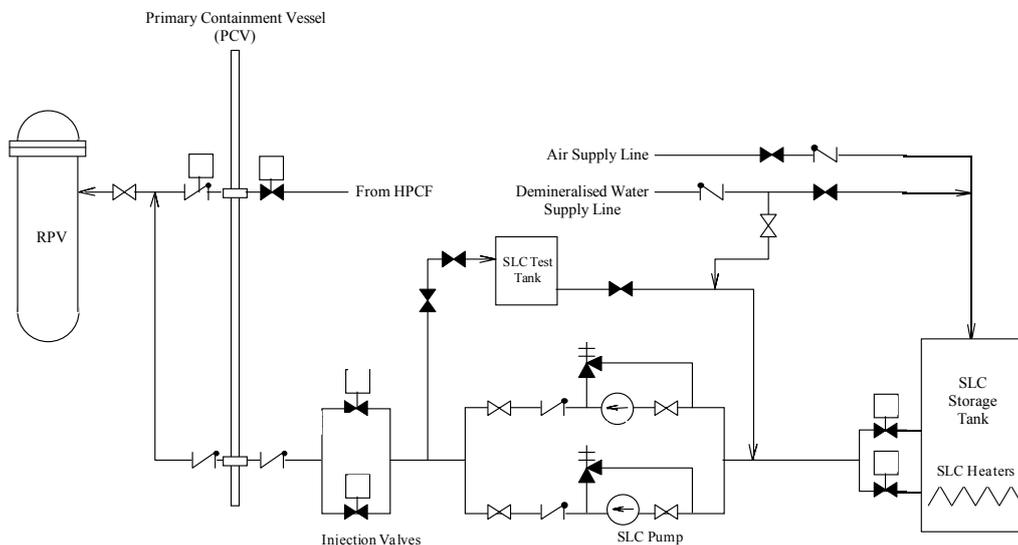
## **23.7 Standby Liquid Control System Water Chemistry**

The Reactivity Control Systems for the UK ABWR consist of the CR and the CRD, and the Standby Liquid Control System (SLC). The CR and CRD are discussed in PCSR Chapter 11: Reactor Core and Chapter 12: Reactor Coolant Systems, Reactivity Control Systems and Associated Systems, respectively and are not further described here. The SLC chemistry requirements only are described in this section. Therefore, this section specifies the boron concentration in the SLC tank and the monitoring and control of the SLC tank to enable Reactor Shutdown.

### **23.7.1 Brief Description of the Standby Liquid Control System**

The SLC is a secondary shutdown system that will bring the reactor to a cold shutdown and maintains sub-criticality if the reactor cannot be shutdown by Reactor Emergency Shutdown (Safety Control Rod insertion) (SCRAM) (i.e. the inability to insert CRs). Such an event is known as an Anticipated Transients Without Scram (ATWS).

The SLC engineering and mechanical detailed system design and the safety categorisation and classification justification applied for the UK ABWR are addressed in the PCSR Chapter 12, Section 12.4. The chemistry related justification for the system is detailed in the TR on Design Justification in Chemistry Aspect for Ancillary Systems [Ref-45]. The SLC is shown schematically in Figure 23.7-1.



**Figure 23.7-1: Standby Liquid Control System Schematic Drawing**

The SLC injects a sodium pentaborate solution, as a source of boron for the neutron absorber into the core from the SLC Storage Tank through the HPCF sparger. Two trains (pumps, motor-operated injection valves) are provided to assure there is sufficient redundancy for the system. The SLC is designed such that the system functions can be implemented with either of the trains in operation. The section of the SLC that is downstream of the SLC pump forms the RCPB.

**23.7.2 Chemistry Functions of the Standby Liquid Control System**

The safety case for the SLC water chemistry is developed from the safety objectives identified in Section 23.3, and the top claim and claim that has been derived from them is presented in Table 23.7-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

The reactor chemistry claim is linked to the UK ABWR FSF 1 for the control of reactivity, and the SLC HLSFs stated in PCSR Chapter 12.

**Table 23.7-1 Safety claims for Standby Liquid Control System Water Chemistry for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Maintain the secondary shutdown capability and maintain sub-criticality	RC SC14: The UK ABWR Standby Liquid Control System chemistry will ensure safe shutdown of the reactor in the event of Anticipated Transient Without Scram (ATWS) by injecting neutron absorber solution into the reactor water.	RC SC14.1: Sufficient and available sodium pentaborate solution is stored and maintained in an available state in the SLC.	23.7.3	12

**23.7.3 Chemistry Control for the Standby Liquid Control System**

The SLC is designed to provide the capability of bringing the reactor, at any time in a cycle, from a full power and minimum CR inventory (which is defined to be at the peak of the xenon transient) to a sub-critical condition with the reactor in the most reactive xenon-free state. The boron shutdown margin by the SLC is evaluated to be sufficient for UK ABWR [Ref-46].

**Method of Control and Monitoring**

Boron is a good neutron absorber, but many boron containing compounds have limited solubility and saturation can lead to problems with precipitation during storage such as the solution concentration falling below the necessary levels and potential blockages so that the SLC system functions are not achieved effectively. The structural degradation of the SLC during standby itself due to corrosion mechanisms during its standby mode of operation must also not prevent the SLC from performing its safety function and to maintain the integrity of the RCPB.

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For the UK ABWR, sodium pentaborate has been selected as the neutron absorber because it does not give rise to degradation issues for the reactor pressure boundary structures and fuel cladding when injected. It also has high solubility in water. The sodium pentaborate contains natural boron, of which it is the stable isotope B-10 (~20 % of natural boron) that has a high neutron absorption cross-section ( $3.84 \times 10^3$  barns ( $3.84 \times 10^{-25}$  m<sup>2</sup>)). The sodium pentaborate can be enriched in B-10 so the chemical loading to inject is decreased. However, the UK ABWR will use sodium pentaborate with natural boron as it is economically beneficial and has a high degree of reliability, negating the need for enrichment plant and the need for advanced isotopic measurements [Ref-45].

The UK ABWR SLC performs a category A safety function and is safety class 2 since it is the secondary means of achieving reactor shutdown. The SLC LCO 3.1.7 is defined in [Ref-27]. It requires the number of SLC subsystems to be operable during operation Modes 1 and 2 (as defined in PCSR Chapter 5) for the UK ABWR, and the boron solution parameters to be within limits. From the chemistry perspective, this applies to the storage and availability of sufficient sodium pentaborate solution as a neutron absorber to shut down the reactor during these modes of operation. The sodium pentaborate solution is stored and maintained in an available state in the SLC tank in a standby mode, and hence it is available to use if required during the cycle. The boron concentration of the solution and the solution storage capacity of the SLC Storage Tank are based on the quantity of boron necessary to achieve and maintain a sub-critical condition of the reactor after adding the mixture to the RPV and taking into account dilution margins, the concentration is set at 1320 ppm. After, adding the corresponding margins to compensate for evaporation, ineffective volume, etc. the capacity is set at 28.7m<sup>3</sup> and thus satisfies the minimum concentration of boron of 600 ppm claimed to be stored [Ref-45]. The temperature of the saturated sodium pentaborate solution is also monitored and controlled to ensure that precipitation does not occur in the SLC storage tank, since the solution concentration is determined by the water temperature. To ensure that precipitation is prevented the SLC storage tank solution temperature is monitored and maintained between  $27 \pm 3^\circ\text{C}$ . Electrical heaters and a make-up line from the MUWP are installed on the SLC tank to maintain the solution temperature and volume to prevent precipitation during storage. The temperature and solution level in the SLC storage tank are indicated on a local panel and the liquid level is also indicated in the MCR. High or low temperature or liquid level will activate an alarm in the MCR [Ref-45]. Further detail on the required saturation temperature, sodium pentaborate concentration, and volume are in the design specification derived from LCO 3.1.7 and the Basis of Safety Cases on Standby Liquid Control System [Ref-47].

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The sodium pentaborate solution is prepared by dissolving the chemical (sodium pentaborate decahydrate,  $\text{Na}_2\text{B}_{10}\text{O}_{16}\cdot 10\text{H}_2\text{O}$ ) in demineralised water from the MUWP using the water in the Purified Water Storage Tank (PWST), to achieve the water requirements for the LCO 3.1.7. The PWST water chemistry is described in Section 23.8.3.2.

The sodium pentaborate solution will be maintained and sampled, and sampling points are provided in the SLC Storage Tank to measure the boron concentration and verify the boron quantity meets the requirements for the SLC system action levels that should be set by the future licensee, and which will be within the LCO 3.1.7 requirements stated in [Ref-27]. SAM design requirements are further addressed in Section 23.11.

The SLC storage tanks are stainless steel. The degradation of stainless steel does not occur in sodium pentaborate solution which is neutral or weak alkaline. The consideration for the corrosion resistance and structural integrity requirements for the SLC is discussed in TR on SLC Storage Tank Structural Integrity [Ref-48]. Additionally, PCSR Chapter 12 links to PCSR Chapter 8: Structural Integrity where the materials and corrosion considerations for the SLC are summarised.

## **Possible faults**

The fault schedule for the SLC is addressed in PCSR Chapter 12.

From a chemistry perspective, in the event of inadvertent actuation of the SLC, the CUW will be utilised to remove the soluble boron that has been injected into the reactor after stopping the SLC. However, since the SLC is a shutdown system which is functionally capable of shutting down an operating reactor, spurious operation of the SLC is a reactor fault which terminates generation of electricity and places a demand on the reactor cooling systems. Spurious SLC operation is on the fault schedule.

The temperature and concentration control of sodium pentaborate solution is described in [Ref-47], and to meet the requirement to prevent sodium pentaborate from precipitating in the SLC Tank.

Boron precipitation can become significant at temperatures below 15°C. Precipitated boron dilutes the poison available for injection and in severe cases may significantly clog the pipe and pump suction reducing the pumping capacity. To help prevent any clogging caused by precipitate, the suction point is raised above the tank bottom. Tank heaters are installed to minimise boron precipitation on surfaces and within equipment. The SLC Storage Tank, connecting pipework and

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valves are designed to prevent precipitation of sodium pentaborate by minimising the distance of the discharge lines between the SLC Storage Tank and the tank outlet valves.

**23.7.4 Assumptions, Limits and Conditions for Operation**

The SLC LCO 3.1.7 is defined in [Ref-27] which is intended to be transferred to the future licensee to operate the plant as designed in the safety case. The LCO requirement has been identified throughout Section 23.7.3. The SLC water quality specification is stated in [Ref-45], and is referenced in Table 23.7-2. The PWST water is used to make-up the SLC solution. The PWST water chemistry specification is described in Section 23.8.3.2.

**Table 23.7-2 Limits and Conditions Operating Controls Standby Liquid Control - Sodium Pentaborate Solution Water Chemistry [Ref-27]**

Parameter	Limit Value (LCO)	Section Reference
SLC availability	See 'Generic Technical Specifications' [Ref-27]	23.7.3

## **23.8 Make-up Water, Treatment and Storage**

The most important aspect for the Make-up Water Condensate System (MUWC) and CST is to control the water quality adequately. The Make-up Water Purified System (MUWP) supplies pure water from the Purified Water Storage Tank (PWST).

The MUWC system design detail, safety category and classification are described in PCSR Chapter 16: Auxiliary Systems, Section 16.3.4.

### **23.8.1 Brief Description of the MUWC, CST and MUWP for the UK ABWR**

#### **23.8.1.1 MUWC and CST**

The MUWC is designed to supply condensate water at start-up, shutdown and during power operation to RCS and associated systems components which are potentially in contact with radioactive water. It is also used as a water source for the ECCS components. The supply water for the MUWC is stored in the CST, and the water is supplied from the CST to the components via make-up water condensate pumps. The MUWC supplies water for purposes such as filling water and water for washing components during refuelling outages. The sources of water that are used by the MUWC are from the MUWP, recycled cleaned water from the Low Chemical impurities Waste (LCW) Treatment System (see PCSR Chapter 18: Radioactive Waste Management, and Section 23.12.3), and the condensate spill-over line. During a reactor shutdown, the reactor water is returned to the condenser and is recovered to the CST via the condensate spill-over line, where it can be stored. The MUWC supplies water to the following major systems:

- SPCU: The MUWC is one of the sources for make-up water through the SPCU to the SFP,
- CRD: The MUWC supplies purge water through the CRD to the FMCRD, RIPs and the CUW when the condensate spill-over line is not available,
- Turbine gland steam system (TGS): The MUWC supplies the make-up water as a steam generation source in the gland steam evaporator (GSE),
- Condenser: The MUWC supplies the make-up water to the condenser to control the condenser hotwell water level,

- Reactor core isolation cooling system (RCIC): the MUWC is one of the water sources for make-up water through the RCIC to the reactor pressure vessel, and
- High pressure core flooder system (HPCF): the MUWC is one of the water sources for make-up through the HPCF to the reactor pressure vessel.

The schematic drawing of the MUWC and CST is shown in Figure 23.8-1, in which the connections to all of the systems it serves are depicted.

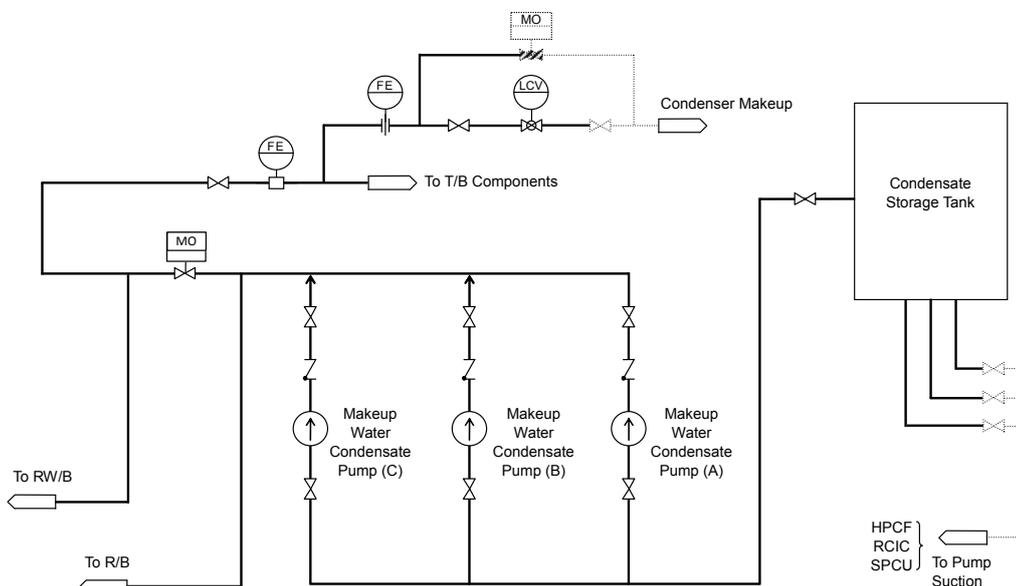


Figure 23.8-1: Schematic drawing of MUWC and CST

23.8.1.2 MUWP and PWST

The PWST takes the output from the site Make-up Water Treatment Plant (that treats the raw water to supply the station), and then distributes it to other systems such as the CST. It is also used to top up the SLC storage tank directly to make the sodium pentaborate solution.

The PWST does not receive water from any other source linked to the reactor and so its contents are non-radioactive. The raw water that is treated is site specific and so that cannot be specified, and so the make-up water treatment design and process is not considered within GDA. However, the quality

of the treated water for the UK ABWR operation is required in GDA to ensure the procurement specifications for the supply of a suitable pure water supply to the utility is adequate.

**23.8.2 Chemistry Functions of the MUWC, CST and MUWP for the UK ABWR**

The safety case for the MUWC and CST water chemistry is developed from the safety objectives identified in Section 23.3, and the top claim and claims that have been derived from them are presented in Table 23.8-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

**Table 23.8-1 Safety claims for MUWC, CST and MUWP for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC16: The water quality produced and stored by the MUWC and CST is very pure and therefore it will not contribute to the equipment material degradation that it comes into contact with.	RC SC16.1: Water quality control within specified limits in the CST will ensure the water quality of the RCS and associated systems.	23.8.3	16, 18
		RC SC16.2: Water quality control within specified limits in the MUWP (Purified Water Storage Tank water) will ensure the water quality of the RCS and associated systems.	23.8.4	16

### **23.8.3 Chemistry Control for the MUWC, CST and MUWP for the UK ABWR**

#### **23.8.3.1 MUWC and CST**

##### **Method of Control and Monitoring**

The MUWC supplies condensate water to the RCS and associated systems components, including the ECCS components, as described in Section 23.8.1.1. These components are required to maintain structural integrity to ensure the safe operation of the reactor. For this reason, the MUWC and CST water quality must meet the water quality specification requirements of each system to which it provides coolant make-up to ensure it contributes to the maintenance of the integrity of the equipment that the water makes contact with.

As the supply water of the MUWC is stored in the CST, the chemistry control is focused on the water quality in the CST. The CST takes water from the pure water tank and from the LCW treated effluent, and so their water chemistries are designed to meet the CST water quality.

Since the purified water in the CST is supplied to the core components such as the CRD, its quality must be maintained to the highest standard. For this reason, it is desirable to suppress the concentrations of chloride and sulphate to below the LCOs specified for the RCS and associated systems. The LCOs for the CST water and the and make-up water added to be stored in the tank (at any time) are the same as the LCOs of the conductivity, chloride and sulphate for the reactor water during power operation, as stated in [Ref-1] and described in Section 23.4.3.1.

Total organic carbon is also specified to be controlled for the CST controlled to reduce the generation of sulphate in the reactor water. The TOC originates from sources outside of the plant such as raw water, and the rust-inhibiting paint and/or corrosion inhibitor that can be used in the system components. The TOC itself is not necessarily harmful to the structural integrity. However, as the temperature of the reactor water rises during start-up, any TOC impurities present in the reactor water can undergo thermal decomposition and radiolysis leading to the production of ionic species such as halogens, sulphate and carbonate ions. This can also result in an increase in the conductivity of the reactor water. The amount of ionic species generated as a result of TOC decomposition during start-up depends on the initial amount of TOC present. Limiting the TOC concentration in the RCS and associated systems is important. Since the systems use water from the CST, controlling the TOC concentrations of the CST tank water will contribute to ensuring that the

reactor water quality does not deteriorate due to the decomposition of TOC during start-up. It is therefore important that the ingress of TOC be controlled. When systems are filled with water prior to start-up, the water is supplied from the CST which could be a source of TOC ingress. For this reason, the acceptance criterion for the CST has an upper limit of TOC based on the conductivity peak during start-up. The details are explained in [Ref-1] and [Ref-45].

To monitor the water quality, the sampling and measurements are carried out in line with the parameters stated in [Ref-1]. Conductivity is continuously measured and the other chemistry parameters are monitored by grab sampling. The SAM and sampling and monitoring design requirements are addressed in Section 23.11.

**Possible Faults**

Water quality will be assured by sampling and monitoring. In the case of impurities increase in the tanks and system, it can be purged to improve the water quality.

**23.8.3.2 MUWP and PWST Water Chemistry**

**Method of Control and Monitoring**

The water in the PWST is brought in or prepared from outside of the UK ABWR reactor plant building. This water will be used on the plant for purposes such as make-up water to the RCS and associated systems, and top up to the non-radioactive systems on the plant. The raw water treatment is outside of the GDA scope, but the minimum requirements for the water quality of the outlet water from the water treatment system regardless of any water source and water treatment system design is within GDA. This is specified as the PWST water quality in GDA [Ref-1].

The PWST water quality requires a similar quality to the expected water quality in the CST, as the CST takes its water from the PWST. For this reason, there are LCOs for the pure water tank water direct conductivity (maximum of 100  $\mu\text{S/m}$ ), chloride (maximum of 20 ppb) and sulphate (maximum of 20 ppb). These LCOs have been determined based on the suggested first action level for the CST which is provided in the [Ref-1]. The PWST water quality also requires LCOs for the silica concentration (maximum of 10 ppb) and suspended solids concentration (insoluble materials as iron, maximum of 200 ppb) and TOC concentration (maximum of 400 ppb). This is because the PWST water originates from raw water that is treated for use outside of the reactor system, and a more conservative approach is taken to ensure the water quality is adequate. Borate ( $\text{BO}_3^{3-}$ ) is also considered as a parameter, with an LCO maximum limit of 100ppb in the GDA design for the UK

ABWR, although no measurement is required for this parameter if there is no source and possibility of ingress. It is likely that borate will not be present in the raw water supply in the UK, based on the expected raw water sources. The limits proposed for all of these control parameters for the Pure Water Tank water quality are justified by being within or similar to the industry good practice [Ref-1].

To monitor the water quality, the sampling and measurements are carried out in line with the parameters stated in [Ref-1], which include the LCO requirements detailed in Table 23.8-2 for the CST. The SAM and sampling and monitoring design requirements are addressed in Section 23.11.

#### **Possible Faults**

Water quality faults are likely to be related to site specific raw water treatment process faults.

#### **23.8.4 Assumptions, Limits and Conditions for Operation**

The LCOs for the MUWC and CST water chemistry and the MUWP and Pure Water Tank water chemistry have been identified throughout Section 23.8.3.

#### **Condensate Storage Tank Water Chemistry**

The water specification for the CST stored water is shown in Table 23.8-2. These LCOs are taken from [Ref-1]. The water quality of the CST water and the make-up water stored in this tank must be lower than the LCO and control parameter values of the reactor water during power operation.

The LCOs are stated for the CST tank control parameters for GDA. Post GDA, the future licensee is expected to define and consider whether these values require to be further defined as LCOs.

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**Table 23.8-2 Limits and Conditions Operating Controls for CST Water Chemistry**

Parameter	Limit value (LCO)	Section Reference
CST Direct Conductivity, $\mu\text{S/m}^{*1*2}$	600 (max)	23.8.3
CST Chloride, ppb	600 (max)	23.8.3
CST Sulphate, ppb	600 (max)	23.8.3
CST TOC, ppb	5,000 (max)	23.8.3

\*<sup>1</sup>: Conductivity can be converted by  $1 \mu\text{S/m} = 0.01 \mu\text{S/cm}$ , \*<sup>2</sup>: at 25°C.

## Pure Water Tank Water Chemistry

The LCOs of the pure water and make-up water stored in the Pure Water Tank are shown in Table 23.8-3. These are the minimum requirements for the water quality of the outlet water from the water treatment system regardless of any water source and water treatment system design.

**Table 23.8-3 Water Specification Control Parameters for the Pure Water Tank Water Chemistry [Ref-1]**

Parameter	Limit value (LCO)	Section Reference
Pure Water Direct Conductivity, $\mu\text{S/m}^{*1*2}$	100 (max) <sup>*3</sup>	23.8.3
Pure Water Chloride, ppb	20 (max)	23.8.3
Pure Water Sulphate, ppb	20 (max)	23.8.3
Pure Water pH <sup>*2</sup>	5.6 (min) and 8.0 (max) <sup>*3</sup>	23.8.3
Pure Water TOC, ppb	400 (max)	23.8.3
Pure Water Borate, ( $\text{BO}_3^{3-}$ ), ppb <sup>*4</sup>	100 (max)	23.8.3
Pure Water Silica ( $\text{SiO}_2$ ), ppb	10 (max)	23.8.3
Pure Water Insoluble material (Fe), ppb	200 (max)	23.8.3

\*<sup>1</sup>: Conductivity can be converted by  $1 \mu\text{S/m} = 0.01 \mu\text{S/cm}$ , \*<sup>2</sup>: at 25°C, \*<sup>3</sup>: The value has been corrected for dissolved  $\text{CO}_2$ ; \*<sup>4</sup> No measurement for borate is required if there is no reasonable

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source for ingress or contamination. It is expected the UK ABWR raw water supplies are not borated, and therefore this parameter should not be required for the UK ABWR site specific plants.

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## **23.9 Component Cooling Water Systems Chemistry**

This section will describe the sodium nitrite corrosion inhibitor chemistry control regime for the auxiliary component cooling water (CCW) systems in the UK ABWR.

### **23.9.1 Brief Description of the Component Cooling Water Systems**

The CCW systems consist of multiple, independent systems, which are classified in accordance with the system purpose and its supply area. These systems are:

- Reactor Building Cooling Water System (RCW),
- Reactor Building Service Water System (RSW),
- Turbine Building Cooling Water System (TCW),
- Turbine Building Service Water System (TSW),
- HVAC Emergency Cooling Water System (HECW),
- HVAC Normal Cooling Water System (HNCW), and
- Emergency Equipment Cooling Water System (EECW)

The detailed descriptions of the system design are delivered in PCSR Chapter 16: Auxiliary Systems, Section 16.3 and the chemistry aspects of these systems are described in detail in [Ref-45]. The RCW, TCW, HECW, HNCW and EECW comprise a closed loop in which water coolant is recirculated to remove heat emanating from equipment both of low or high safety significance, while the RSW, TSW and CW comprise an open loop to transfer the heat to the ultimate heat sink (UHS) via a heat exchanger. As a constituent material, carbon steel is used for the piping, and materials with high thermal conductivity are applied to the heat exchanger tubes for an effective heat exchange.

### **23.9.2 Chemistry Functions of the Component Cooling Water Systems**

The safety case for the CCW water chemistry is developed from the safety objectives identified in section 23.3, and the top claim and claim that has been derived from them is presented in Table 23.9-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

**Table 23.9-1 Safety Claims for the Component Cooling Systems Water Chemistry for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC15: The chemistry of the component cooling water contributes to minimise the corrosion of its system materials to maintain their integrity and heat transfer function by ensuring a corrosion controlled environment when operated within the limits and conditions.	RC SC15.1: Corrosion of SSCs of carbon steel, stainless steel and copper will be minimised by the addition of nitrite based corrosion inhibitors.	23.9.3	16

**23.9.3 Chemistry Control for the Component Cooling Water Systems**

This section is based on describing the use of sodium nitrite as a corrosion inhibitor for the CCW systems in the UK ABWR. However, it is recognised that other corrosion inhibitor regimes may be employed by a future licensee and will be considered during the site specific stage. Other CCW corrosion inhibitor options that might be applicable to the UK ABWR are discussed in [Ref-45] to provide guidance on suitability to the future licensee post GDA.

**Method of Control and Monitoring**

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To deliver the component cooling function reliably, it must be ensured that the auxiliary systems maintain the structural integrity of the system that they are cooling. The main safety issue is the material corrosion under the ambient temperatures to which systems are exposed. Therefore, the purpose of controlling the CCW chemistry is to minimise the component corrosion. This is achieved by maintaining the component integrity and equipment performance with a stable cooling water supply and good heat exchanger efficiency. In the UK ABWR, the CCW piping is made of carbon steel.

The pure water tank water will be used to fill and make-up the CCW systems.

The CCW water will be corrosion inhibitor treated. The purpose for chemically treating the cooling water in the CCW systems is to:

- Minimise corrosion,
- Control microbiological growth,
- Control the deposition of suspended solids, and
- Prevent scale deposition.

For GDA sodium nitrite ( $\text{NaNO}_2$ ) has been recognised as the most favourable chemical for the CCW protection. Its validity has been demonstrated through long operational experience from the J-ABWR plants, which only use sodium nitrite based inhibitors [Ref-45].

Immediately after the initial injection of sodium nitrite, its concentration should be targeted to be near the upper limit of the expected value in order to ensure sufficient protection for the system until the next dose is added. It should be added as applicable, depending on the corrosion inhibitor concentration decrease but ensuring it is carried out prior to falling below the recommended range. Therefore, the system nitrite ion concentration will be routinely sampled and monitored and the results trended to ensure timely dosing is carried out. The nitrite ( $\text{NO}_2^-$ ) is monitored through the measurement of conductivity with 100 mS/m recommended as an action level, to check the system, but the conductivity parameter is not set as a safety parameter with a LCO. The LCO for the nitrite concentration is to control it between a minimum of 100 ppm and a maximum of 4,000 ppm to ensure that:

- the corrosion of carbon steel is prevented,

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- the chemistry can be monitored effectively, and
- no damage to carbon pump seals used in the system will occur [Ref-1].

There are other parameters to be monitored for the sodium nitrite regime chemistry control, and also have LCOs. These are nitrate, pH, ammonia, chloride and insoluble material. The ammonia and pH are important when there are copper components in the CCW system.

It is required to maintain the concentration of nitrate ( $\text{NO}_3^-$ ) below the LCO of 200 ppm, as it is formed by the oxidation of nitrite resulting in a decrease in the anti-corrosive protection of the system as the nitrite concentration falls. If the nitrate level is high then the system water shall be purged to reduce, and the system can be subsequently dosed accordingly.

The LCO for CCW chloride ion concentration is a maximum of 10 ppm. The LCO for the CCW insoluble iron is a maximum of 2 ppm. The chloride limit is based on prevention of increased corrosion rates for stainless steel components, and no plant detriment or integrity concern has been experienced or reported in the past for similar systems. The insoluble iron is not expected to cause any issues with regard to fouling, impaired cooling capacity or under deposit corrosion, but the LCO ensures that corrosion is being prevented by maintaining the insoluble corrosion products below the limit value. These chloride and iron values align with the recommendations given in the EPRI Cooling Water guidelines, although they are considered to be diagnostic parameters in that document rather than control parameters with set limits [Ref-1].

Copper alloys exhibit limited corrosion weight loss when the pH of the condensate water is within the range of 5 to 11, except when in the presence of ammonia when a high degree of copper corrosion can occur. The rate of copper dissolution is also dependent on the pH moderator in the corrosion inhibitor package used. The LCO for CCW ammonia concentration is at a maximum of 10 ppm to suppress the corrosion of copper when the pH is  $>10$ . The LCO for the CCW pH is to operate within a minimum of 5 and a maximum of 11, and this is to control the copper corrosion in the system. If a pH  $>10$  is observed, then the ammonia in the component cooling water should be measured to evaluate its effect. If the pH value falls  $<7$ , it should be adjusted by adding sodium hydroxide.

In the case of applying corrosion inhibitors the systems will be regularly sampled and monitored to ensure that corrosion inhibitor concentrations are effective in suppressing system corrosion. Any

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stationary cooling water system that uses component water cooling should be circulated periodically so that the concentration of anti-corrosion agent will be uniform and can be sampled and tested. To monitor the water quality, the sampling and measurement are carried out in line with the parameters stated in [Ref-1], which include the LCO requirements detailed in Table 23.9-2 for the CCW. The SAM and sampling and monitoring design requirements are addressed in Section 23.11.

**Possible Faults**

A potential detriment of sodium nitrite dosing is that nitrite is a potential food source for nitrifying bacteria (if present) and this may increase the risk of Microbiologically Influenced Corrosion (MIC), resulting in the loss of the nitrite inhibitor by its oxidation under the microbial action to nitrate. Nitrate is an aggressive anion in a similar way to chloride and sulphate, although much higher concentrations of nitrate are required to cause the breakdown of passivating films and promote corrosion of the system components. The consumption of nitrite by bacterial growth can also produce nitric acid which can lower pH, and ammonia which is corrosive towards copper alloys. However, in a closed and demineralised water system, the risk of MIC is considered to be negligible. Furthermore, international OPEX suggests that there have been very few known MIC problems with nitrite dosed systems reported.

A significant reduction in the concentration of sodium nitrite may be a result of a water leakage from the system or due to microbial activity in the system. In all cases of unexpected results further investigation should be sought and the chemistry rectified as soon as practicable. The direct conductivity measurement will provide the initial indication that the system is dosed adequately. The conductivity:nitrite ratio establishes a direct relationship between the inhibitor concentration in the system and the conductivity. The ingress of impurities, especially those derived from seawater, to a relatively low concentration nitrite dosed circuit would increase the conductivity noticeably. Conversely, leakage and automatic make-up from the demineralised water supply will decrease conductivity markedly. Monitoring this ratio helps to distinguish between the two main mechanisms for loss of inhibitor (i.e. system leaks and chemical / biological degradation). The chemical / biological degradation of nitrite will leave the conductivity unchanged (when nitrite is converted to nitrate), but the nitrite concentration will fall. This means that a direct analysis of the nitrite content is also required, which justifies it being a control parameter, [Ref-1][Ref-45].

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## 23.9.4 Assumptions, Limits and Conditions for Operation

The LCOs for the CCW systems water chemistry have been identified throughout Section 23.9.3 and are summarised in Table 23.9-2. These LCOs are taken from the [Ref-1] and [Ref-45].

**Table 23.9-2 Limits and Conditions Operating Controls for Component Cooling Water System Water Chemistry**

Parameter	Limit value (LCO)	Section Reference
Direct Conductivity, mS/m <sup>*1</sup> <sup>*2</sup>	(see note below) mS/m <sup>*1</sup>	23.9.3
pH <sup>*2</sup>	5 (min) and 11 (max)	23.9.3
Chloride, ppm	10 (max)	23.9.3
Insoluble material (Fe), ppm	2 (max)	23.9.3
Nitrite (NO <sub>2</sub> <sup>-</sup> ), ppm	100 (min) and 4,000 (max)	23.9.3
Nitrate (NO <sub>3</sub> <sup>-</sup> ), ppm <sup>*1</sup>	200 (max)	23.9.3
Ammonium (NH <sub>4</sub> <sup>+</sup> ), ppm <sup>*3</sup>	10 (max)	23.9.3

<sup>\*1</sup>: Conductivity is the parameter to judge whether the nitrate measurement is necessary or not. Therefore, the conductivity measurement is also required, however, the value itself is not a safety boundary, and nitrate concentration should be measured when the conductivity is >100 mS/m, <sup>\*2</sup>: at 25°C, <sup>\*3</sup>: Ammonium should be measured when pH >10.

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## **23.10 Back-up Building- FLSS Water Chemistry Control**

The UK ABWR will have a dedicated Backup Building as a key mitigation/resilience measure for specific frequent faults, beyond DBA and SA scenarios. The SA mechanical systems are described in PCSR Chapter 16: Auxiliary Systems, Section 16.7. In the safety facilities categorised in that chapter, the FLSS is described. The FLSS is considered in this PCSR Chapter 23 due to the water storage chemistry management.

### **23.10.1 Brief Description of the FLSS**

The main role of FLSS is to supply cooling water via the FLSS pumps installed in the Backup Building (B/B) to prevent core damage as a backup of the ECCS low-pressure core injection function [Ref-45]. The FLSS is also initiated to mitigate serious core damage, RPV breakage and PCV breakage. Furthermore, the FLSS provides cooling and make-up water for the SFP to maintain the SFP water level in the event that the normal water supply and cooling function to the SFP fails.

The FLSS is designed to perform the following functions:

- The FLSS provides cooling water to the reactor core,
- The FLSS provides cooling water to the PCV spray header,
- The FLSS provides cooling water to the lower Drywell (D/W),
- The FLSS provides cooling water to the reactor well, and
- The FLSS provides cooling water to the SFP.

The FLSS initiates automatically as a backup of the ECCS for design basis faults and is designed to be operated manually from either the MCR or the B/B for beyond design basis faults.

The major components forming the FLSS are as follows:

- FLSS Pump: 4 units (50 % capacity × 4),
- FLSS Water Storage Tank: 10 units (full capacity can be stored in 9 tanks allowing one for maintenance as required),
- Piping and Valves: 1 set, and
- Instrumentation and Controllers: 1 set

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The FLSS tanks are made from stainless steel.

The FLSS Water Storage Tanks are designed to be capable of preserving total amount of water 10,000m<sup>3</sup> which is required to manage SA for seven days without water supply from offsite. Connecting ports are installed on each tank in order to utilise the FLSS storage water as a water source for mobile facilities. The FLSS Water Storage Tanks are designed to be capable of taking water supply from the mobile facility during an accident.

In normal plant operation, water to the FLSS is supplied from the MUWP. The FLSS Water Storage Tanks are designed to prevent water degradation in consideration of outside installation. Each FLSS Water Storage Tank is designed to prevent the water from freezing as a result of its outside installation (i.e. if exposed to cold temperatures). This is enabled as a steam line from the Heating Steam System (HS) is provided in each tank to prevent freezing.

The detailed design, safety functions and modes of operation and injection that are delivered by the FLSS, are detailed in PCSR Chapter 16, Section 16.7. The schematic drawing of the FLSS is provided in Figure 23.10-1, in which the connections to the tanks and the systems it supplies are shown.

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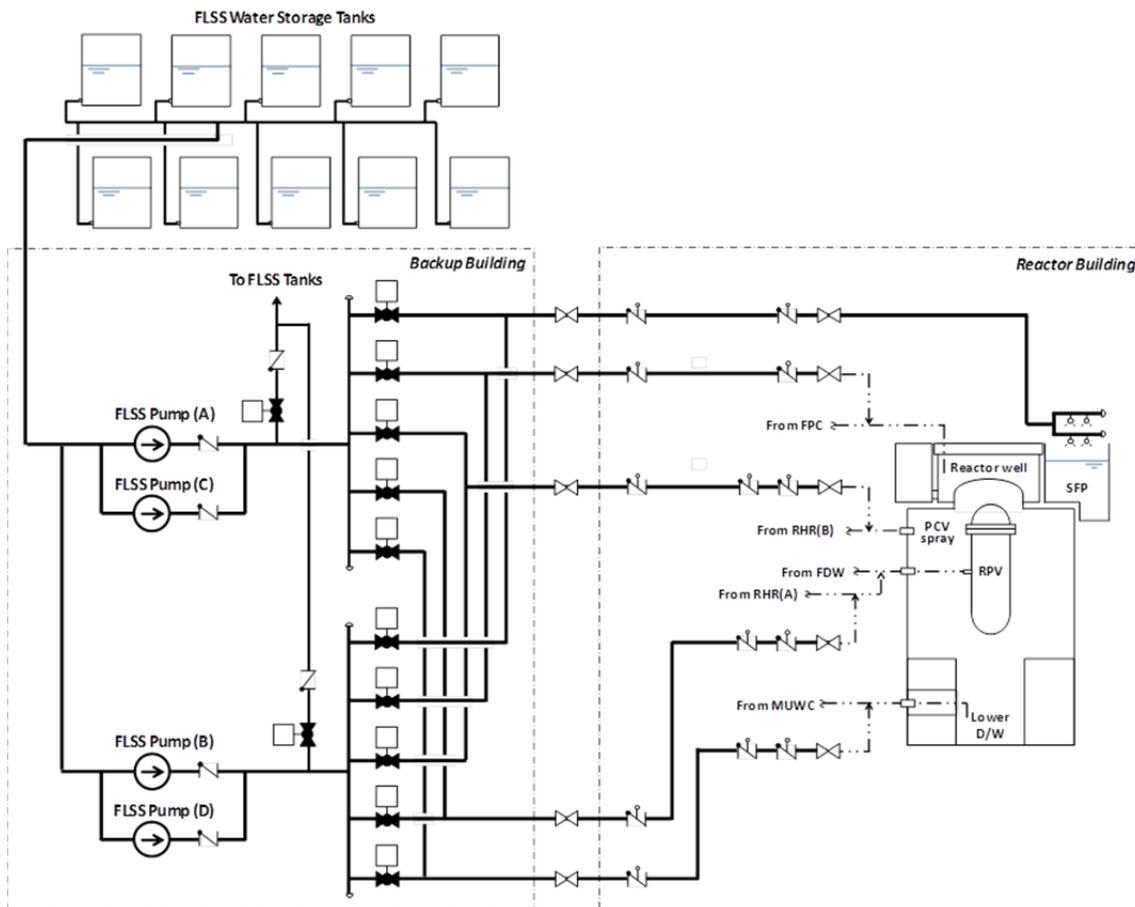


Figure 23.10-1: Outline of the Flooder System of Specific Safety Facility

23.10.2 Chemistry Functions of the FLSS

The safety case for the FLSS water chemistry is developed from the safety objectives identified in section 23.3, and the top claim and claim that has been derived from them is presented in Table 23.10-1. These are then supported by the arguments and evidence which are addressed in the following narrative of this section.

**Table 23.10-1 Safety claims for FLSS Water Chemistry for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC17: The UK ABWR FLSS water quality will ensure the system will provide cooling water to prevent core damage when required (i.e. as backup to ECCS).	RC SC17.1: The water quality will be maintained and will not degrade the integrity of the structural material of the FLSS during the standby mode.	23.10.3	16

**23.10.3 Chemistry Control for the FLSS**

**Method of Control and Monitoring**

Since the FLSS is the backup safety facility for SA management, the integrity of the system must be maintained during the standby period in order to deliver its safety function reliably in the event of a SA.

Demineralised (pure) water from the MUWP will be used for the filling of the FLSS tanks. The chemistry control for the FLSS is based on the monitoring of the water quality in the tanks during the long-term standby period, and that the deterioration of the stainless steel FLSS components does not proceed rapidly in the ambient temperature of the system. Stainless steel has durability to the long term corrosion mechanisms and will ensure the structural integrity of the system is maintained. Based upon the ambient temperatures being below 66°C, and as the conductivity of the water represents the quantity of the ionic impurities, its continuous monitoring is the most pertinent and convenient method to verify the FLSS water quality in the tanks. The LCO for the FLSS direct conductivity is a maximum of 10,000 µS/m [Ref-1] and the basis of this is stated in [Ref-45].

The water chemistry sampling and monitoring is discussed in Section 23.11.

**Possible Faults**

The FLSS water is intended to be stored on a long term basis, and this is considered in the LCO for the water conductivity. In the case of a deviation from the water quality specification, the water inventory of the system should be replaced with pure (demineralised) water.

There is a possibility that microorganisms may be transferred into the FLSS from the outside environment and it may cause water quality deterioration. However, it is considered that such water quality deterioration would be very slow [Ref-43][Ref-45].

**23.10.4 Assumptions, Limits and Conditions for Operation**

The LCOs for the FLSS water chemistry have been identified throughout Section 23.10.3 and are summarised in Table 23.10-2. These LCOs are taken from the [Ref-1] and [Ref-45].

**Table 23.10-2 Limits and Conditions Operating Controls for Flooder System for Specific Safety Facility Water Chemistry**

Parameter	Limit value (LCO)	Section Reference
FLSS Direct Conductivity, $\mu\text{S}/\text{m}^{*1*2}$	10,000 (max)	23.10.3

\*1: Conductivity can be converted by  $1 \mu\text{S}/\text{m} = 0.01 \mu\text{S}/\text{cm}$ , \*2: at  $25^\circ\text{C}$

## **23.11 Sampling and Monitoring**

The objective of sampling and monitoring is to obtain the necessary data to verify the performance of the plant for operation and maintenance (i.e. general plant, systems and components). This is achieved by taking measurements of plant process fluids for parameters such as conductivity, pH, hydrogen concentration, DO, chemical impurities and radioactive species. Such measurements are obtained either by using on-line process instruments or by chemical analysis of samples extracted from systems at grab sampling points. These aspects are described in this section.

The Sampling System (SAM) design roles and safety functions are addressed in PCSR Chapter 16: Auxiliary Systems, Section 16.4.3.

The sampling capability of chemistry parameters in design basis faults is discussed in Section 23.11.3.6.

### **23.11.1 Brief Description of the Sampling Systems (SAM)**

The objective of the sampling systems and their procedures is to obtain the necessary chemistry data to verify the plant conditions in normal operations and post DBA environments.

The purposes of sampling and monitoring equipment are:

- to provide the ability to monitor and measure chemical control items established in [Ref-1] for both control and diagnostic parameters. The design of the sampling equipment also facilitates the extraction of samples for analysis in the laboratory,
- to provide the ability to detect the fault, raise an alarm for the abnormal event occurrence, e.g. an electric conductivity meter in the condenser hotwell outlet will alert operators to an increase in water conductivity,
- to be suitable for required portable sampling, and for portable equipment to be used, and
- to provide chemical performance monitoring equipment at the inlet and outlet of the chemistry control systems, i.e. clean-up systems, to determine the performance of the equipment and to carry out operations appropriately.

The UK ABWR SAM design is in line with worldwide conventional and nuclear power industry good practice, and also has some specific features adopted across multiple plant systems. The RGP incorporated in the design is discussed in [Ref-3].

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Each system has a main process line that carries the bulk of the fluid media. A bypass line spur (or extraction point) is introduced into each of the main process lines with an isolation/flow regulating valve. This section of pipe is as short as possible and is made from relatively inert austenitic stainless steel to minimise interaction between the process fluid and pipe materials. For those plant systems where the process line carries high temperature water, a cooler is fitted as close to the isolation valve point as is practicable. The cooler reduces fluid temperature to below 40°C to minimise interaction of the fluid with internal wall surfaces [Ref-3].

To avoid the potential for interaction of some grab samples with air, continuous integrated sampling is adopted for the UK ABWR SAM design. Filter holder cartridges consisting of a 0.45-micron filter together with anion and cation ion exchange membranes are inserted into the sample lines for measurement of radioactive and stable corrosion product and zinc concentrations in CFDW and CUW. The feedwater integrated sampling system processes a relatively large volume of fluid (i.e. 1,000 to 2,000 litres) in order to collect sufficient activity that can be measured using current analytical instruments in the laboratory [Ref-3].

For the reactor water system, the necessity for a large throughput volume is not required and the integrated flow is limited typically to 10-20 litres in order to keep dose rates on the filter holder low. The volume of the fluid to be integrated should be determined by considering the concentration of the particulates to be measured and radioactivity in the fluid [Ref-3].

It is noted that as with other BWRs, there is no sampling manifold in the UK ABWR SAM design. In general, each sampling point has a separate sampling line and instruments. In a few systems, sampling points share the same instruments or grab sampling points [Ref-3].

No specific maintenance activities are required for high pressure lines in the UK ABWR SAM design since all sampling points have separate sampling lines.

A typical UK ABWR SAM system configuration is shown in Figure 23.11-1.

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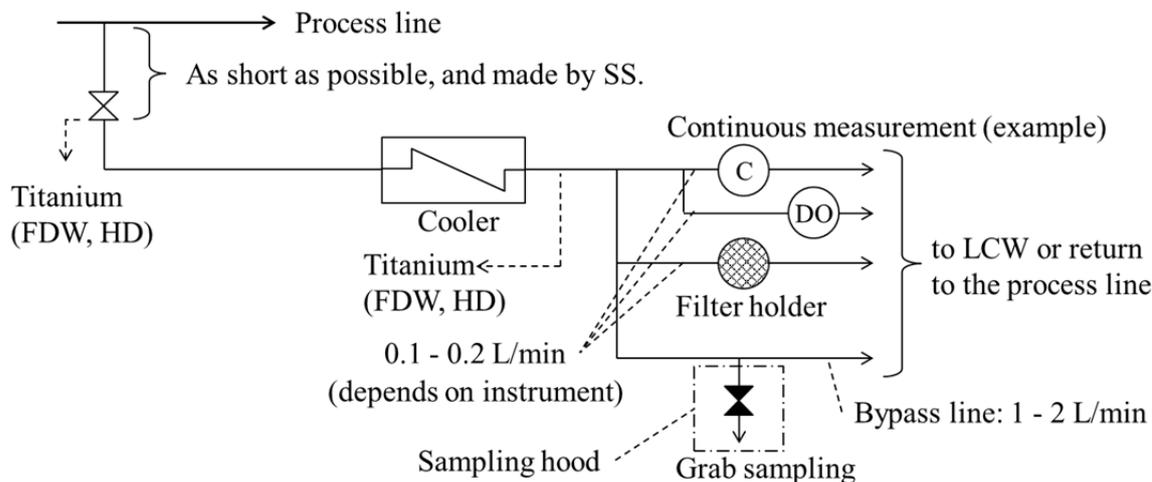


Figure 23.11-1 Typical configuration of a UK ABWR Sampling System [Ref-3]

Table 23.11-1 shows a summary of the UK ABWR design features that consider the industry RGP.

Table 23.11-1: Summary of UK ABWR GDA Sampling and Monitoring Technologies

High-level area of RGP	Specific RGP feature	Additional comments relating to UK ABWR
Sampling methods	On-line sampling	Used for pH, conductivity, temperature, dissolved gases. Potentially viable for effluent recycling.
	Grab sampling	Used for more detailed complex analysis, e.g. total radioactivity, full spectrum chemical analysis, some ionic species and key $\gamma$ -emitting radionuclides.
	Integrated sampling	This is the intended use for continuous integrated measurements of stable and radioactive corrosion product concentration in the relatively low active CFDW.
	Use for low radioactivity lines (Continuous)	Used for soluble/insoluble corrosion product concentration measurement and injected DZO concentration.

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**Table 23.11-1: Summary of UK ABWR GDA Sampling and Monitoring Technologies**

High-level area of RGP	Specific RGP feature	Additional comments relating to UK ABWR
	Integrated sampling	Continuous integrated sampling for high radioactivity lines is suitable due to technical accuracy of the measurement. The dose exposure can be managed by regular filter replacement before dose fields become high. It is noted that the operational procedures will be determined by the plant utility.
	Avoid for high radioactivity lines (Periodic)	Used for soluble/insoluble corrosion product concentration measurement and injected DZO concentration.
Interaction of reactive species with sample lines	Minimise pipe length	Pipe lengths (fabricated from austenitic stainless steel) between the process line and first isolation valve are reduced to minimise the potential for fluid/wall interactions.
	Use cooler to reduce fluid temperature	The post-cooler fluid temperature is lowered to reduce the rate of downstream fluid/wall interactions.
	Use inert (non-reactive) pipe material	To allow flexibility in combination with cooler positioning, ultra-inert titanium pipe is used in some SAM systems. This minimises fluid/wall adsorption/desorption characteristics even for high temperature fluid.
Interactions between samples and the air environment	Avoid the use of grab sampling where environmental contact of air with fluid is likely to affect analysis results	pH, conductivity, DO, DH and non-radioactive metal impurities (incl. Zn) are measured in-line (not exposed to the air). Radioactive species are measured by taking grab samples. They are not affected by exposure to the air significantly.
Sample flow conditions	Pipe distance sufficient for mixing	The total distance of pipework between the injection point and the sampling/monitoring point is sufficiently large to allow complete fluid mixing.

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**Table 23.11-1: Summary of UK ABWR GDA Sampling and Monitoring Technologies**

High-level area of RGP	Specific RGP feature	Additional comments relating to UK ABWR
	Turbulent flow conditions	The bypass line flow rate is maintained at a regular sample flowrate to prevent turbulence.
	Continuous and constant flow conditions	Continuous and constant flow conditions are maintained in the main bypass line and continuous monitoring sample lines. This ensures good reproducibility in measurements.
	Avoidance of dead legs and stagnant regions	Grab sample lines contain short lengths of dead leg pipework upstream of the main tapping valve, where there is no regular flow. The UK ABWR procedure is to flush this section of pipework prior to taking samples.
	Sampling points on sides of horizontal pipes	Correct sampling point position in all SAM systems avoids the potential to collect non-representative particulate samples.
	Nozzle insertion into the process flow line	The UK ABWR design for GDA considers the insertion of a nozzle into the process line as RGP. This is because it can avoid the potential for break-off whilst still obtaining a representative particulate fluid sample free from surface/pipe wall effects.
Miscellaneous design features	Manifolds to collect different sample lines	Although the use of common collection manifolds is regarded as RGP for pressurised water reactors, the larger scale of BWRs combined with differences in radioactivity content of different systems results in the UK ABWR SAM systems being single purpose lines.
	Pressure reduction measured	The UK ABWR SAM system lines will include various pressure reduction measures (e.g. valves).

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### **23.11.2 Chemistry Functions of the Sampling Systems (SAM)**

Since the role of the sampling and monitoring systems is to provide operators with the correct information on the plant chemistry conditions, the chemistry safety functions are focused on the system reliability and ability to provide the correct data.

The reactor chemistry controls for the key systems have been described in Sections 23.4 to 23.10. The sampling and monitoring for each of the systems is aligned to those requirements. Therefore, the sampling and monitoring is aligned to operate the plant within the LCOs, i.e. in accordance with [Ref-1], and in accordance with the sampling philosophy [Ref-11] to ensure that it is suitable, reliable and representative. This requirement is reflected in the sampling and monitoring chemistry related top claim and claim stated in Table 23.11-2, and which are derived from the safety objectives in Section 23.3. The arguments and evidence to support the claims is provided in the following sub-sections.

**Table 23.11-2 Reactor Chemistry Safety Claims for Sampling Systems for the UK ABWR**

<b>Main Nuclear Safety Objective Issues for Chemistry Control</b>	<b>Top Claim</b>	<b>Claim</b>	<b>PCSR Chapter 23 Section</b>	<b>Other Related PCSR Chapter</b>
Material degradation, leading to structural degradation of SSCs	RC SC13: The UK ABWR sampling and monitoring systems will ensure that the plant is operated within the limits and conditions.	RC SC13.1: Chemistry and radiochemistry control parameters will be sampled and monitored in accordance with the sampling philosophy.	23.11.3	16

The UK ABWR SAM are used during normal operations and transient conditions and are designed to meet the SFCs that are addressed in PCSR Chapter 16, Section 16.4.3 and its Appendix A.

The sampling capability for chemistry related parameters in design basis faults are addressed in [Ref-49], and the expectations of the systems that support the accident management requirements are summarised in Section 23.11.3.6. For further information on the UK ABWR accident monitoring, please see PCSR Chapter 14: Control and Instrumentation, where the Severe Accident C&I (SA C&I) System safety functions and interfaces are described. The SA C&I system is required to monitor the plant parameters which, in the event of a severe accident, are necessary to understand the accident conditions and facilitate actions to mitigate the consequences of the accident. The SA C&I is required to monitor the accident status of the core and spent fuel pool cooling, containment of radioactivity and radioactive discharges.

**23.11.3 Chemistry Control by the Sampling Systems**

Due to design changes to the UK ABWR (compared with the J-ABWR reference design), further consideration is given to chemistry and materials issues in this section.

### 23.11.3.1 Consideration of Chemistry Changes

Due to the change in reactor water chemistry (NWC to HWC+OLNC) from the reference J-ABWR design, hydrogen ( $H_2$ ) monitors will be added to the CUW and CFDW SAM systems and an ECP sensor will be added to the CUW system in the UK ABWR design. Specifically:

- **Hydrogen ( $H_2$ ) measurement in Feedwater** – The addition of the  $H_2$  meter in the feedwater line will strengthen the confidence in the amount of  $H_2$  injected. Control of  $H_2$  injection (including interlock) will be carried out by the  $H_2$  injection rate as the conventional method.
- **$H_2$  measurement in Reactor Water** – The  $H_2$  concentration in reactor water will be measured using a dissolved hydrogen (DH) meter. Since UK ABWR will apply OLNC, platinum will deposit on the sampling line for reactor water in the CUW. Therefore, DH and DO will recombine in the sampling line and their concentration will decrease. However, when the molar ratio of  $H_2/O_2$  is  $>2$  in the reactor water, residual DH will remain in the sampled water. Otherwise, the DH concentration will approach zero. The LCO for the reactor water  $H_2/O_2$  molar ratio can be judged by the DH measurement.
- **ECP monitor in Reactor Water** – An ECP sensor will be installed in the CUW line to monitor the ECP in the reactor water. By adding the ECP sensor, there will be no knock-on effect on the other systems because there will be no effluent discharges and no interaction between the sensor and the sample water.

The concentration of zinc (Zn) will be measured in both feedwater and reactor water using continuous integrated sampling using filter holders. The key points are:

- **Zn measurement in Feedwater (Japanese Experience)** – For the UK ABWR, titanium piping will be used for the high temperature sections (when process water is  $>200^\circ C$ ) to minimise interaction between the water and the piping inner surface.
- **Zn measurement in Reactor Water** – The temperature of the sample for the reactor water (CUW after heat exchangers) is around  $60^\circ C$ . At this temperature, the interaction with piping surfaces is very low. Therefore, the use of stainless steel is adequate to take representative samples for Zn and corrosion product measurements.

### 23.11.3.2 Consideration of Material Changes

The main material changes in UK ABWR design compared with the reference plant (J-ABWR) are:

- CUW high temperature section (replaced carbon steel with austenitic stainless steel).

- Feedwater (replaced carbon steel with carbon steel containing chromium >0.1 %, and the Class 1 feedwater piping will be changed from carbon steel to low alloy steel. However, this will have no impact because there is no sampling point in the section.

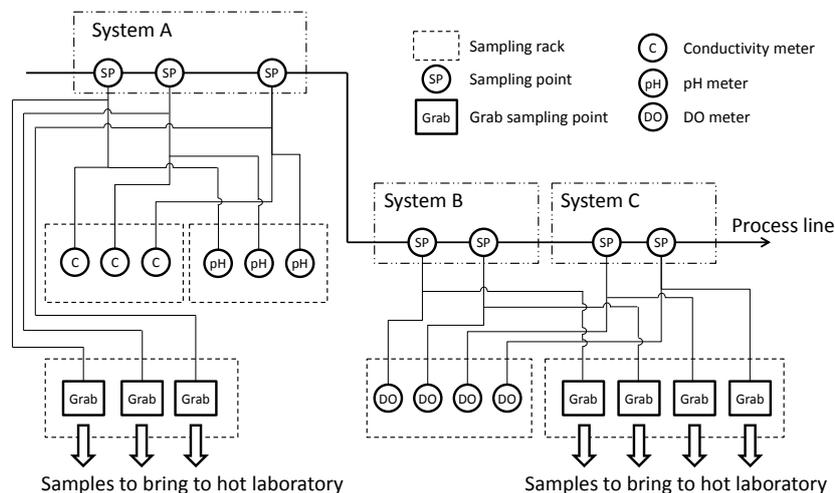
There are no impacts on sampling due to the material changes because the material of the sampling lines has not been changed from the reference design.

**23.11.3.3 Consideration of Operator Safety**

Operator safety measures consider the protection from high temperature, high pressure, external radiation exposure and radioactive material contamination. These aspects have been considered in the UK ABWR SAM design and are addressed in [Ref-3].

A decay coil is not necessary for the UK ABWR because N-16 decays to a negligible level when the reactor water reaches to the sampling point. More detail is described in [Ref-3].

In the UK ABWR, multi-sampling lines in each group (e.g. CUW) are routed to one sampling room to collect multi grab samples as illustrated as an example in Figure 23.11-2. This arrangement can make plant workers task easier and reduce the potential exposure time. Further detail is provided in [Ref-3].



**Figure 23.11-2: Schematic sampling arrangement for three separate systems**

The radiation monitoring of each sample line is not useful for the radiation protection in the UK ABWR sampling arrangements. In the sampling room, multi-sampling lines are routed. A workers dose is, therefore, the total of exposure from each line. In the UK ABWR, a major source term in the

reactor water sample arises from the CPs and APs, whilst FPs, which have a potential of rapid increase following a fuel failure tend to migrate to the OG system. The time variation of the CPs (or APs) is much slower than that of the FPs. Therefore, an increase of the activity will be identified long before the activity reaches unacceptable levels. Fuel failures are detected when FPs migrate to the OG system. Therefore, the risk of unnecessary exposure during sampling and monitoring is reasonably reduced by the current design. Further detail is provided in [Ref-3].

#### **23.11.3.4 Consideration of Sampling and Monitoring Effluent**

It is the baseline for the generic design consideration to return the sampling effluent to the original process piping and to reuse the effluent as the process fluid. This approach reduces the liquid waste discharged to the Radwaste Systems and can also reduce the solid waste such as spent filters and resins, through the plant lifecycle. From the safety perspective, a reduction of worker dose would be expected in proportion to a reduction in the waste treatment processing (see also PCSR Chapter 18: Radioactive Waste Management and Section 23.12).

However, not all effluent can be returned to the process line. There are systems where the effluent conditions such as pressure, temperature, chemical properties etc. are not compatible with reuse by re-injection back into the original process piping. In addition, it may not be always practicable to reuse the sampling fluid in the original process piping if the resultant quantity of waste is reduced to ALARP.

Therefore, the process fluids that are extracted from the main system lines into the SAM system are typically reused within the UK ABWR plant. The effluent from sampling will be returned to the process piping where it is originally extracted. However, if the conditions of the effluent do not permit reuse in the original process piping, the effluent will be discharged to the appropriate Radwaste System, i.e. the LCW or High Chemical impurities Waste (HCW) Treatment System (see Section 23.12). Further detail on the handling of the sampling and monitoring effluent from the system streams (such as CUW, CFDW, RHR, and HD), and a high-level summary of the effluent treatment routes is provided in [Ref-3].

#### **23.11.3.5 Main Sampling and Monitoring Schedule**

The sampling schedule for the UK ABWR main SAM systems is provided in the Appendix B: Sampling Schedule in [Ref-3].

**23.11.3.6 Consideration of Sampling Capability in Design Basis Faults**

Design Basis (DB) Faults are faults whose potential unmitigated consequences would be above the Basic Safety Level (BSL) and whose initiating event frequency is greater than once in one-hundred thousand years ( $10^{-5}$ /year). Because such consequences are unacceptable, the safety systems provided in the design of the UK ABWR successfully control all transients and accidents that make up the design basis in all operating modes, ensuring these consequences are prevented or reduced. The possible faults are described in PCSR Chapter 24: Design Basis Analysis and Chapter 26: Beyond Design Basis and Severe Accident (SA) Analysis.

In a design basis fault, it is not necessary to sample water or gas for chemical and radiochemical species analysis before stable conditions have been established, and there are no formal claims made for this in the UK ABWR safety case, and no LCOs are set in GDA. After stable conditions have been established, chemistry related parameters that are to be used for the assessment of the radiation exposure and the longer term integrity of the structural material and fuel will be sampled. These can include radiochemistry and impurity concentrations. To support this, the following systems and their safety functional claims in abnormal conditions are briefly described below, and are further addressed in the TR on Sampling Capability of Chemistry-related Parameters in Design Basis Faults [Ref-49]. The Sampling Systems are further described in PCSR Chapter 16, Section 16.4.3, and the SA C&I System in PCSR Chapter 14, Section 14.6.6.

**(1) SAM**

As previously discussed, the SAM are designed to safely collect principle fluid process streams to directly measure chemistry parameters in normal operational conditions and transient conditions. During a design basis reactor fault or non-reactor fault condition, if available, the SAM may provide supplemental information for the operator to check the plant condition during the accident as necessary, and so forms a part of the SAM SFC 5-4.1 (PCSR Chapter 14 and [Ref-49]).

After cold shutdown, and stable conditions have been achieved during the short and medium term, the SAMS may be available for the long term post-accident sampling, which can be used to maintain and monitor the safety of the conditions, and to provide chemistry data that may support the decision making for the recovery actions.

(2) Containment Radiation monitor (CRM)

The CRM is a part of the Process Radiation Monitoring System (PRM), and performs accident monitoring functions to ensure the UK ABWR safety case is met. The CRM continuously monitors the radiation level in the PCV during a DBA to provide signals to the Safety Auxiliary Control System (SACS). The measurements are necessary parameters in the accident management requirements. The CRM forms a part of the SACS SFC 5-4.1 requirements (PCSR Chapter 14 and [Ref-49]).

(3) Containment Atmospheric Monitoring System (CAMS)

The Containment Atmospheric Monitoring System (CAMS) performs accident monitoring functions to ensure the UK ABWR safety case is met. The CAMS continuously monitors oxygen and hydrogen concentration in the PCV during DBA to provide signals to the SACS. The measurements are necessary parameters in the accident management requirements. It should be noted that the measurements do not demand any manual operations to be carried out, due to the passive treatment of the flammable gas. Therefore, although CAMS forms a part (supporting function only) of the UK SACS SFC 5-4.1 requirements (PCSR Chapter 14 and [Ref-49]).

(4) Off-gas System Post-recombination Hydrogen Monitor (OG PO HM)

The OG PO HM generates the actuation for the OG isolation valves and provides is to the SACS in order to prevent the release of the radioactive off-gas due to flammable faults. The OG PO HM forms a part of the OG SFC 4-11.3 (PCSR Chapter 18) and SACS SFC 4-8.1 (PCSR Chapter 14 and [Ref-49]).

(5) CIPS

The CIPS is based upon conductivity sensors and meters linked to an automatic interlock system which can close the HPCP downstream of the CF/CD to prevent contaminated condensate being fed forward. The automatic operation of the CIPS or its failure will cause a loss of feedwater fault. The interlock will ultimately result in a reactor scram. However, because the unmitigated radiological consequences are not severe considering the timescale of the phenomena following a condenser tube leak, and plant behaviour where an additional interlock stops the HPCPs in the event of a condenser

tube leak is bounded by a loss of all feedwater fault. Therefore, a condenser tube leak is not included in the fault schedule as a design basis event.

#### **23.11.4 Assumptions, Limits and Conditions for Operation**

The key references for detailing the reactor chemistry parameters that are to be sampled and monitored, and are the guidance for the future licensee for the sampling systems design post GDA are:

- Water Quality Specification [Ref-1],
- TR on Design Justification in Chemistry Aspect for Primary Water Systems [Ref-3], and
- TR on Sampling and Monitoring Philosophy for Chemical and Radiochemical Parameters [Ref-11]

There are no chemistry related LCOs for ‘sampling systems’ in the GDA. However, the sampling and monitoring methods, instruments and equipment used by a future licensee will be detailed in operating instructions during the site specific stage, and will be designed in accordance with the sampling philosophy and capable of meeting the chemistry parameter analysis requirements.

## **23.12 Radioactive Waste Management – Impact from System Chemistry Regimes**

The UK ABWR has facilities to manage the radioactive waste that is generated as a result of the plant operations and decommissioning. This section describes the linkages between the radioactive waste streams safety functions and claims and the operational chemistry management controls that have been described in Sections 23.4 to 23.10.

### **23.12.1 Brief Description of the Radioactive Waste Management**

As a result of the UK ABWR operation and final decommissioning, quantities of radioactive waste forms will be produced. The UK ABWR design and operations will minimise the creation and discharges of the radioactive waste SFAIRP, and ensure the optimal disposal routes are selected.

The Radioactive Waste (Radwaste) system designs, safety functions and schematic figures are addressed in detail in PCSR Chapter 18: Radioactive Waste Management. Note that for GDA the majority of the Radwaste systems discussed, including the Liquid Waste Management Systems (LWMS) and Wet-Solid Waste Management Systems (SWMS) are at the concept design phase, and will be finalised for the UK ABWR design during the site specific stage. The Radwaste system can be sub-divided into the LWMS, the SWMS, and the OG.

The radioactive liquid wastes generated in the controlled areas of the UK ABWR are collected and transferred to collection tanks in the Radwaste building for treatment by the LWMS. The LWMS comprises several sub-systems so that the liquid wastes for various sources can be segregated and processed separately. These sub-systems are:

- Low Chemical impurities Waste (LCW) treatment system,
- High Chemical impurities Waste (HCW) treatment system,
- Spent Resin and Sludge (SS) system, and
- Concentrated Waste (CONW) system.

Wet solid waste generated in the LWMS is collected in tanks prior to transfer to the Solid Waste Management System (SWMS).

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Solid wastes are categorised as wet solid wastes (e.g. spent ion exchange resin), or dry solid wastes (e.g. High Efficiency Particulate Air Filters (HEPA), protective clothing). Low level waste and intermediate level waste are processed by the SWMS. The SWMS controls, collects, processes and stores the wet and dry solid Radwaste prior to shipment or for onsite interim storage. It comprises several sub-systems which are:

- Wet-solid Intermediate Level Waste Processing System (WILW),
- Wet-solid Low Level Waste Processing System (WLLW),
- Intermediate Level Waste Store (ILWS),
- Solid Waste Processing,
- Transportation on and off-site, and
- High Level Waste (HLW) Decay Store.

The gaseous radioactive waste systems controls and processes the gaseous radioactive species generated during normal operation. The gaseous management waste systems comprise of:

- Off-gas system (OG),
- Heating Ventilating and Air Conditioning systems (HVAC), and
- Tank Vent Treatment System (TVTS).

The OG is a key component of the UK ABWR design, and the OG system reduces the radiological release to the environment during normal operations by performing the primary functions of maintaining the main condenser vacuum by extracting air and non-condensable gases, providing abatement for minimisation of the gaseous radioactive species prior to atmospheric discharge, and recombining radiolytic hydrogen and oxygen generated in the reactor.

After passing through the recombiner the off-gas is cooled and dried and sent to the OG charcoal absorbers to reduce short-lived radionuclides activity by delaying their release and allowing adequate decay. Such radionuclides include xenon (Xe), krypton (Kr) and iodine (I). Furthermore, particulates are removed by the OG filter before the off-gas is discharged to the environment. The OG also transfers the off-gas from the Gland Steam Exhauster to the stack. The system performs the required functions during all operating modes based on the established environmental design conditions and requirements.

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The OG recombination of hydrogen and oxygen radiolytic gases generated in the reactor coolant prevents the risk of a flammable mixture occurring. The OG recombines the hydrogen and oxygen diluted with steam from the SJAE by passing it over a catalyst bed in a recombiner. Further information on the chemistry control for control of the radiolytic gases is addressed in Section 23.4.6.

**23.12.2 Chemistry Functions of the Radioactive Waste Management**

The Radwaste systems safety function claims (SFC) are addressed in PCSR Chapter 18.

The reactor coolant chemistry has a direct impact on the radioactivity levels, and hence on the Radwaste Management Systems. The linked Radwaste Systems SFCs to the chemistry safety case are shown in Table 23.12-1.

**Table 23.12-1 Radwaste Systems SFC Linked to Chemistry Safety Case**

<b>PCSR Chapter 18- Radwaste SFC</b>	<b>PCSR Chapter 23 Section Link</b>	<b>Linked RC Claim*</b>
LWMS SFC 4-12.3: The LWMS facilities shall be designed to ensure that doses to both the workers and the public from normal operation of the UK ABWR LWMS are ALARP.	23.12.3.1	RC SC5, RC SC6, RC SC7
LWMS SFC 5-9.1: The LCW and HCW systems treated effluent shall meet the re-use criteria specified in the Water Quality Specification [Ref-1].	23.12.3.1	RC SC16
OG SFC 4-7.1: The OG minimises the dose to worker during normal operation conditions.	23.12.3.3	RC SC5, RC SC7
OG SFC 4-11.1: The OG minimises the release of radioactivity to the environment during the start-up, power and shutdown operations.	23.12.3.3	RC SC6
OG SFC 4-11.2: The OG reduces the risk of hydrogen combustion arising from the reaction of radiolytic hydrogen produced in the reactor.	23.12.3.3, 23.4.6	RC SC4

Note: RC SC4, RC SC5, RC SC6, and RC SC7 are in Table 23.4-1, and RC SC16 is in Table 23.8-1.

### **23.12.3 Chemistry Control for the Radioactive Waste Management**

The design of the UK ABWR and the associated facilities has been developed to minimise the volumes of radioactive wastes. A key contributor to radioactive waste generation is the reactor chemistry regime, the associated processes and material selection that have been described in Sections 23.4 – 23.10. These have taken into account the minimisation of radioactive waste SFAIRP [Ref-33][Ref-34][Ref-35].

The following section presents the chemistry management linkages for the liquid, solid and gaseous waste streams.

#### **23.12.3.1 Chemistry Aspects for Liquid Radioactive Waste Processing**

##### **Recycling of Waste**

The UK ABWR radioactive waste management system designs and operations allow re-cycling of as much of the liquid effluent as possible. This includes the effluent treatment of the water in the steam circuit, the SFP, S/P to alleviate the need to make liquid discharges from these systems. The majority of the water is recycled within each of the systems. In some instances, (e.g. after refuelling), water may be sent to the LCW for further treatment. This is then recycled back to the CST for re-use (see also Section 23.8.3).

Liquid effluent from the chemistry sampling and monitoring will be recycled back to the process line, or discharged to the LCW or HCW.

The LCW and HCW systems are functionally capable of adequately treating the UK ABWR systems liquid effluent and, in the unlikely event of the reuse criteria not being met, provide the ability to:

- Retreat effluent for both the HCW and LCW systems.
- Provide additional treatment of LCW effluent via the HCW system.

The recycled water is transferred from the LCW and HCW sample tanks to the CST prior to reuse on the plant. Purified water from the MUWP is also added to the CSTs as necessary but, to avoid overfilling of the CST, priority is for using the water from the LCW over the purified make-up water. Therefore, the LCW and HCW treated effluent reuse criteria must meet the CST water quality specification as stated in [Ref-1], and described in Section 23.8. The demonstration that the LWMS

meets the CST water quality requirements is addressed in the ALARP assessment for the liquid waste processing which is referenced in PCSR Chapter 18.

The processing means that the radioactivity and chemical impurities in discharges are minimised through the use of filtration, ion exchange resins, evaporation and other mechanisms. The residual waste that cannot be reused will have been minimised by the processing and is further treated as waste and then stored or disposed of appropriately. Provisions for sampling at important process points are included in the design of the LWMS. Protection against accidental discharge is provided by detection and alarm of abnormal conditions and by administrative controls. Therefore, the impact on public dose by re-cycling is minimised to ALARP. The operation of these systems is further described in Chapter 18.

**Possible Faults**

Associated faults and hazards with the Radwaste system are addressed in PCSR Chapter 18.

**23.12.3.2 Chemistry Aspects for Solid Radioactive Waste Processing**

The RCS and associated systems chemistry clean-up systems will use ion exchange resins as non-regenerative and replace them when required.

By comparing the amount of waste produced if chemical regeneration has not been applied, to the amount of waste produced if chemical regeneration has been applied, lower waste production found in the case without chemical regeneration [Ref-3]. However, there will be an impact due to the increased spent resins waste that will be collected in tanks prior to transfer to the SWMS where it is processed as Wet-solid ILW or Wet-solid LLW as appropriate.

The RCS and associated systems materials selection and chemistry management (described in Sections 23.4 to 23.10) will minimise the impact of particulates such as corrosion products in the system, which will contribute to the reduction in solid waste to be handled by the SWMS.

**Possible Faults**

Associated faults and hazards with the Radwaste system are addressed in PCSR Chapter 18.

**23.12.3.3 Chemistry Aspects for Gaseous Waste Processing**

**Dose to Workers**

The reactor chemistry regime has been optimised to ensure that the source term is minimised during normal operational modes. A particular chemistry regime aspect is the HWC+OLNC regime which ensures the protection of the structural integrity for the SSCs in the reactor, but also minimises the N-16 source term during power operation, as detailed in Section 23.4.5. Additionally, the water chemistry contributes to reducing the risk of fuel failures that could impact on the source term and the processing through the OG. During normal power operation, it is not necessary for workers to enter the rooms containing the OG equipment, which are mainly categorised as R4, and so entry is not permitted. The rooms surrounding the OG equipment are shielded to ensure that dose rates are minimised. In an outage, planned maintenance of the OG is required, but since the reactor is not at power the N-16 source term impact to dose rates quickly becomes negligible due to its short half-life, and so access to the OG rooms is permitted. The worker dose aspects are also discussed in PCSR Chapter 18 and Chapter 20: Radiation Protection.

**Radiolytic Gases Control in OG**

Radiolytic gases are produced as a result of the reactor operation as discussed in Section 23.4.6. The hydrogen concentration from the OG input to the OG Recombiner during normal operation presents a deflagration / detonation event risk, and as such suitable hydrogen management techniques are included in the OG design. Dilution by steam using the SJAE reduces the risk of a hydrogen explosion by increasing the LFL of hydrogen up to the OG Recombiners. The OG Recombiners convert hydrogen and oxygen into water vapour within the OG process stream during normal operation. Degraded performance or failure of the OG Recombiner is mitigated directly by having redundant OG Recombiners in parallel. Additionally, the design reduces the sources of ignition that could cause hydrogen combustion within the OG process stream.

Operating experience from J-ABWRs has identified that increased hydrogen concentration can be experienced in the OG system as a result of degradation of the catalyst in the recombiner caused by an inflow of volatile organic silicide (siloxane). The siloxane source was in the composition of a turbine seal material. Iron oxide, silicon, phosphorus, heavy metal (zinc, lead), sulphide, halide-chlorine or iodine aerosols have also been identified as detrimental substances to the catalyst. Therefore, the UK ABWR design has minimised the use of these detrimental substances as referenced in [Ref-40].

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Hydrogen detection is installed in the OG after the 2nd stage SJAE, and after the OG Cooler Condenser in order to detect abnormal hydrogen concentrations that could result from degraded performance in the SJAE dilution and OG Recombiners. Further detail is provided in PCSR Chapter 18. PCSR Chapter 18, Section 18.7.2, also links to PCSR Chapter 7: Internal Hazards regarding explosion hazards.

**Dose to the Public**

Operating Chemistry does not reduce the FP and ActP release for the PST, but the Operating Chemistry such as OLN, Zinc injection and impurity levels, notably copper are controlled to minimise enhancing fuel failure (Section 23.4.4), which would impact on the gaseous discharges. Fuel failures are detected by monitoring the OG for FPs and noble gases.

During normal operations, the OG ensures that the release of radioactive gases and particulates into the atmosphere is minimised and controlled by delaying and filtering the off-gas waste process stream to adequately decay short lived radioactive isotopes and filter out particulate matter. The OG system will process all the non-condensable gas that is extracted from the condenser hotwell during normal power operation. In terms of radionuclide behaviour, this will include xenon, krypton and volatile iodine isotopes, H-3, Ar-41, C-14, N-13 and in the initial OG system stages N-16, before it decays. Any iodine that is not removed in the OG condenser and OG cooler condenser will be trapped on the first charcoal hold-up bed, and then undergo decay. A significant contribution to the radioactivity is from the noble gases of xenon and krypton. The radioactivity will be mostly on the first of four charcoal beds, with successively lower proportions on the remaining three beds. The noble gas adsorption is a temporary process, having a characteristic delay time related to the molecular properties of the noble gas, flowrate and temperature. The OG charcoal absorber is required to retain xenon and krypton isotopes for minimum periods of 30 days and 40 hours, respectively, to reduce radioactivity release to acceptable levels. It is assumed that gaseous C-14 and Ar-41 will be released to the environment without appreciable decay [Ref-29]. Implicitly, the OG also reduces emissions from tritium and radioisotopes of oxygen, through recycling coolant water and recombining hydrogen and oxygen into water, which is then returned to the reactor coolant circuit as previously discussed (above, and Section 23.4.36).

The UK ABWR OG charcoal absorber design provides a conservative margin to accommodate deviations in off-gas conditions (e.g. temperature, pressure, and humidity).

The chemistry of iodine in accidents is addressed in PCSR Chapter 26 and the chemistry of iodine in normal operation is detailed in [Ref-36]. The minimisation of the discharges of iodine to the environment in normal operation is enabled by the UK ABWR OG system design that addresses the speciation and volatility impact. Furthermore, the iodine in the discharges during normal operation is orders of magnitude lower than the other important nuclides from the PST, except Xe-133. Therefore the noble gases dominate the activity in the OG system. This is because any carry-over of iodine from the RCS and associated systems is retained in the main condenser. Carry-over from the main condenser is retained in the OG Condenser and cooler condenser.

The off-gas monitor and the stack monitor measure the level of radioactivity in the off-gas that is present and discharged.

The functions of the HVAC system that are of relevance to the management of gaseous radioactive wastes are also addressed in PCSR Chapter 18.

#### **Possible Faults**

Associated faults and hazards with the Radwaste systems are addressed in PCSR Chapter 18.

#### **23.12.4 Assumptions, Limits and Conditions for Operation**

The key references for the justification of the impact that the chemistry controls (regimes or systems) described in Sections 23.4 to 23.11 have on the radioactive waste discharges and the design of the Radwaste systems are:

- Water Quality Specification [Ref-1],
- TR on Design Justification in Chemistry Aspect for Primary Water Systems [Ref-3],
- TR on Reduction of Source Terms by Operating Practices [Ref-34], and
- TR on Reduction of Source Terms by Operating Chemistry [Ref-35].

The CST LCO chemistry control parameters listed in Section 23.8.4 Table 23.8-2, are linked to LWMS SFC 5-9.1, which requires that the treated effluent will be sampled, and only when it meets the CST water quality specification will it be recycled to the CST. Therefore, the LWMS treated effluent must meet the CST chemistry requirements. The claim and arguments for the treated effluent (LWMS SFC 5-9.1) are addressed in PCSR Chapter 18, Section 18.5.3.1.

The SFCs for all of the Radwaste systems are in PCSR Chapter 18.

### **23.13 Summary of ALARP Justification**

This section presents a high level overview of how the ALARP principle has been applied for the systems covered by Chapter 23, and how this contributes to the overall ALARP argument for the UK ABWR. Chapter 28: ALARP Evaluation, presents an overview of how the UK ABWR design has evolved, and how this evolution contributes to the overall ALARP case. The approach to ALARP during GDA is further described in the GDA ALARP Methodology [Ref-50].

The chemistry safety case for the UK ABWR has been presented and demonstrates that the chemistry regimes and controls for the various systems that have been described ensure the structural integrity of the SSCs, fuel integrity, that the radiological dose to workers and the public is minimised, and that hazardous gas products generated through water radiolysis are adequately managed in all modes of operation.

The RCS and associated systems and key auxiliary systems reactor chemistry safety case is presented as a cross-cutting topic for the UK ABWR design. The reactor chemistry safety case is, and needs to be, a holistic balance of the cross cutting factors, that include the engineering and mechanical design, the materials selection, management of the source term, handling of the radioactive products and wastes, and operational considerations for generation. LCOs and appropriate linkages to the other PCSR chapters have been made to show the extent of the safety case requirements.

The water chemistry control of the RCS and associated systems is an example of a risk reduction method for the plant design, and the water chemistry control regime for the UK ABWR has therefore been determined appropriately as a result of optioneering to ensure that all relevant risks are ALARP. In the case of RCS and associated systems chemistry detailed ALARP workshops have been held covering all modes of operation, and with multidiscipline teams to ensure that a holistic approach for the objectives and the views of the various disciplines that are impacted by the chemistry regimes have been considered. This has achieved the optimised balance and ensured that the risks have been minimised to ALARP [Ref-51][Ref-52].

The development of the options has involved cross cutting of disciplines, review of existing operating regimes across the industry, how the chemistry regime is applied, expected future developments, and the review and learning from relevant good practice. Relevant good practice is defined as those standards for controlling risk that have been judged and recognised as satisfying the

law, and when applied to a particular relevant case, in an appropriate manner. This includes a comparison with international and national practices.

Section 23.4 demonstrates the holistic approach that has been considered in the ALARP assessment for the RCS and associated systems chemistry management for all modes of the UK ABWR operation including commissioning. It demonstrates that the risks associated with the plant operation have been reduced and are ALARP. The main risks have been mitigated by ensuring good water chemistry control, and operational practices, and the design materials choices.

The four main safety objective issues to which the UK ABWR reactor chemistry management will positively contribute for mitigation have been addressed. These are summarised as:

- material degradation, leading to structural degradation of SSCs,
- material degradation, leading to fuel degradation,
- radionuclide inventory and release, and radiological dose to the public and workers, and
- hazardous and flammable gas products generated through radiolysis.

This has been done by demonstrating the good practice that has been adopted for the coolant chemistry to reduce the risks associated with these safety objectives to ALARP.

The ALARP reactor chemistry regime for normal power operation the UK ABWR is HWC+OLNC+DZO, and has been based on the balance of risk in reducing the onset and development of SCC versus the increase in worker dose during normal operation and during outages. The following good practice has been adopted for coolant chemistry to mitigate the risks and is based on OPEX:

- Adoption of hydrogen water chemistry to mitigate against SCC,
- Use of noble metal injection. This allows lower hydrogen concentrations to be employed and hence reduces N-16 activity. On-line noble metal addition has currently been adopted on BWRs,
- Use of zinc injection. This reduces the deposition of radioactivity, e.g. Co-60,
- Appropriate Fe control. This is linked to oxygen injection and feedwater line materials specification, and controls the quantity of corrosion products in the coolant, and

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- Commissioning chemistry is currently under review. Growth of an appropriate oxide film prior to fuel loading will be important in reducing worker doses during operation.

The regime has been holistically optimised to address the safety objectives with the other mitigations that are materials selection and operating practices.

The preferred option has been developed for the RCS and associated systems chemistry for each mode of operation to demonstrate that the risks are reduced to ALARP during shutdown and start-up. Although commissioning plans will be further developed in the site specific stage, the focus on achieving the structural integrity protection and minimisation of the source term impacts, both during the commissioning and for the future operation are considered. The system cleanliness during the phases with and without fuel loading and temperature raising, and operator practices and timings for starting the reactor chemistry regime have been justified for the generic UK ABWR design.

For all normal operational modes, it has been presented that the radiological dose exposure to workers and the public from the source term has been minimised SFAIRP by the materials selection, the operational chemistry and the operating practices that will be employed for all modes of the operation. Supporting documentation has been provided on source terms, which covers fission products, corrosion products and activation products. In terms of source term management and minimisation the reactor coolant chemistry regime will implement DZO injection, and implementing the iron control for the system will also minimise the dose rates in the system. The implementation of the HWC + OLNC is for the mitigation of SCC risk of stainless steel and nickel based alloys, and reduces the ECP of the system to a level where SCC will be suppressed. The implementation of OLNC means that hydrogen can be injected at a lower level that ensures the structural integrity is managed but that the transfer of N-16 source term to the steam is minimised. The materials selection choices for the systems and the components that will be exposed to the reactor coolant in the UK ABWR have been considered holistically for the structural integrity issues and the source term reduction to maintain the risk and radiological exposure levels ALARP, and to ensure that the overall choice is the ALARP choice for the plant. The materials have been selected for resistance to corrosion mechanisms such as SCC and FAC, and also to minimise the amount of activated corrosion products which are the sources of radiation during maintenance after shutdown. The source term has been reduced to ALARP through the removal of and reduction of cobalt from component materials.

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In normal operation, Iodine-131 (I-131) is a significant FP/radionuclide during reactor refuelling if there has been fuel damage during the previous fuel cycle and release of FPs into the reactor water. To mitigate the risk for the increased worker dose during the RPV head removal for outage the I-131 LCO limit has been determined.

The chosen reactor chemistry regimes for all modes of operation for the UK ABWR have reduced the associated risks SFAIRP. The ALARP assessment for the regimes has considered world best practice and OPEX, and a detailed assessment has been completed within the GDA process. The associated clean-up systems (CUW, FD, CF/CD), and injection systems (HOIS, NMIS, ZNIS and OI) that allow the RCS and associated systems chemistry to be managed have been described and justified in terms of their chemistry functions.

Other system chemistry regimes and controls have been addressed in this chapter, and have been linked to the relevant other PCSR chapters where the system design engineering and mechanical aspects, safety functions and safety categorisation and classification, and ALARP justifications are described. The discussion on ALARP in respect of the chemistry control is generally described in this chapter and the references that have been used. The chemistry related LCOs that apply to the individual systems described in this chapter have been described. These LCOs contribute to ensuring the availability of the system safety functions, and so that the risks for structural integrity of the SSCs and the fuel, radiological hazards, and management of wastes are reduced to ALARP for the UK ABWR lifetime. Key systems that have been described are:

Spent Fuel Storage Pool and Suppression Pool

The SFP and S/P chemistry related limits and conditions have been justified, and are based upon the reactor water chemistry controls since they are open to the reactor well water during outages. The capability of the FPC and the SPCU to maintain the system cleanliness, and maintain the structural integrity of the SFP and S/P and the system components for the UK ABWR lifetime has been described and justified.

The iodine behaviour during SA has been discussed, and the UK ABWR GDA design employs S/P pH control. Additionally, the release of iodine and long lived FPs to the atmosphere during a severe accident is reduced to ALARP by the safety functions of the FCVS vent filter. This includes the LCO requirement to maintain the FCVS Vent Filter scrubber solution concentration. Accident chemistry scenarios and related system safety functions are linked to PCSR Chapter 24 and 26.

Sampling and Monitoring System

The sampling and monitoring design objectives for the chemistry management of the UK ABWR has been presented in Section 23.11. These are based upon the need to sample, suitable sampling and monitoring methods, ensuring samples are representative, and the safe handling of the sampling fluids to ensure that worker dose and release to the environment are minimised. Recycling of the sample effluents has been discussed and the ALARP justification presented. The data collected from sampling and monitoring systems ensures the performance of the plant for proper operation and maintenance (i.e. general plant, systems and components). This is achieved by taking measurements of plant process fluids for parameters such as, direct conductivity, pH, dissolved hydrogen, DO, chemical impurities and radioactive species. Such measurements are obtained either by using on-line process instruments or by chemical analysis of samples extracted from systems at grab sampling points. Sections 23.4-23.10 have presented the parameters that are necessary to be managed for safe operation.

Radioactive Waste Management System

The OG system management of the radiolysis gases by recombination of hydrogen and oxygen to water to prevent flammability in the system has been addressed in the Primary Coolant section 23.4.6. Furthermore, the OG reduces the emissions from tritium and radioisotopes of oxygen, through the recycling of the primary system coolant water and the recombined water, which is returned to the reactor coolant circuit for reuse. The ALARP justification for the OG system, including this aspect, is addressed in PCSR Chapter 18.

Since modern fuel is designed to be more robust to cladding defects that will lead to fission product release to the coolant, the fission products, iodine and noble gas discharges are expected to be relatively low in comparison to the industry standards.

The noble gases are abated by the configuration of the OG, which has four, all welded, activated charcoal beds in series, and effects good practice and operating experience from across the nuclear industry. This ensures that the doses to the public during normal operations are minimised by reducing the potential for leakage of gases (thereby ensuring the gaseous discharges pass through filtration systems that remove particulate material) and providing an effective delay time for radionuclides.

### Summary of ALARP Justification

In summary, the materials selection and the chemical controls for the auxiliary systems that are described in this document have been optimised to ensure that the risk of corrosion related failure has been reduced to ALARP. This also ensures that the systems are able to perform to the design expectations and meet the safety functions, according to their safety categorisation and classification as detailed in the referenced engineering and mechanical PCSR chapters.

The generic UK ABWR system design, chemistry controls, and materials selection has been optimised and is based upon RGP, industry standards and operating experience. These incorporate the following factors:

- Proven system designs from OPEX and industry standards,
- Optimised materials selection,
- Minimisation of impurities ingress, and mitigations for control and prevention, and
- Representative and timely sampling and monitoring for detection and intervention, based on OPEX and RGP.

The benefits and detriments of the chemistry regimes that are proposed for the UK ABWR GDA design systems covered by PCSR Chapter 23 are therefore ALARP.

It can be expected that technology developments will continue for the industry as a result, and these can be expected to be reviewed and assessed if they are considered to be of proven effectiveness, reliable and are reasonably practicable for implementation for the UK ABWR through its lifetime.

## **23.14 Conclusions**

This PCSR Chapter - Reactor Chemistry provides a summary description of the reactor chemistry safety related considerations for the UK ABWR RCS and associated systems and the auxiliary systems. It also summarises additional UK ABWR design aspects related to chemistry controls such as sampling and monitoring, back-up building (the FLSS), make-up water chemistry, and the radioactive waste management system. It makes linkages to elsewhere within the safety case for PCV, FCVS, decommissioning and accident chemistry.

The choice of materials for the systems is a key parameter in ensuring the safe operation of the UK ABWR. Based upon the materials choices, the chemistry controls that are in place have been optimised to ensure that the integrity of the materials in terms of corrosion risk and for the minimisation of the source term are holistically and sufficiently met in the generic UK ABWR design.

The key chemistry parameters that have been described and justified in PCSR Chapter 23 include the main aspects of the design optimisation. The design optimisations provide the means to achieve the nuclear safety objectives of radiation protection, SSC and fuel integrity, minimisation of the environmental impact, minimisation of hazards (such as flammability hazards), whilst reducing the overall risk to the workers and public ALARP, and additionally maintaining suitable operational performance.

Due to the number of chemistry and radiochemistry parameters that comprise the chemistry regimes (RCS and associated systems and auxiliary systems) both as additives and as impurities, and their variation in concentration and behaviour throughout the different modes of the reactor operational cycle, an overall balance has been carried out to establish the benefits and disbenefits of each possible solution, in accordance with demonstrating the principles of ALARP.

PCSR Chapter 23 describes where the claims, arguments and evidence that substantiate the safety case for reactor chemistry have been presented in the supporting documents. Top claims have been identified for the reactor chemistry safety case, of which seven top claims are directly related to the RCS and associated systems chemistry management and control. The remaining top claims relate to the specific auxiliary systems described. For ease of reference the claims and the key supporting documents relevant to reactor chemistry are also presented in the 'Reactor Chemistry Claim Table'

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presented in Appendix A, and the 'Document Map' in Appendix B respectively. The links to the other chapters of the PCSR have been identified to ensure that consistency across the whole safety case is clear.

As a result of the studies and optioneering carried out, the preferred option for the UK ABWR reactor chemistry regime is to implement HWC+OLNC+DZO. A comprehensive and holistic optioneering and safety assessment approach has been undertaken considering all modes of operation and the potential risks associated with the reference design in order to determine the preferred options. This approach has confirmed that the risks are reduced to ALARP through incorporation of the chemistry regime proposed and it is now an input into the UK ABWR design.

The auxiliary systems that play a role in the chemistry (and radiochemistry) of the RCS and associated systems, or contribute to achieving the claims associated with the RCS and associated systems for the generic UK ABWR design have been considered in this PCSR chapter. These systems include the sections 23.5 to 23.8 for the SFP, SLC, S/P, and Make-up Water, Treatment and Storage respectively, and describe how the high purity water supply is distributed to the PWST, CST and the major system components, the auxiliary systems, back-up building systems (the FLSS), and the radioactive waste management system. The chemistry of the auxiliary systems contributes to the safety of the plant during normal operation through the management of the closed cooling water systems and radioactive waste.

The reactor chemistry control parameter action levels to ensure good management of the chemistry are not fixed in the GDA scope, and are therefore not described in this PCSR chapter. However, the LCOs for the chemistry control have been included and support the claims. The ability of the plant to implement the chemistry regimes proposed has been incorporated into the generic design, and hence the capability and availability of the plant to deliver the chemistry is assured.

The Sampling Systems of the generic UK ABWR will be able to carry out measurement techniques that are suitable to achieve the representative monitoring and sampling of the chemistry parameters that are specified for the plant process fluids (liquids and gases) so that the operators have accessible, accurate and reliable information about the plant status. This ensures that the chemistry will be controlled to ensure the nuclear safety objectives, and to ensure operational availability. Section 23.11 details the sampling system design considerations related to the generic UK ABWR, and which are taken forward for the site specific stage.

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It is concluded that the UK ABWR design incorporates features that facilitate the implementation and maintenance of the reactor chemistry regime, and therefore enables the UK ABWR to be operated safely using the procedures and equipment described. Faults and hazards have been identified and all risks are shown to be reduced, or capable of being reduced to ALARP. Therefore, PCSR Chapter 23 demonstrates that the generic UK ABWR chemistry regimes for the plant systems described can be implemented safely with the associated risks reduced to ALARP.

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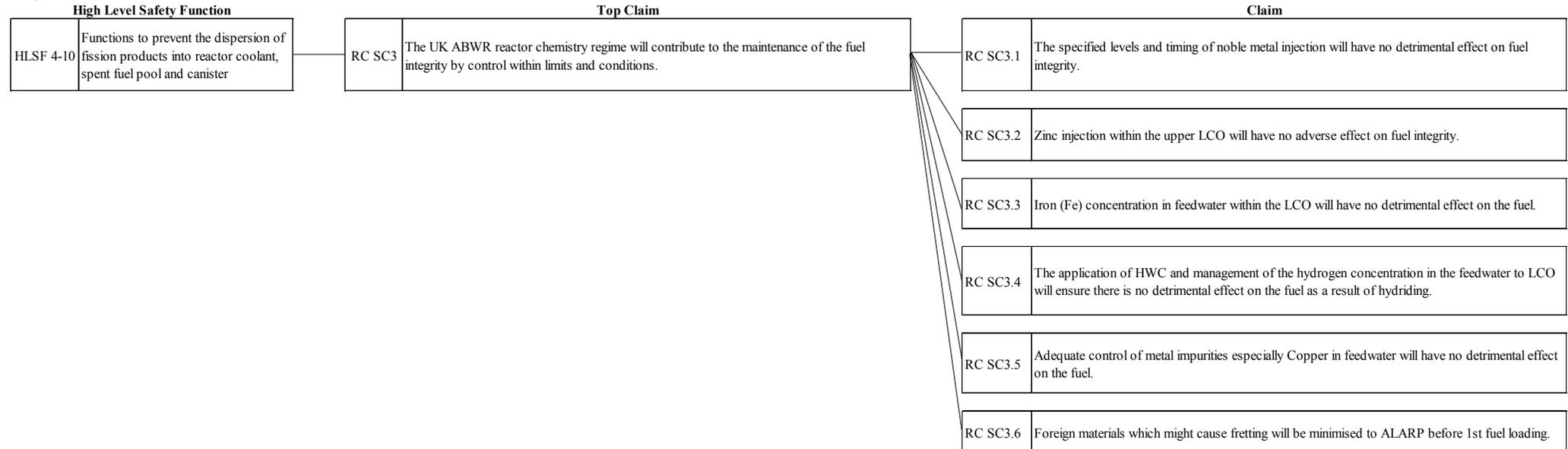
## Appendix A Reactor Chemistry Claim Table

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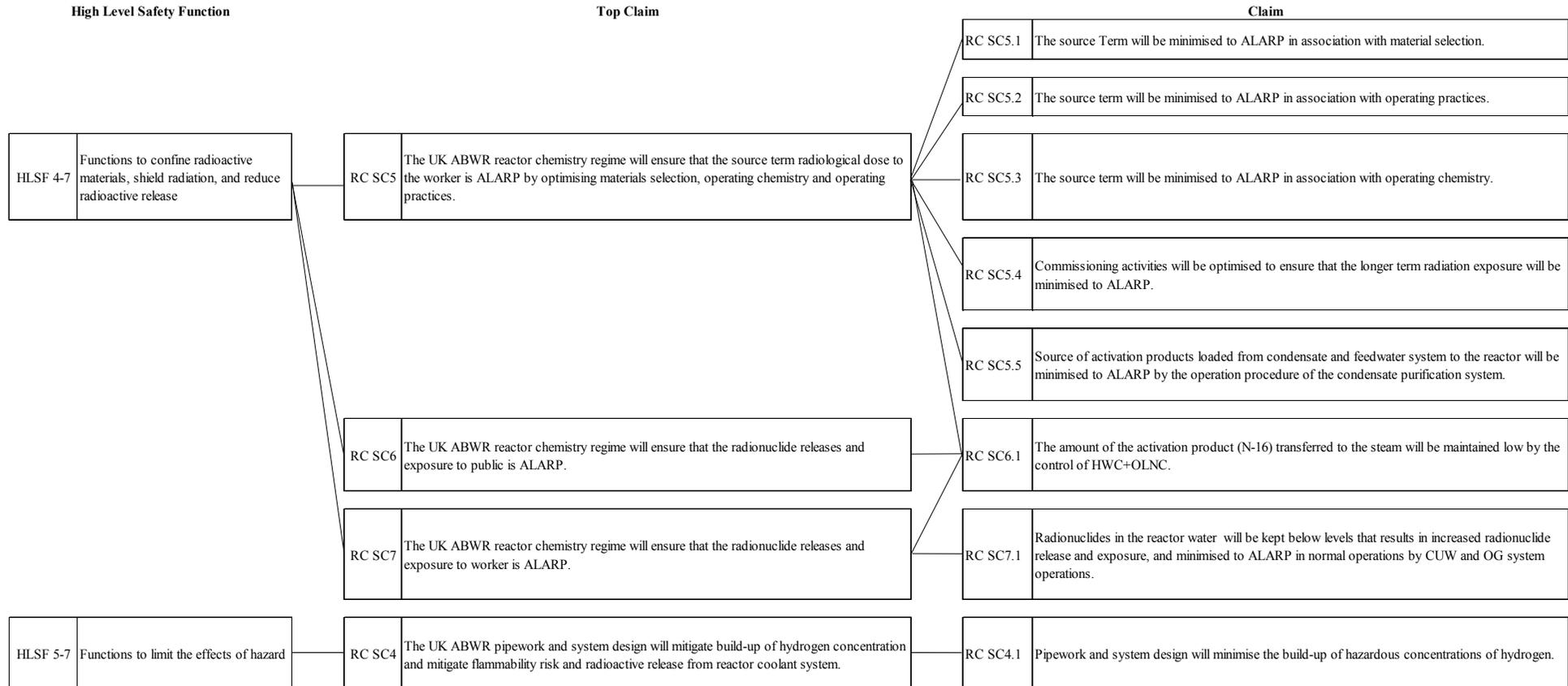
23.4 Reactor Coolant System and Associated Systems Chemistry

High Level Safety Function		Top Claim		Claim	
HLSF 4-1	Functions to form reactor coolant pressure boundary	RC SC1	The UK ABWR reactor chemistry regime will contribute to the maintenance of the integrity of the Reactor Pressure Vessel (RPV) and SSCs in contact with the reactor coolant by controlling within the limits and conditions.	RC SC1.3	Stress Corrosion Cracking (SCC) propagation will be mitigated during startup by minimising the reactor water oxygen.
		RC SC2	The UK ABWR reactor chemistry regime will contribute to the maintenance of the integrity of the associated SSCs which contact with reactor water outside of the RPV by controlling within the limits and conditions.	RC SC1.1	Stress Corrosion Cracking (SCC) propagation will be mitigated by appropriate Electrochemical Corrosion Potential Control by HWC and OLNLC.
				RC SC1.2	Corrosion (such as SCC, FAC)and corrosion rates will be mitigated by control of impurities by operation of the clean-up systems.
				RC SC2.1	Corrosion such as Flow Accelerated Corrosion (FAC) and pitting corrosion will be reduced by O <sub>2</sub> control.
				RC SC2.2	Impurities such as silica will be minimised to ALARP to reduce the scale adhesion in turbine system by operation of the CUW.

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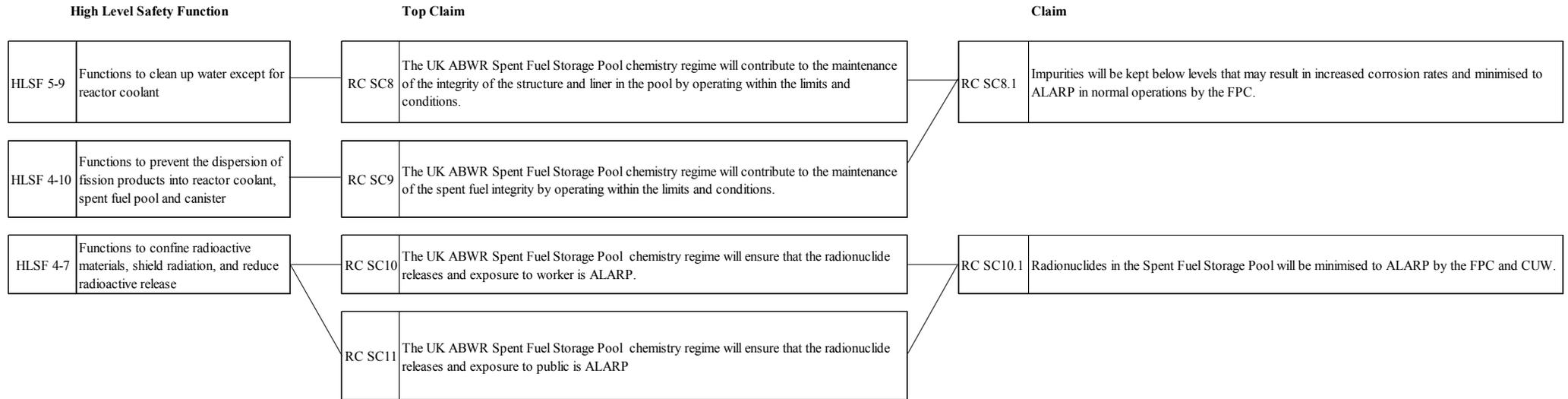


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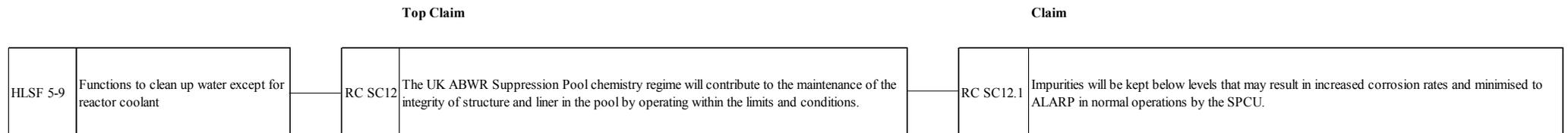


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23.5 Spent Fuel Storage Pool Chemistry Control



23.6 Suppression Pool Chemistry Control



Chapter 5.6

23.11 Sampling and Monitoring

High Level Safety Function

Top Claim

Claim

HLSF 5-4	Monitoring functions of plant conditions to support operator actions
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RC SC13	The UK ABWR sampling and monitoring systems will ensure that the plant is operated within the limits and conditions.
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RC SC13.1	Chemistry and radiochemistry control parameters will be sampled and monitored in accordance with the sampling philosophy.
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23.7 Standby Liquid Control System Water Chemistry

Top Claim

Claim

HLSF 1-5	Function of alternative reactivity control
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RC SC14	The UK ABWR Standby Liquid Control System chemistry will ensure safe shutdown of the reactor in the event of Anticipated Transient Without Scram (ATWS) by injecting neutron absorber solution into the reactor water.
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RC SC14.1	Sufficient and available sodium pentaborate solution is stored and maintained in an available state in the SLC.
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23.9 Component Cooling Water Systems Chemistry

Top Claim

Claim

HLSF 2-4	Function to cool spent fuel outside the reactor coolant system
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RC SC15	The chemistry of the component cooling water contributes to minimise the corrosion of its system materials to maintain their integrity and heat transfer function by ensuring a corrosion controlled environment when operated within the limits and conditions.
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RC SC15.1	Corrosion of SSCs of carbon steel, stainless steel and copper will be minimised by the addition of nitrite based corrosion inhibitors.
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Chapter 5.6

23.8 Make-up Water, Treatment and Storage

High Level Safety Function

Top Claim

Claim

HLSF 5-11	Supporting functions to supply power (except for emergency supply)
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RC SC16	The water quality produced and stored by the MUWC and CST is very pure and therefore it will not contribute to the equipment material degradation that it comes into contact with.
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RC SC16.1	Water quality control within specified limits in the CST will ensure the water quality of the RCS and associated systems.
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RC SC16.2	Water quality control within specified limits in the MUWP (Purified Water Storage Tank water) will ensure the water quality of the RCS and associated systems.
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23.10 Back-up Building - FLSS Water Chemistry Control

Top Claim

Claim

HLSF 2-2	Function of alternative fuel cooling
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RC SC17	The UK ABWR FLSS water quality will ensure the system will provide cooling water to prevent core damage when required.
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RC SC17.1	The water quality will be maintained and will not degrade the integrity of the structural material of the FLSS during the standby mode.
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Appendix B Document Map

