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General Nuclear System Ltd.

UK HPR1000 GDA Project

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Preliminary Safety Report
Chapter 21
Reactor Chemistry

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21.1 List of Abbreviations and Acronyms

ALARP	As Low As Reasonably Practicable
APG	Steam Generator Blowdown System [SGBS]
ATE	Condensate Polishing system [CPS]
AVT	All Volatile Treatment
BAT	Best Available Techniques
BFX	Fuel Building
BOC	Beginning of Cycle
BRX	Reactor Building
CGN	China General Nuclear Power Corporation
CIPS	Crud Induced Power Shifts
DBC	Design Basis Condition
DEC	Design Extension Condition
EBA	Enriched Boric Acid
EPRI	The Electric Power Research Institute
FAC	Flow-Accelerated Corrosion
GDA	Generic Design Assessment
HPR1000	Hua-long Pressurized Reactor
HPR1000 (FCG3)	Hua-long Pressurized Reactor under construction at Fangchenggang nuclear power plant unit 3
IAEA	International Atomic Energy Agency
IGA	Intergranular Attack
IRWST	In-Containment Refuelling Water Storage Tank
IVR	In-Vessel Retention
KRT	Plant Radiation Monitoring System [PRMS]
LOCA	Loss of Coolant Accident
NDT	Non Destructive Test
PSR	Preliminary Safety Report
pH_T	High-temperature pH Value
PTR	Fuel Pool Cooling and Treatment System [FPCTS]

PWSCC	Primary Water Stress Corrosion Cracking
PZR	Pressurizer
RBS	Emergency Boration System [EBS]
RCP	Reactor Coolant System [RCS]
RCPB	Reactor Coolant Pressure Boundary
RCV	Chemical and Volume Control System [CVCS]
REA	Reactor Boron and Water Makeup System [RBWMS]
REN	Nuclear Sampling System [NSS]
RGP	Relevant Good Practice
RIS	Safety Injection System [SIS]
RPE	Nuclear Island Vent and Drain System [VDS]
RPV	Reactor Pressure Vessel
RRI	Component Cooling Water System [CCWS]
SCC	Stress Corrosion Cracking
SED	NI Dematerialized Water Distribution System [DWDS(NI)]
SER	CI Dematerialized Water Distribution System [DWDS(CI)]
SFAIRP	So Far As Is Reasonably Practicable
SFP	Spent Fuel Pool
SG	Steam Generator
SIT	Feedwater Chemical Sampling System [FCSS]
STP	Standard temperature and pressure (273.15 K and 1 atm)
TEG	Gaseous Waste Treatment System [GWTS]
TEP	Coolant Storage and Treatment System [CSTS]
TSP	Tri-Sodium Phosphate
UK HPR1000	The UK version of the Hua-long Pressurized Reactor
VCT	Volume Control Tank
WANO	World Association of Nuclear Operators

System codes (XXX) and system abbreviations (YYY) are provided for completeness in the format (XXX [YYY]), e.g. Reactor Coolant System (RCP [RCS]).

21.2 Introduction

The chemistry programme for the UK version of the Hua-long Pressurized Reactor (UK HPR1000) will be developed during the next stages of the Generic Design Assessment (GDA) process based on that currently proposed for the Hua-long Pressurized Reactor under construction at Fangchenggang nuclear power plant unit 3 (HPR1000 (FCG3)). For the Preliminary Safety Report (PSR), this chapter describes the proposed chemistry programme for the HPR1000 (FCG3).

The aim of a reactor chemistry programme is defined in Reference [1] as follows:

The chemistry programme should provide the information and support relating to chemistry and radiochemistry necessary to ensure safe operation, long term integrity of structures, systems and components, and minimization of buildup of radioactive material and limiting of radioactive and chemical discharges to the environment.

First of all, in sub-chapter 21.3 the design objectives are made on reactor chemistry to support the top level design objectives for the PSR and then in sub-chapter 21.4, the design principles that support these reactor chemistry design objectives are outlined.

Sub-chapter 21.5 provides an overview of the evolution of the HPR1000 (FCG3) design and how relevant good practice has been incorporated into the design.

Then, how the HPR1000 (FCG3) intends to satisfy the design principles for the primary circuit, secondary circuit, auxiliary and other systems is described in sub-chapters 21.6, 21.7 and 21.8 respectively in terms of the chemistry regimes and material selections. This supports chapters 5 and 6 respectively.

Sub-chapter 21.9 briefly considers chemistry in accident conditions.

21.3 Reactor Chemistry Design Objectives

This chapter supports the following high level objectives made in chapter 1 of the PSR, namely:

- Design Development & Organisational Arrangements

  UK HPR1000 design will be developed in an evolutionary manner, using robust design processes, building on relevant good international practice, to achieve a strong safety and environmental performance.

- Nuclear Safety - protection of the workers and the public

  The design and intended construction and operation of UK HPR1000 will protect the workers and the public by providing multiple levels of defence to fulfil the fundamental safety functions.

- Radiological & Environmental Protection, Security & Industrial Safety

  The design, and intended construction and operation, of UK HPR1000 will be developed to reduce the impact on the workers, the public, and the environment So Far As Is Reasonably Practicable (SFAIRP) in Reference [2].

- Decommissioning

  UK HPR1000 will be designed, and is intended to be operated, so that it can be decommissioned safely, using current methods, and with minimal impact on the environment and people.

This chapter will demonstrate the following aspects:

- Primary System Water Chemistry is controlled to avoid corrosion compromising the integrity of the fuel cladding and the primary circuit components.
- Secondary System Water Chemistry is controlled to avoid compromising the effectiveness of the heat transfer, and to reduce corrosion to the secondary circuit components.
- Primary Circuit Water Chemistry and material selection will control the formation and transfer of activated corrosion products.

How reactor chemistry supports these top level design objectives is described in turn for each design objective below.

21.3.1 Support for Top Level Design Objectives

- Design Development & Organisational Arrangements

  UK HPR1000 design will be developed in an evolutionary manner, using robust design processes, building on relevant good international practice, to achieve a strong safety and environmental performance.

  Sub-chapter 21.5 below describes how the HPR1000 (FCG3) has been developed with respect to reactor chemistry and material selection and how relevant good international practice has been incorporated into the design.

- Nuclear Safety - protection of the workers and the public

  The design, and intended construction and operation of UK HPR1000 will protect the workers and the public by providing multiple levels of defence to fulfil the fundamental safety functions.

  The three fundamental safety functions are:

  - Control of reactivity.
  - Removal of heat from the reactor and from the fuel store.
  - Confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases.

Reactor chemistry plays a central role in all three aspects as outlined below:

- Control of reactivity

  Reactivity control is supported through addition of boron neutron absorber to the reactor coolant.

- Removal of heat from the reactor and from the fuel store

  Primary circuit water chemistry is controlled (in all operational modes) to maintain effective heat transfer (for example by limiting deposits on the fuel cladding).

  Secondary circuit water chemistry is controlled (in all operational modes) to maintain the integrity and heat-transfer performance of Steam Generator (SG) tubes.

  Chemistry in the Spent Fuel Pool (SFP) is controlled to minimise corrosion of the fuel assemblies to ensure effective heat transfer from the fuel and also to minimise corrosion of construction materials to ensure there are no leakages from the SFP.

- Confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases

  Primary circuit water chemistry is controlled (in all operational modes) to maintain the integrity of the fuel cladding, to maintain the integrity of the primary circuit structural materials, and to control the formation, build-up, and transport of radioactive activation and corrosion products and the transport of radioactive fission products so as to balance effectively - and reduce SFAIRP - doses to personnel, formation of operational and decommissioning radioactive wastes, and discharges to the environment.

  Secondary circuit water chemistry is controlled (in all operational modes) to maintain the integrity of the Reactor Coolant Pressure Boundary (RCPB), SG internals and other secondary system components and thereby prevent any radioactivity in the primary coolant from being released to the environment.

- Radiological & Environmental Protection, Security & Industrial Safety

The design, and intended construction and operation of UK HPR1000 will be developed to reduce the impact on the workers, the public and the environment SFAIRP.

As mentioned above, formation, build-up, and transport of radioactivity are reduced SFAIRP; this will reduce the impact on the operators in terms of dose. However, it is not possible to eliminate this completely and then the competing objectives of reducing accumulation of radioactive waste and hence doses to workers (during operation and decommissioning) and reducing discharges to the environment need to be effectively balanced or optimised.

- Decommissioning

  UK HPR1000 will be designed, and is intended to be operated, so that it can be decommissioned safely using current methods and with minimal impact on the environment and people.

  This design objective as described above is supported by reducing formation, build-up and transport of radioactivity SFAIRP.

21.3.2 Defence-in-Depth

The reactor chemistry described here is mainly concerned with the first two levels of Defence-in-Depth which are defined in Reference [3] as follows:

- The purpose of the first level of defence is to prevent deviations from normal operation and the failure of items important to safety.
- The purpose of the second level of defence is to detect and control deviations from normal operational states in order to prevent anticipated operational occurrences at the plant from escalating to accident conditions.

Reactor chemistry in accident conditions is described in sub-chapter 21.9; however, this has yet to be fully developed for UK HPR1000 and is not described in any detail here.

21.4 Design Principles on Reactor Chemistry

21.4.1 Primary Water Chemistry

From Reference [4], the design principles for primary water chemistry are:

- Reactivity control will be supported through addition of boron neutron absorber in reactor coolant.
- Primary circuit water chemistry is controlled (in all operational modes) to maintain the integrity of the fuel cladding, to maintain the integrity of the primary circuit structural materials, to maintain effective heat transfer and to control the formation, build-up, and transport of radioactive activation and corrosion products and the transport of radioactive fission products so as to balance effectively. And this will reduce doses to personnel, formation of operational and decommissioning radioactive wastes and discharges to the environment SFAIRP.
- An important consideration of material selection used in UK HPR1000 primary circuit components is the resistance to corrosion, appropriate surface finishing and/or pre-treatment of surfaces and absence or low content of isotopes susceptible to activation to significant radionuclides. In order to reduce doses to personnel, formation of radioactive waste, and discharges to the environment As Low As Reasonably Practicable (ALARP). For another factor, formation of radioactive waste discharges to the environment and alignment to the chosen chemistry regime will be controlled.

- An important consideration in the choice of additives to the primary coolant will be absence or low content of isotopes susceptible to activation to significant radionuclides so as to reduce doses to personnel, formation of radioactive waste and discharges to the environment SFAIRP.
- The purity of the coolant and any chemical additives will be controlled to limit the presence of any impurities and especially those susceptible to activation to significant radionuclides SFAIRP.
- Operating limits for chemical parameters important for safety or diagnostic for the intended operation of the chemical regime will be specified as will actions to be carried out in the event that any limit is breached.
- Detection, monitoring, and sampling will be carried out to confirm the behaviour of primary chemistry is as intended and to confirm operation is within specified limits for chemical parameters, ensure doses to personnel are ALARP, and formation of radioactive waste, and discharges to the environment, are reduced in line with Best Available Techniques (BAT) principles.

Auxiliary systems and other systems that interface with the Reactor Coolant System (RCP [RCS]), in addition to maintaining the integrity of their own components, help to support the primary chemistry design principles listed above. These systems are described in more detail in sub-chapter 21.8.1 and chapter 10 and in sub-chapter 21.9 and in chapter 7; they include:

- Chemical and Volume Control System (RCV [CVCS])
- Reactor Boron and Water Makeup System (REA [RBWMS])
- Coolant Storage and Treatment System (TEP [CSTS])
- Safety Injection System (RIS [SIS]) which includes the In-Containment Refuelling Water Storage Tank (IRWST)
- Emergency Boration System (RBS [EBS])
- Nuclear Sampling System (REN [NSS])
- Component Cooling Water System (RRI [CCWS])

21.4.2 Secondary Water Chemistry

The design principles for secondary water chemistry are:

- Secondary water chemistry is controlled to maintain the integrity and heat-transfer performance of SG tubes, and to maintain the integrity of the RCPB, SG internals and other secondary system components.
- To reduce corrosion and Flow-Accelerated Corrosion (FAC) of SG internals and other secondary system components.

- Operating limits for chemical parameters important for safety or diagnostic for the intended operation of the chemical regime will be specified as will actions to be carried out in the event that any limit is breached.

- Detection, monitoring, and sampling will be carried out to confirm the behaviour of the secondary circuit chemistry is as intended and to confirm operation is within specified limits for chemical parameters, ensure doses to personnel are ALARP, formation of radioactive waste, and discharges to the environment, are reduced in line with BAT principles.

Auxiliary systems and other systems that interface with the secondary circuit, in addition to maintaining the integrity of their own components, help to support the secondary chemistry design principles listed above. These systems are described in more detail in sub-chapter 21.8.2 and for some also in chapter 10 or chapter 11, they include:

- CI Demineralised Water Distribution System (SER [DWDS(CI)])

- Steam Generator Blowdown System (APG [SGBS])

- Condensate Polishing System (ATE [CPS])

- Nuclear Sampling System (REN [NSS])

- Feedwater Chemical Sampling System (SIT [FCSS])

- Plant Radiation Monitoring System (KRT [PRMS])

21.4.3 Spent Fuel Pool Water Chemistry

The design principles for the SFP water chemistry are:

- SFP water chemistry is controlled to reduce corrosion of the spent fuel assemblies and the structural components of the SFP.

- The SFP water is filtered and the surface skimmed to maintain visibility in the SFP.

- Detection, monitoring, and sampling will be carried out.

The Fuel Pool Cooling and Treatment System (PTR [FPCTS]) auxiliary system interfaces with the SFP, and helps to support the chemistry design principles listed above. This system is described in more detail in sub-chapter 21.8.3 and chapter 10.

21.5 Design Evolution and Incorporation of RGP into Design

The HPR1000 (FCG3) has been developed from PWR in China incorporating over 30 years' operating experience from that design at Daya Bay Nuclear Power Plant. Several new design features have been incorporated into the HPR1000 (FCG3) design including:

- Use of Enriched Boric Acid (EBA)

- Direct hydrogen injection from the hydrogenation station instead of using the Volume Control Tank (VCT)

The benefits of these new features are discussed in sub-chapter 21.6 below.

China General Nuclear Power Corporation (CGN) has also conducted its own research programmes and, for example, has built a test facility to test the capacity of hydrogen dosing system in the hydrogenation station of the RCV [CVCS] - one of the new design features mentioned above.

In addition to its own operating experience, CGN is able to take advantage of developments and advances made worldwide through its membership of World Association of Nuclear Operators (WANO) and its participation in the following Electric Power Research Institute (EPRI) programs:

- Water Chemistry
- Advanced Nuclear Technology
- Nuclear Maintenance Applications Centre
- Steam Turbines-Generators and Auxiliary Systems
- Fuel Reliability
- Instrumentation and Control

An example of the incorporation of international Relevant Good Practice (RGP) is the use of a constant high High-temperature pH Value (pH_T) regime which is discussed in sub-chapter 21.6.1 below.

In addition to EPRI, other sources of international good practice such as the IAEA - who has produced the Reference [1] mentioned earlier and Reference [5] - will be drawn on and monitored for any new information during the project.

This information and experience will be supplemented by additional theoretical analysis specific for UK HPR1000 during the GDA.

During the lifetime of the plant, CGN operating experience from the HPR1000 (FCG3), the Taishan EPR (which also incorporates use of EBA and the hydrogenation station design improvements mentioned above), and UK HPR1000, as well as relevant good practice from other plants worldwide, will be monitored and if possible used to improve performance and ensure doses to personnel are ALARP, and formation of radioactive waste, and discharges to the environment if possible, are reduced in line with BAT principles.

There is no zinc injection implementation for HPR1000 (FCG3); however, CGN has already paid great attention to this RGP, and will determine whether zinc injection in the primary coolant will be implemented for UK HPR1000 according to the research results.

21.6 Primary Circuit

As mentioned earlier, the specific primary circuit chemistry regime and material selection for UK HPR1000 GDA design reference point have not yet been decided. The description below is based on what is proposed for the HPR1000 (FCG3).

As mentioned above the water chemistry regime and material selection sometimes have to balance the competing objectives of fuel integrity, integrity of other components, exposure of workers, production of radioactive waste, and discharges to the environment.

The design intent of UK HPR1000 at the PSR stage is to not preclude scope for the eventual operators of the plant to adjust this balance to suit their own reliability or regulatory requirements; the operating envelope within which parameters may be varied will be specified at a later stage in the UK licensing.

21.6.1 Primary Water Chemistry

21.6.1.1 Reactivity Control

The HPR1000 (FCG3) will use EBA to control reactivity. B-10 is a neutron absorber and so dissolving boron in the primary coolant in the form of boric acid allows the reactivity to be controlled by varying the boric acid concentration.

The means of reactivity control is described in more detail in chapter 5 describing the Reactor Core (sub-chapter 5.4.2.4.2).

Adding boric acid would reduce the pH and increase corrosion and so the pH has to be controlled by adding lithium as discussed next. Adding boric acid can also result in boron deposits which can lead to Crud Induced Power Shifts (CIPS).

The quantity of boric acid that needs to be added to control reactivity can be reduced by enriching the B-10 - the neutron absorbing isotope - in natural boron. Natural boron contains about 20% B-10 and so enrichment would reduce the boric acid needed proportionately. The use of EBA would in turn reduce the lithium needed to control the pH and may reduce the risk of boron deposition, although any crud formed would also be enriched in B-10 and so crud minimisation continues to be important for avoiding CIPS.

The use of EBA has a number of benefits including:

- It allows a high pH to be used throughout the cycle (see discussion on pH control below).
- It allows a constant pH to be used throughout the cycle (once the xenon equilibrium has been achieved after the first few days) avoiding any effects induced by changing the pH.

- The maximum lithium levels needed to maintain the high pH at the start of cycle are lower reducing the potential for corrosion of zirconium alloy fuel cladding.
- The volume of borated water that the RBS [EBS] needs to inject in the event of Design Basis Condition (DBC) 2-4 and Design Extension Condition (DEC) -A conditions is less avoiding overflow of the Pressurizer (PZR).

This is an example of the adoption of relevant good practice and incorporation of operational experience.

21.6.1.2 pH Control

Lithium is added to maintain an optimal pH_T to limit corrosion and maintain the structural integrity of core components, and to control the solubility and transport of activated corrosion products around the primary circuit.

A Li-B coordinated regime will be used maintaining a constant high $pH_{300℃}$ of 7.2 throughout the cycle (once the xenon equilibrium has been achieved after the first few days of the cycle).

A $pH_{300℃}$ of 7.2 (as a maximum level) has been used successfully at Daya Bay Nuclear Power Plant and moving to a constant high pH is expected to yield even better results.

EPRI reports that elevated and constant pH_T regimes have been employed at a number of PWRs worldwide as a means of reducing corrosion product deposition in-core; emphasis was placed on a constant pH_T regime with tight lithium control rather than the previous modified pH_T approach in an attempt to reduce the mobility of crud during the operating cycle.

For UK HPR1000, a detailed ALARP assessment will be performed to determine the optimum regime taking account of the latest operating experience and recommendations available at the time.

As less boric acid is needed as fuel is depleted through the cycle, less lithium is also needed to maintain the pH value.

Formation of tritium from activation of Li-6 (~7% in natural lithium) is minimised by using lithium enriched to 99.9% in Li-7.

Too high a concentration of lithium can increase corrosion of zirconium alloy fuel cladding and the fuel manufacturer may impose a limit on the maximum lithium concentration. For UK HPR1000, the decision has not yet been taken by fuel supplier, as detailed technical evaluation of the supply chain is proposed before this selection is made (see chapter 5). The type of fuel cladding, fuel assembly or core component is therefore not defined; this will be determined in a later stage of GDA. However, the use of EBA means that less lithium is needed to maintain the pH than would be the case with natural boric acid. The maximum lithium concentration to be used for the HPR1000 (FCG3) is 3.5 mg/kg; this value was chosen on the basis of CGN’s good operating experience at Daya Bay Nuclear Power Plant.

The pH is controlled by the RCV [CVCS] (see sub-chapter 21.8 below and chapter 10).

21.6.1.3 Electrochemical Potential Control

Radiolysis of the coolant will produce oxygen which would lead to Stress Corrosion Cracking (SCC) of stainless steel. Oxygen production is suppressed by adding hydrogen and maintaining the hydrogen concentration at an optimal level to keep the electrochemical potential sufficiently low to prevent the SCC of stainless steel during power operation. In addition, make-up water to the primary circuit will be degassed to keep the oxygen levels within the specified limits.

Hydrogen is added from the hydrogenation station of the RCV [CVCS] instead of to the VCT. This is a design improvement introduced for the HPR1000 (FCG3) and has the following benefits:

- The VCT has a nitrogen blanket instead of hydrogen which reduces the hydrogen explosion hazard (internal hazards are discussed in chapter 19).
- With direct hydrogen injection, hydrogen concentration control is more accurate and efficient.
- It avoids the complex operation of gas displacement in the VCT during shutdown and startup–hydrogen replaced by nitrogen replaced by air and then back again.

The hydrogenation station may have the disadvantage of introducing N-14 into the primary circuit as a nitrogen blanket is maintained in the VCT; this may lead to the formation of C-14 from activation of N-14. This will need to be balanced with the benefits to show that this measure is ALARP for UK HPR1000.

CGN has built a test facility to test the capacity of the hydrogen dosing system and testing is ongoing.

The TEP [CSTS] degasification unit can remove hydrogen or oxygen from the reactor coolant if needed. The REA [RBWMS] adds deaerated water to the RCP [RCS] via the RCV [CVCS]; also the void space at the top of the boric acid storage tanks is connected to the Gaseous Waste Treatment System (TEG [GWTS]) to prevent re-oxygenation of the boric acid solution (see sub-chapter 21.8 below and chapter 10). All the water is deaerated as the oxygen concentration needs to be limited when temperature of coolant from the primary circuit is higher than 120 ℃.

Hydrogen addition can have some negative effects such as hydriding of the zirconium alloy fuel cladding and accumulation of combustible gases. It can also lead to the deposition of metallic nickel in the core and production of Co-58 by activation. Therefore an optimal level needs to be determined.

Another factor in identifying the optimum hydrogen concentration may be its effect on the initiation and propagation of Primary Water Stress Corrosion Cracking (PWSCC) in susceptible alloy 600, 82 and 182 components. HPR1000 (FCG3) steam generators will be tubed with alloy 690, and there are no PWSCC-susceptible alloy 600, 82 or 182 components in the primary circuit.

Daya Bay Nuclear Power Plant has operated with hydrogen levels limited to be in the range 20-50 cm^3(STP)/kg and Siemens plants have operated with levels between 17-45 cm^3(STP)/kg without significant drawbacks over the last decades. However, to reduce the negative effects mentioned above a lower level was considered for the HPR1000 (FCG3) but still high enough to remove oxygen; the EPRI Guidelines [3] state that the hydrogen levels required to suppress oxygen generation from radiolysis during power operation are in the range of “>1-5 cm^3 (STP)/kg” even when sub-cooled boiling is occurring.

The optimal limits for hydrogen for the HPR1000 (FCG3) were determined to be in the range 17-50 cm^3 (STP)/kg - the lower level being high enough to suppress radiolytic oxygen generation and the upper level being low enough to limit negative effects such as zirconium hydride and Co-58 production. A hydrogen level of 17-50 cm^3 (STP)/kg is also proposed for the Taishan EPR.

Again, for UK HPR1000, a detailed ALARP assessment will be performed to determine the optimum hydrogen levels taking account of the latest operating experience and recommendations available at the time.

21.6.1.4 Impurity Control and Primary Coolant Treatment

Impurities will be controlled to reduce local corrosion of structural materials and scaling of fuel cladding. For example, impurities such as chlorides, fluorides, and sulphates can cause corrosion of the primary system components and low solubility species such as calcium compounds, magnesium compounds, aluminium compounds, and silicon dioxide can deposit on fuel surfaces.

The various systems maintaining the purity of the primary coolant are described below.

The NI Demineralised Water Distribution System (SED [DWDS(NI)]) supplies non-degassed purified water make-up for the primary system and the nuclear auxiliary systems (at pH=7).

The RCV [CVCS] removes radioactive corrosion products, dissolved fission products, and gaseous fission product (via TEP [CSTS] degasification unit) from the RCP [RCS] (see sub-chapter 21.8 below and chapter 10). The majority of impurities in the primary circuit are removed by this system.

The TEP [CSTS] removes solid and ionic impurities and radioactive fission gases to reduce the radioactivity of the reactor coolant to be treated; it also removes the non-radioactive impurities listed above (see sub-chapter 21.8 below and chapter 10).

21.6.1.5 Other Operating Modes

Modification to the chemistry regime outlined above may be needed in operating modes other than normal power operation.

Startup and shutdown involve more radical changes to the coolant and material temperatures and pressures and to the chemical regime than is experienced during normal power operation; this may lead to effects such as crud bursts and SCC. Particular care will be needed in determining the chemical regime, monitoring its behaviour, and removing any additional activation and fission products that may become mobile particularly to avoid workers being exposed to higher doses during shutdown.

At Beginning of Cycle (BOC), a relatively high $pH_{300℃}$ of 7.1 is used until xenon equilibrium is reached after a few days; from this point on a constant high $pH_{300℃}$ of 7.2 is maintained.

During startup, oxygen needs to be removed; the concentration of dissolved oxygen must be less than 0.1 mg/kg during all sequences in which reactor coolant temperature is greater than 120 ℃. As the temperature is increased, oxygen can be reduced initially by venting the RCP [RCS] and vacuum pumping via the Nuclear Island Vent and Drain System (RPE [VDS]) (see chapter 23) and then up to 80 ℃ by injecting hydrazine at the charging pump inlet.

During startup, nickel is also removed at low temperature.

During shutdown, boration is carried out for reactivity control and the chemistry is changed from a reducing environment to an oxidizing environment to remove corrosion products.

The regime for commissioning will be developed much later in Nuclear Site Licensing and that industry operating experience will be taken into account in developing the chemistry commissioning regime for HPR1000 (FCG3).

21.6.2 Primary Circuit Material Selection

Chapter 6 provides more detail on materials, manufacture, and inspection for the components of the primary circuit.

For the Reactor Pressure Vessel (RPV), the reactor vessel internals and other parts of the primary circuit, materials will be selected from those for which there is mature engineering experience with consideration of resistance to irradiation, resistance to corrosion, resistance to abrasion and erosion, and good manufacturing performance. The materials used, Non Destructive Test (NDT), welding, and the requirements of the manufacture should conform to are described in chapter 6.

The chemical element content of cobalt is strictly controlled in the core active region to limit the formation of activation products and reduce dose to workers during operation and decommissioning and radioactive waste to be decommissioned. Trace element optimisation will be considered during the procurement selection process for the forgings for the active region for UK HPR1000 as part of a review aimed at ensuring optimal materials performance.

21.7 Secondary Circuit

As with the primary circuit regime discussed above, the specific secondary circuit chemistry regime and material selection for UK HPR1000 GDA design reference point have not yet been decided. The description below is based on what is proposed for the HPR1000 (FCG3).

21.7.1 Secondary Water Chemistry

The secondary circuit will be operated according to an ‘All Volatile Treatment’ (AVT) with ammonia for pH control and hydrazine for oxygen scavenging.

An optimised pH_T will be selected with the following main objectives:

- Corrosion of SG tubes is minimised.
- FAC of other secondary components is minimised.
- Deposition of corrosion products in the SG is minimized.

Other considerations include:

- Compatibility with purification systems (e.g. more resin is consumed at higher pH).
- Planned radioactive discharges and generation of waste are minimised.

For the HPR1000 (FCG3), a $pH_{25℃}$ equal to 9.6~9.8 is proposed for the feedwater; this is based on CGN’s operating experiences at Daya Bay Nuclear Power Plant.

Hydrazine is used to scavenge oxygen and maintain a reducing environment in the secondary circuit. The reducing environment limits localized corrosion by Intergranular Attack (IGA) and SCC and by reducing the ferric oxide to magnetite can limit iron release and transport as sludge which might otherwise have harmful oxidising effects.

For UK HPR1000, the optimum pH, the pH raising additive (ammonia and/or an amine), hydrazine level, and whether to have a ATE [CPS] have yet to be determined and will be the subject of ALARP assessments later in the GDA.

21.7.2 Secondary Material Selection

In the HPR1000 (FCG3), Alloy 690 is used for the SG tubes to limit SCC, and trefoil design is selected for the broach holes geometry of the tube sheet and tube support plate; For other secondary systems susceptible to FAC, the systems are designed without copper material and the tubing material of the condenser is titanium. Carbon steel with chromium content restrictions is used as well as increasing the thickness. More detail on the materials, manufacture and inspection of the SGs can be found in chapter 6.

21.8 Auxiliary and Other Systems

The auxiliary systems and other systems that support control of the chemistry regime in the primary circuit, secondary circuit, and in the SFP are described in turn below. More detail on the auxiliary systems and some of other systems described below can be found in chapter 10, chapter 11, and chapter 7.

21.8.1 Primary Circuit Chemistry Control

The RCV [CVCS], REA [RBWMS] and TEP [CSTS] control primary water chemistry by:

- Adjusting the boron concentration.
- Removing impurities, corrosion products and radioactive species.
- Regulating concentrations of chemical agents.

The IRWST will be connected to the RCP [RCS] during refuelling and outage, whose water chemistry is controlled via PTR [FPCTS] filter and ion exchange resins, to limit impurities ingress into RCP [RCS].

The RRI [CCWS] protects the integrity of heat exchange interfaces by controlling the pH and removing impurities to limit material corrosion and scaling.

The role of the REN [NSS] is to provide suitable and sufficient monitoring, sampling and analysis of chemistry parameters of primary and auxiliary systems. It has on-line monitoring for boron, hydrogen, oxygen, Na^+, pH and conductivity. The primary sampling system also obtains liquid and gaseous samples from the primary coolant system, primary auxiliary systems, liquid and gaseous waste treatment systems, in order to determine the physical and chemical characteristics of these samples by measurement and analysis.

21.8.2 Secondary Circuit Chemistry Control

The SER [DWDS(CI)] supplies purified conditioned demineralised water for filling and make-up of conventional systems (at pH>9).

The APG [SGBS] and ATE [CPS] are used to purify the secondary water; they are described in turn below and in more detail in chapter 11.

The APG [SGBS] collects and treats the SG blowdown water to maintain the characteristics of the secondary side water within predetermined limits. After being cooled and depressurised, the blowdown water is transferred to the demineralising units for purification before being transferred to the condenser. The demineralising units consist of two lines in parallel, each of which has a cation bed demineralizer, an anion bed demineralizer, and a resin trap filter.

The ATE [CPS] is used to remove trace silicon, copper, iron and dissolved salts from the condensate at startup and in case of condenser leakage; this improves feedwater and steam quality and protects the steam-water system against contamination by the impurities seeping or leaking into the condensate. This helps decrease corrosion and fouling inside the SGs.

The REN [NSS] takes liquid samples from the SGs wet layup and the APG [SGBS] whose water chemistry parameters are then analysed by on-line instruments or laboratory equipment. The SIT [FCSS] monitors and takes samples of water or steam from other secondary circuit systems such as the feedwater and main steam for example. The KRT [PRMS] detects any increase of radioactivity in the secondary circuit which would be indicative of a leak between the primary and secondary circuits. The following are monitored: N-16 in the main steam, total γ in the SG blowdown, and total γ in the condenser. The sampling and monitoring are continuous and the samples are returned to the system.

21.8.3 Spent Fuel Pool

The PTR [FPCTS] carries out purification of the water in the Reactor Building (BRX) pools (including Reactor Cavity and Internals Storage Compartment), Fuel Building (BFX) pools (including the SFP, the BFX transfer compartment and cask loading pit), IRWST and In-Vessel Retention (IVR) tank. This is to remove impurities and dissolved radioactivity from the water; to maintain the chemical regime so as to minimize corrosion of stored fuel assemblies and of construction materials; and to maintain the visibility of the water.

21.9 Accident Chemistry

Modelling iodine behaviour under accident conditions will be one of the most important areas in the analysis of accident chemistry. In the severe accident analysis performed for HPR1000 (FCG3), CGN has modelled the pH of the containment water during the course of the accident and from this determined the re-suspension of any dissolved iodine into the containment atmosphere as elemental iodine. The analysis is ongoing and will be developed for UK HPR1000.

Some of the systems involved in and measures to control accident chemistry are described below.

The REN [NSS] post-accident sampling system can obtain gaseous samples from containment atmosphere and liquid samples from the IRWST in post-accident conditions.

In the event of a Loss of Coolant Accident (LOCA), pH control is achieved using Na_3PO_4 (Tri-Sodium Phosphate (TSP)) to limit re-suspension of dissolved iodine to the containment atmosphere and to limit component corrosion and the resulting hydrogen.

The RIS [SIS] and RBS [EBS] inject boron into the primary circuit for reactivity control during accidents. The RIS [SIS] and RBS [EBS] systems are described in more detail in chapter 7.

21.10 Conclusions

This chapter has shown how the proposed reactor chemistry programme for UK HPR1000 intends to support the top level design objectives of the PSR and supports the fundamental safety functions.

The HPR1000 (FCG3) reactor chemistry programme is based on well-established approaches and materials that have been developed and evolved over many years of PWR development in China and worldwide.

It would therefore be expected that UK HPR1000 would be comparable to other modern PWR designs in terms of safety, occupational exposure, radiological discharges, and radioactive waste production; this will be confirmed during the GDA and site licensing processes. The gap analysis underway will bring forward any areas that need further analysis or justification and these will be addressed during the GDA process or in site licensing as appropriate.

21.11 References

[1] IAEA, IAEA Safety Standards, Chemistry Programme for Water Cooled Nuclear Power Plants, Specific Safety Guide No. SSG-13, July 2011.

[2] ONR, New nuclear reactors: Generic Design Assessment Guidance to Requesting Parties, ONR-GDA-GD-001 Revision 3, September 2016.

[3] IAEA, IAEA Safety Standards, Safety of Nuclear Power Plants: Design, Specific Safety Guide No.SSR-2/1, February 2016.

[4] ONR, Nuclear Safety Technical Assessment, Chemistry of Operating Civil Nuclear Reactors， NS-TAST-GD-088, May 2017.

[5] IAEA, Optimization of Water Chemistry to Ensure Reliable Water Reactor Fuel Performance at High Burnup and in Ageing Plant (FUWAC), TECDOC-1666 October 2011.